Joonhong Ahn · Cathryn Carson
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Reflections on the Fukushima Daiichi Nuclear Accident

Toward Social-Scientific Literacy and Engineering Resilience

Springer Open

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Foreword

Looking back on the history of nuclear reactor accidents and incidents, it appears that serious or near-serious events have happened at least once a decade. With deep regret we must observe that the Fukushima Daiichi accident, which brought about a socially unprecedented disaster and has required an enormously lengthy process of cleanup, once again poses a fundamental question: can science and technology forestall the inevitability of serious reactor accidents? This publication is a leading attempt put forward by a U.S.–Japan team of experts to answer this question.

A number of investigative committee studies made thus far on each of the past accidents have repeatedly indicated that the vulnerability revealed of reactor safety is more or less closely connected with socio-technical factors, as well as insufficiency of appropriate technical measures. The necessity of managing these factors has been recognized as well, in the aftermath of the Fukushima Daiichi accident. For instance, it has been concluded that overconfidence regarding safety measures against tsunami events was a major cause of the accident. The reason for that overconfidence was obviously not purely technical but conspicuously socio-technical, suggesting it was due to the lack of a so-called "safety culture," broadly construed, which notably rests on the social system and social structure including behaviors in both individual and organizational or institutional levels. Hence, the management of "safety culture" would not be possible without proper consideration of behavioral sciences concerning the interface between nuclear technology and the society using it. In my view, the comprehensive assembly of papers collected in this book is the first academic joint product aimed at looking into such interfacial issues from a multiplicity of professional perspectives.

No doubt, the nuclear future, not only in Japan or the U.S. but more broadly worldwide, depends on active and continuous contributions from younger generations, and I do hope the voyage of reading this book will provide a unique opportunity to foster their in-depth understanding of implications of learning about nuclear engineering, sciences for nuclear energy, behavioral sciences for nuclear risks, sciences for resilience, and other relevant fields.

Tokyo, Japan

Atsuyuki Suzuki
Professor Emeritus, The University of Tokyo
Former Chair, Nuclear Safety Commission, Japan, and
Former President, Japan Atomic Energy Agency

Preface

This book was assembled by the interdisciplinary team that organized the 2011 Advanced Summer School of Nuclear Engineering and Management with Social-Scientific Literacy held in August 2011 at the University of California, Berkeley. This was about 5 months after the Fukushima Daiichi Nuclear Power Station accident in Japan. Our team initially intended to publish a book consisting of the lectures and discussions that took place in that setting, and some chapters were submitted to the editors soon after the summer school. At that time, however, things were still evolving rapidly, and many pieces of the jigsaw puzzle were missing. We even did not know what the entire picture of the jigsaw puzzle would look like. Soon, we, the editors, realized that publishing a book by the first anniversary of the accident in March 2012 was totally unrealistic. We all were so busy in catching up with rapidly evolving situations in the aftermath of the accident.

These situations are still evolving swiftly as of March 2014, and in that regard, it became clear that time would never ripen fully for publishing a book about the accident itself. All the editors agreed, however, that now would be the best timing to compile a book focused on nuclear engineering education in the post-Fukushima era coming out of reflections on the Fukushima Daiichi accident.

The accident caused great damage and hardship in varied ways to multiple sets of stakeholders across society, including more than 100,000 citizens who are still evacuated from their homes as of March 2014. However, many of the societal damages had not been anticipated or well understood before the accident. While enormous financial and human resources have been devoted to preparedness and mitigation, their impact and effectiveness are not clear.

Historically, the level of safety that a nuclear system can achieve has been measured by the expected number of deaths from radiation. In the concept of defense-in-depth developed by International Atomic Energy Agency (IAEA), Levels 1–4 are about defense through design, construction, and operation of an engineered system to minimize the magnitude and frequency of radioactive release in a severe accident, and the fifth level defense is achieved by mitigation of radiological consequences of significant external releases of radioactive materials. Actually, because of the fact that no one died due to radiation, it is often said (mostly by nuclear engineers) that the Fukushima Daiichi accident is a good demonstration of the effectiveness of the defense-in-depth concept. While it is true that there were no deaths due to radiation from the accident, more than one thousand people died during the evacuation and while living in temporary housing as a result of various causes that were triggered by the evacuation. In addition to these deaths, thousands of families, local communities, and industries were damaged or completely destroyed. On a national scale, Japan is experiencing difficult and complicated situations in international relations and economics. On a global scale, carbon dioxide emission to the atmosphere increased significantly. These consequences should have been properly analyzed, discussed in public, and prepared for prior to the accident, but there had been serious oversight and misunderstanding about what harms must be protected against in such a severe accident. This insufficient preparedness has been compounded by the lack of an effective decision-making process with participation from a broad range of stakeholders, resulting in intolerable delays in societal recovery after the accident. Numerous cases can be found in which decisions led to greater injury due to lack of timely decision-making informed by solid scientific evaluation of various risks, including those of low-dose radiation.

The bitter reality is that severe nuclear accidents will occur in the future, no matter how advanced nuclear technologies become; we just do not know when, where, and how they will occur. Of course, we should continue our efforts to improve technologies toward minimizing the frequency and consequences of accidents as discussed in detail in Chap. 12, but, in addition, we should develop effective aftermath management for enabling swift recovery. Scientific and academic communities should start efforts for establishing the scientific bases, both natural and social, for better societal resilience. Naturally, as a part of such efforts, the education of nuclear engineering professionals at the college and graduate levels must be reinvented.

In fact, to some extent, the team responsible for the present book had shared this recognition in advance of the accident, and efforts had been started before 2011, as Chaps. 1 and 21 describe in detail. For the 4 years (2007–2010) prior to the accident, the Department of Nuclear Engineering and Management at the University of Tokyo and the Department of Nuclear Engineering at the University of California, Berkeley had already started a collaboration called GoNERI for developing advanced educational programs for nuclear engineering. The collaboration was funded by the Global Center-of-Excellence (G-COE) program of the Japan Society for the Promotion of Sciences (JSPS). GoNERI was motivated by the particular relevance and importance of social-scientific approaches to various crucial aspects of nuclear technology, such as the nuclear fuel cycle, radioactive waste disposal, implementation in rising countries, etc. Therefore, special emphasis was placed on integrating nuclear science and engineering with social science. However, at the same time, it was also recognized that we did not yet have sufficient command of the fundamentals of the social sciences (such as their domain, concepts, terminology, methodology, etc.), which limits nuclear engineers in collaborating with social scientists, and that the new generation of nuclear engineers must understand societal aspects of nuclear technologies sufficiently to serve the public good. This understanding was encapsulated in the formulation within GoNERI of PAGES, the Program for Advanced Graduate Education System for Nuclear Science and Engineering with Social Scientific Literacy. Prior to the accident, various efforts had been made in this direction, including a series of bi-weekly seminars and field trips to Waste Isolation Pilot Plant (WIPP) at Carlsbad, New Mexico, and Toyo-Cho and Rokkasho-Mura, Japan. The collaborating partners conducted the 2009 Advanced Summer School of Radioactive Waste Disposal with Social Scientific Literacy at Berkeley and the 2010 Advanced Summer School of Nuclear Engineering and Management with Social-Scientific Literacy at Honolulu, in collaboration with Tokai University, Japan.

In response to the occurrence of the Fukushima Daiichi nuclear power station accident on March 11, 2011, we decided that the 2011 summer school should focus on reflections on the accident. This accident raised many fundamental and controversial questions about the traditional approach of nuclear engineering and its utilization in society, as described above. The 2011 summer school provided an arena for the discussions to find and create a renewed platform to renovate engineering practices, and thus nuclear engineering education, which are required in the post-Fukushima era nuclear scene. We offer this book to document and share our approaches, with the goal of spurring wider discussions and changes.

This book includes most of the lectures given in the 2011 summer school as well as additional chapters to fill in gaps that could not be filled 3 years ago. Chapters written right after the 2011 summer school were once returned to the authors in order to supplement their accounts with any developments over the past 3 years. Chapter 1 is the introductory chapter, which provides the perspectives and aims that were set in GoNERI activities and the 2011 summer school. The following chapters are grouped into five parts.

Part I is about "what happened." Chapter 2 provides information for the reader to understand what happened in the damaged reactors. Chapters 3 and 4 focus on consequences of the accident observed in the area exterior to the Fukushima Daiichi site, including environmental contamination and remediation. Chapter 5 discusses impacts of the accident on national economy, particularly energy demand and supply in Japan. Chapter 6 gives a brief summary of the deadlocked situation after the accident for conventional nuclear fuel cycle policy, while in Chap. 7, observations are given from a European viewpoint.

Part II is about "why this accident occurred." Observations and discussions are made from regulatory systems by focusing on the defense-in-depth concept (Chap. 8), ethical and cultural factors (Chap. 9), and social and organizational systems (Chap. 10). Chapter 11 provides the historical perspective by comparing the Three Mile Island and Fukushima Daiichi accidents.

Part III gives collective bases necessary for considering a better "system." Here, the "system" includes different aspects. Chapter 12 discusses potential improvements for engineering, operation, and maintenance of nuclear reactors. Chapter 13 summarizes the state of the art for the effects of low-dose radiation on human bodies, which the aftermath of the Fukushima Daiichi accident once again has indicated to be crucial for restoring damaged communities. Improvements should be made in the regulatory systems, the subject of Chap. 14. Because the accident generated new categories of radioactive wastes, we need to improve waste management schemes, and the accident also let us notice that the traditional approach for radioactive waste management needs to be rethought, as discussed in Chap. 15. Chapter 16 is a speech given at the dinner at the 2011 summer school by the then vice chair of the Atomic Energy Commission of Japan.

Part IV is a collective view of students and mentors who participated in the 2011 summer school. The student group included students from nuclear engineering as well as from social science, from the US, Japan, and other Asian countries. Each student chose a question of interest from those suggested by the lecturers and wrote his/her essay in response. Their essays are collected in Chap. 17. Part IV also includes Chaps. 18–20 made by three younger scientists who mentored students' discussions. They played the important role of catalyst between the professors and the students. If we raise one most important key factor for the success of this summer school, it is excellence of the mentors.

Chapters in Part V offer thoughts and recommendations for new nuclear engineering education. Chapter 21 was contributed by a historian as a reflection on the challenges of implementing social-scientific literacy for nuclear engineers. The following two chapters discuss importance of social-scientific literacy to implement diversity and independence in nuclear engineering from viewpoints of sociology (Chap. 22) and communication with the public (Chap. 23). Bridging those observations made by the preceding three chapters, Chap. 24 focuses on the overall concept of resilience engineering as a new horizon of systems safety.

Regardless of whether a country is launching a new nuclear program, maintaining its current fleet of nuclear reactors, or heading toward phase-out, we need nuclear engineers who are technically competent and trusted in society, for which suitable education must be provided. We hope that this book will provide useful materials for conducting constructive discussions and development of future generations.

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Cathryn Carson
Mikael Jensen
Kohta Juraku
Shinya Nagasaki
Satoru Tanaka

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Dr. Daisuke Kawasaki and Prof. Tatsuhiro Kamisato of the University of Tokyo played leading roles for the 2009 and 2010 summer schools, respectively, which provided us with indispensable preparation and foundation for the 2011 summer school.

We wish to thank the authors of the chapters for their excellent contributions, which cover a broad range of topics with profound depth. In developing this book,

we have been blessed with editorial assistance from Dr. Samuel Evans of CSTMS and Ms. Beth Cary. Beth edited chapters written by non-native speakers of English. Mr. Taewoo Ahn gave valuable comments from the reader's point of view.

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Chapter 1
Integrating Social-Scientific Literacy in Nuclear Engineering Education

Approaches Developed in the GoNERI Program

Kohta Juraku, Cathryn Carson, Shinya Nagasaki, Mikael Jensen, Joonhong Ahn and Satoru Tanaka

Abstract This introductory chapter explains the historical background, outline, basic concept, and objective of the Program for Advanced Graduate Education system for nuclear science and engineering with Social scientific literacy (PAGES), under which the 2011 summer school was organized and this book was developed. Early efforts and trials in PAGES started in 2008 toward integrating social sciences in nuclear engineering education mainly by organizing summer schools as a test bed. Various important insights on how pedagogically effective integration could and should be achieved were obtained through the summer schools held in 2008–2010. When the Fukushima Daiichi accident occurred in

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March 2011, the organizing committee of the 2011 summer school, which consisted of the authors of this chapter, immediately recognized that this would be a time when PAGES faced a test with regard to its effectiveness, and the previous efforts under PAGES should be fully utilized to understand and address the accident. The organizing committee concluded that while it is still in its infancy, the PAGES approach successfully established an integrated framework for both engineers and social scientists. It changed the perspectives of the participants, both the students and the organizers, and it laid groundwork that the organizers hope that they and others will be able to build upon.

Keywords PAGES · GoNERI · Nuclear engineering education · Social scientific literacy for engineers · Integration · Fukushima Daiichi accident

1.1 Preamble

Words such as “interdisciplinary,” “collaboration,” and “social aspects” had regularly appeared in various nuclear contexts since long before the Fukushima Daiichi nuclear accident on March 11, 2011. It had already become common understanding that we need to bring together a wider range of knowledge and expertise to deal more appropriately with the place of nuclear technology in society.

This trend had also come to Japan at least about 10 years before the Fukushima Daiichi accident. Responding to that, the Nuclear Engineering Department of the Graduate School of the University of Tokyo was reformed in 2004, to integrate international, social, and even humanistic factors with conventional science and technology research and education. The new English name of the department was “Department of Nuclear Engineering and Management” (UTNEM) and its prospectus [1] describes its purpose as follows: “the Department is involved in international cooperation for education and research with added humanities and social science aspects, including sending its members to international organizations and prominent foreign universities.” The “Nuclear Socio-Engineering Laboratory” was established within UTNEM for exploring “the relation and interaction between technologies and human life” [2] by the strong initiative of Prof. Haruki Madarame,[1] who was well known as one of the most influential advocates of this direction. This laboratory had faculty members who specialized in social scientific fields such as Social Psychology, Communication Studies, Economics, Regulation and Legal System, Risk Studies, Social Studies of Science, and so on, and educated graduate and undergraduate students who worked on research topics closely related to such fields.

However, the “integration” of “humanities and social science aspects” was still only partial, strictly speaking. Even after the reformation described above,

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[1] After retirement from the University of Tokyo in 2010, Prof. Madarame became the Chairman of the Nuclear Safety Commission of Japan.

the group that studied social scientific topics on nuclear technology was somehow “separated” from the rest of department as conventional engineering research labs were the majority. From the point of view of an observant social scientist, the situation after the 2004 reformation at the UTNEM was just an “addition” of the social scientific part, appropriately suggested by the prospectus cited above. This addition model was not a totally meaningless change, of course, but it was not sufficient to cope with contemporary difficult issues centering around nuclear utilization in a so-called post-industrial society.

This process of “integration” seems to require a long-term effort to be accomplished. The Fukushima Daiichi accident clearly exposed the incompleteness of the past efforts at “integration,” as various chapters of this book discuss in detail; even in 2014, three years after the accident, it seems to be still on going.

The abilities required of leading engineers in this post-industrial era are not just to pursue technological development as prescribed (typically by governmental long-term plans or other national programs), but to grasp multi-dimensional needs for technology, to develop technology in collaboration with different stakeholders under a more open societal process, and to fulfill their social responsibility in compliance with values shared within society.

1.2 GoNERI

In 2007, the proposal prepared by UTNEM professors for a brand-new initiative, titled “Nuclear Education and Research Initiative” (GoNERI),[2] for achieving further integration of engineering and social sciences into their education was successfully awarded a grant under the Global Centers-of-Excellence (COE) program by the Japan Society for the Promotion of Science (JSPS), funded by the Ministry of Education, Culture, Sports, Science and Technology (MEXT), Japan. The GoNERI program included various tasks for the purpose of developing an advanced nuclear engineering curriculum. Among them, the task of “integration” was given the highest priority. An official statement of the GoNERI program framed this attempt as “the first systematic education on nuclear energy in the world … incorporating the social, liberal arts and technical subjects as they relate to nuclear utilization.” [3] The UTNEM professors were aware that the faculty and students of UTNEM in many cases did not yet have sufficient command of the fundamentals of the social sciences (their domain, concepts, terminology, methodology, etc.), and that this separated them from social scientific activities even at the time when GoNERI started in 2007 and limited them in collaborating with social scientists and citizens. Consequently, three researchers with different social scientific backgrounds (history of science, risk communication studies, and sociology

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[2] “Go” is short for Global COE program.

of science and technology) were invited into GoNERI to pursue this concept, and they began their work to develop an advanced graduate educational program with social scientific literacy.

1.3 PAGES

To this end, in partnership with the Nuclear Engineering Department of the University of California, Berkeley (UCBNE), UTNEM engaged in various efforts. Those included a series of bi-weekly seminars and field work at the Waste Isolation Pilot Plant (WIPP), at Carlsbad, New Mexico in January 2009, as well as the Japanese sites of Toyo-Cho and Rokkasho-Mura in July 2008. Of particular importance was a one-day workshop held in Santa Fe, New Mexico, embedded in the field trip to WIPP. Intensive discussions were conducted to clarify the challenges and to explore approaches and solutions toward better integration [4]. Through these discussions, we came to share the basic understanding that engineers can gain from, and indeed be expected to have, basic literacy in the social sciences as part of their essential competence, not as an "additional" or "optional" skill that might sometimes be admired.[3] In particular, opening up the decision-making process on socio-technical issues (e.g., introducing participatory methods) calls for more insightful, communicative, and open-minded engineers who can interact with other stakeholders, naturally including ordinary citizens. Engineers should be able to more fully understand various subtle, but critically important, societal contexts regarding technology, explain available technical options to stakeholders and society, and proactively take part in public discussion. In this context, rather than inventing "the best solution" for problems on behalf of society, engineers are considered to be experts who can offer their formulation of problems, multiple options available to society, and, if possible, proposals of solutions.

Sharing the thoughts listed above, it was decided to organize summer schools for topics that were considered inseparably related to social aspects, such as radioactive waste management, as a test bed for developing an advanced educational program to cultivate leading engineers who have this capacity. This collaborative program was given the name PAGES, Program for Advanced Graduate Education system for nuclear science and engineering with Social scientific literacy. Under PAGES, three summer schools were conducted.

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[3] Conversely, social scientists need a better grasp of engineers and engineering practices, of course.

1.4 PAGES 2009 and 2010 Summer Schools

Before the Fukushima Daiichi accident, PAGES conducted the 2009 Advanced Summer School of Radioactive Waste Disposal with Social Scientific Literacy in Berkeley, California, and the 2010 Advanced Summer School of Nuclear Engineering and Management with Social-Scientific Literacy in Honolulu, Hawaii, with the participation of Tokai University, Japan. Table 1.1 summarizes the outlines of the PAGES 2009 and 2010 summer schools.

The first 2009 PAGES summer school was realized by the strong initiative of Joonhong Ahn, one of the editors of this book. None of the GoNERI members had been involved in such an ambitious project before. But Ahn and other members recognized that radioactive waste disposal was the one of the most urgent issues that should be tackled as an interdisciplinary challenge. Under this understanding, the 2009 PAGES summer school invited guest speakers who could provide "social aspects" education for engineers from the following fields: sociology, social psychology, economics, risk studies, science and technology studies (STS),

Table 1.1 Outlines of PAGES 2009 and 2010 summer school

PAGES 2009	PAGES 2010
List of organizing committee members	
Joonhong Ahn (UC Berkeley)—Chair Satoru Tanaka (U Tokyo)—Co-chair Mick Apted (Monitor Scientific) Cathryn Carson (UC Berkeley) Gary Cerefice (UNLV) James Conca (NMSU) Tom Isaacs (Stanford University) Shinya Nagasaki (U Tokyo) Jooho Whang (Kyung Hee University)	Shinya Nagasaki (U Tokyo)—Chair Tatsuhiro Kamisato (U Tokyo)—Co-chair Joonhong Ahn (UCB)—Co-chair Satoru Tanaka (U Tokyo)
Venue	
University of California, Berkeley	Hawaii Tokai International College, Honolulu
Program	
Registration and reception: Aug. 2 (Sun) Lectures: Aug. 3 (Mon)–Aug. 5 (Wed) Symposium: Aug. 6 (Thu)–Aug. 7 (Fri) Field Trips: Geo tour in Bay Area: Aug. 8 (Sat) Waste Isolation Pilot Plant, Carlsbad, New Mexico: Aug. 10 (Mon)	Registration and keynote lecture: Jul. 25 (Sun) Lectures: Jul. 26 (Mon)–28 (Wed) Special Lecture and Workshop: Jul. 29 (Thu) Workshop: Jul. 30 (Fri) and Aug. 2 (Mon)
Number of participants (students)	
30 (from 5 countries)	15 (from 7 countries)
Number of participants (lecturers)	
28 (from 4 countries)	25 (from 4 countries)
URL	
http://goneri.nuc.berkeley.edu/pages2009/index.html	http://goneri.nuc.berkeley.edu/pages2010/index.html

and consensus building practices. Also, we held a symposium by those lecturers, PAGES members, and student participants on the final day of the program.

After this first trial case, on the one hand, we heard many complaints from student participants that there was not enough time for discussion with lecturers and other participants, even though 60 or 90 min were allocated for each lecture. On the other hand, academic interactions among invited lecturers from different backgrounds were strongly stimulated, extended, and deepened. Both the importance of the concept of PAGES and the actual experiences there were highly appreciated by almost all the expert participants. Such reactions had not been expected beforehand. This reaction reflects the reality that the number of opportunities for such intensive discussion among experts in different fields had been limited, although such efforts had been encouraged for a long time. This situation is no doubt common outside the nuclear field as well.

This experience strengthened our confidence in the PAGES project. In March 2010, about half a year after the first PAGES summer school, a closed workshop "What is social literacy for nuclear engineers? From problem-solving engineering to program-formulation engineering" was held at the University of Tokyo with 9 outside experts. The direction of "social literacy" education including the design of the PAGES summer school program, and more generally the future of engineering education, were intensively discussed. This workshop resulted in two important findings: (1) Engineering students prefer that a more object-oriented educational program be available not only for social-literacy education, but also for general engineering education, rather than the traditional lecture-style program; (2) Social literacy education must be embedded not only in nuclear engineering education, but in other fields of engineering education as well, in light of recent rapid social changes around engineering and technology.

Inspired and driven by these understandings, the second summer school was held in Honolulu, HI, in August 2010, in collaboration with Tokai University, Japan. Honolulu was selected as the venue for the school because it was the "midpoint" between the U.S. and Japan and an "away" place for both Japanese students and continental U.S. students. In the 2009 summer school, which was held in Berkeley, UC Berkeley students and professors (the majority of the participants) went home after each day's program, and interaction between them and the Japanese students was not as deep as the organizers expected. PAGES project members realized that this "home and away" gap should be and could be reduced by the venue selection.

Also, the content of the program was modified in response to the March 2010 workshop's conclusion, feedback from the 2009 PAGES participants, and other discussion among PAGES project members. Tatsuhiro Kamisato, a core member of the PAGES project and a historian of science, took the initiative for this second PAGES summer school in collaboration with Shinya Nagasaki, the chair of the organizing committee and a nuclear engineering professor at the University of Tokyo. In this year, two major improvements were made from the 2009 school.

The first point was the relativization of nuclear engineering as a field in the scholarship. Participants were encouraged to free themselves of stereotypical thinking such as “nuclear engineering as the given (fixed) field + social aspects.” The program was designed to help open their minds more and realize that nuclear technology has been invented, developed, and deployed through interdisciplinary collaboration among various different fields of scholarship. Lectures from engineering fields other than nuclear engineering (i.e., electric engineering, civil engineering, and so on) and social and human sciences (i.e., political science, history, social psychology, and so on) were included in the program, and guest lecturers were invited from various countries and regions including Europe, the U.S. and Japan. The concept of “engineering in society,” including issues centering on technology governance, risk, and ethical considerations, were broadly addressed in lectures and interactively discussed.

Another brand-new idea was the introduction of so-called project-based learning (PBL) for object-oriented education. In the later half of the summer school program, students were divided into small groups and given research topics. They conducted intensive surveys, discussions, and reports during a short period of time and made final presentations at the end of the program. The following four topics were chosen and studied by student groups: “Safety of High Level Waste Radioactive Disposal,” “Introduction of Technology for Society and its Process,” “The Necessity of a HLW Geological Repository,” and “Nuclear Power Generation Systems for the Non-Nuclear Armed Countries.”

1.5 Concept, Aim, and Design of PAGES 2011 Summer School

1.5.1 Planning for PAGES 2011 Summer School

After these two summer schools in 2009 and 2010 as trial cases of the educational program, in January 2011 we started preparing for the third summer school, for which the issue of high-level radioactive waste (HLW) disposal technology and society was selected. It was to be held in Sweden, in collaboration with the Swedish Radiation Safety Authority (SSM). We had a meeting in Stockholm in January 2011 and agreed upon an outline for the approximately 10-day program, which included a series of site visits to so-called back-end nuclear facilities in Sweden and Finland. This program was planned to function as an applied curriculum mainly for alumni of our past summer schools. The site visits were intended to deepen students’ understanding of the societal aspects of nuclear utilization through the site observation tours, conversations with site officials and local people, and discussion with lecturers and fellow students.

However, we found our plans unsettled by one of the most serious nuclear disasters in world history: the Fukushima Daiichi nuclear accident, which was triggered by the Great East Japan Earthquake and its subsequent tsunami on March 11, 2011. From the discussions accumulated in the previous PAGES activities, we immediately thought of the accident as a joint socio-technical failure.[4] This accident raised many fundamental and controverted questions regarding the traditional approaches of nuclear engineering and its utilization in society. We believed that engineers and other experts involved in nuclear utilization needed to take those questions very seriously and be responsive to criticism and concern expressed by citizens.

Consequently, the organizing committee decided to make the third summer school a venue for preliminary, yet multi-dimensional learning from the accident by focusing on reflections on that shocking event (although we still hold that the importance of HLW disposal remains unchanged, or perhaps becomes even more urgent in the disaster's aftermath). This decision led to a change of venue, as well as the introduction of an amended topic for the school. While we first considered the possibility of having the school at the University of Tokyo campus or any other place in Japan, this option was rejected due to (among other reasons) the serious burden of a projected shortage of electricity in the summer season. We also wanted to make this summer school a place that enabled the participants to critically address the situation and issues involved in this accident, and to exchange their views candidly.

Based on such considerations, the 2011 Advanced Summer School of Nuclear Engineering and Management with Social-Scientific Literacy: Reflections on the Fukushima Nuclear Accident (PAGES 2011) was held in Berkeley, California, in the first week of August (July 31–August 5), organized around 12 lectures and a series of facilitated discussions. It attracted 18 students from various fields and countries, principally nuclear engineering students in graduate programs in Japan and the United States, but including some social science students as well as students from other nations studying in these countries. In the rest of this introductory chapter, we will explain the concept, aim, and design of our educational program; offer a brief assessment of its effectiveness; introduce a couple of intriguing discussions held by participants; and discuss the program's implications for the post-Fukushima nuclear context.

1.5.2 Aim and Design of PAGES 2011 Program

The PAGES 2011 summer school was a 5-day program that focused on the issues raised by the Fukushima Daiichi accident, in the larger context of interactions and relations between nuclear technology and society. This program was not intended to reach a single agreed-upon conclusion about the accident. Rather, we designed the program to encourage participants to develop their own philosophies, stances, and/or principles that they believed to be appropriate and responsible in the post-Fukushima nuclear context. These were to be based on the collected and confirmed technical facts on the accident, on social-scientific methods and approaches

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[4] To understand more about this perspective, see Chap. 10 by M. Matsumoto of this volume.

that enable us to think about the event more deeply and analytically, and on intensive dialogue among participants. The word "reflections" in the title of the PAGES 2011 school and the title of this book indicates our intention; it means that as participants we should not make comments or criticisms as outsiders, but instead should critically examine our past practices and thinking and subsequently change our assumptions, approaches, methods, and stances, from a position of open-mindedness.

We understood that this approach would be different from standard nuclear engineering curricula. In particular, we wanted to give an important role to the students themselves. We decided that the best way to implement this intention would be a combination of lectures and intensive facilitated discussions, leading to student presentations and individual written essays (see Part IV).

To realize this concept, we brought together 12 lecturers and 3 discussants from various fields centering on the interface of nuclear technology and society: i.e., the chemistry of radioactive nuclides in the environment, reactor physics, radiation protection, reactor design, engineering ethics, technology governance, sociology of science and technology, history of nuclear technology, and long-term energy portfolios and nuclear policy. Table 1.2 is the list of lectures and lecturers. This book includes the chapters by most of the lecturers listed in the table, though their contents are updated and reflect the discussion during the school.

Each of the first four days included two or three lectures (45 min each). On the first day (August 1), three lectures on a technical analysis of the Fukushima Daiichi accident were provided. Those sessions were intended to provide a common grounding in technical facts for all participants, as the basis for social-scientific discussions in following days.

On the second through fourth days (August 2–4), lecturers with deep knowledge and expertise in various social science disciplines and problem areas demonstrated social-scientific approaches that could be helpful in thinking about this complex and tragic socio-technical failure.

Stemming from these lectures, students were encouraged to join in discussion with their fellow students and lecturers. Morning discussions spanned 30 min, and afternoon classes included a 90 min "reflection and discussion" slot. In these latter sessions, discussants (three postdoctoral researchers took this role) encouraged interaction among participants by proposing points to be explored and steering discussion as needed.

Students formed small groups (about 4–6 people) during the group discussion/work sessions. This grouping was undertaken by the students themselves and was based on shared interests. Students repeatedly held discussions within the groups and formulated tentative answers to some of the questions posed by lecturers, as well as other questions they found important in the larger group discussions.

To accelerate interactions among student participants, "student session" slots were scheduled for the evenings of August 2 and 3. In these sessions, the students gave oral presentations that introduced their own, often quite intensive activities after the Fukushima accident, described their thoughts regarding the event, and sought feedback from other students and lecturers.

Table 1.2 List of lecture(r)s at PAGES 2011 summer school and questions provided by lecturers

8/1 Mon.	Scientific Analysis of Radiation Contamination at the Area around the Fukushima-Daiichi Nuclear Power Station, Prof. Satoru Tanaka (Univ. of Tokyo) 1. How can we improve the transmission of information? 2. How can we accelerate decontamination outside of the reactors site and people's returning home?
	Physics of Fukushima Damaged Reactors and its Preliminary Lessons, Prof. Naoyuki Takaki (Tokai Univ., Japan) 1. How serious is the consequence of Fukushima accident? Consider from various views, such as the number of deaths; health risk for current and future generations; fears and inconvenience imposed on the public; impact on economy, etc. Is it unacceptable even if benefit (energy) derived from it is considered? 2. If society allows continuous use of nuclear, what attributes should a nuclear system in the new era have? Give a concrete image/concept of such a new nuclear system (e.g., reactor plant and its fuel cycle)
	Radiation Safety Regulation under Emergency Condition, Prof. Toshiso Kosako (Univ. of Tokyo) 1. What do we think about the emergency workers dose limit? (Cf. Japanese regulation: 100 mSv, changed to 250 mSv during this period) What happened to the remediators' working conditions when dose limits are exceeded while working on emergency tasks? 2. What do you think about evacuation for general public under a nuclear emergency situation? (Cf. Japanese regulation: 10 km as a typical evacuation zone) What kind of arrangement is possible after using SPEEDI code? The arranged area should be circle or fan-shape? 3. What is the main reason for administration of iodine pills to children? (Japanese regulation: about 40 mg for children) 4. What kind of arrangement is effective for making surface contamination maps? Use only radiation monitoring? 5. What do you think about the radiation level for school playgrounds? What is your idea for a dose rate guideline? 6. Is it possible to remove contaminated soil by slicing off 5 cm for the decontamination of radionuclide in all areas of Fukushima prefecture? 7. What method exists for the control of foodstuffs after the accident? Please explain your idea
8/2 Tue.	Impact of Fukushima for Reactor Design Practice, Prof. Per Peterson (UC Berkeley) 1. Discuss "backfitting" policy (10CFR50.109 in the U.S.) which establishes the types of changes that a national regulatory authority can require to existing nuclear facilities. Consider analogies to policies for when existing buildings must be upgraded to meet new building code requirements, and requirements for when automobiles and consumer products must be recalled for repair or replacement. Discuss the societal tradeoffs in requiring backfitting (balance of the cost of backfitting against the benefit of improved safety). Discuss how backfitting policy might affect decisions to introduce improvements in new reactor designs 2. Considering the vertical axis of the Farmers chart for the frequency of internal initiating events, discuss the commercial risks associated with introducing different fuels and materials in new reactor designs, and how such risks can be reduced

(continued)

Table 1.2 (continued)

	Ethics, Risk and Uncertainty: Reflections on Fukushima and Beyond, Prof. William E. Kastenberg (UC Berkeley) 1. Are risk analysis methodologies robust enough to assess and manage the risk of core-melt accidents, such as at Fukushima, i.e., could the accident have been predicted or mitigated? 2. Was emergency planning and emergency response adequate enough to protect public health and safety both before and after the Fukushima accident? 3. Was there an adequate "safety culture" in place prior to and following the accident? 4. What would it take to improve the quality of risk analysis and emergency planning so that the loss of public confidence could have been avoided?
8/3 Wed.	"Failure" of Regulation and Issues in Public Policy Studies, Prof. Hideaki Shiroyama (Univ. of Tokyo) 1. Who and what mechanism should play roles for searching and integrating diverse knowledge that is necessary for managing a complex system? 2. What is the way for strengthening regulatory capacity? Or how to keep civilian nuclear regulatory power without military use (which provides fund and personnel)? Or is it possible to restructure voluntary safety capability? 3. Is it possible and effective to organize and implement nuclear safety research separated from nuclear research and development in general?
	The Structural Failure of the Science-Technology-Society Interface: A Hidden Accident Long Before Fukushima, Prof. Miwao Matsumoto (Univ. of Tokyo) 1. How was the mutual relationship between success and failure in the little known but serious accident that happened during wartime mobilization? 2. What do you think is the mutual relationship between success and failure in the Fukushima accident? 3. What are the similarity and the difference between the accident during wartime mobilization and the Fukushima accident in terms of the mutual relationship between success and failure in the science-technology-society interface? 4. What do you think about possibility of detecting the cause of structural failure in advance and incorporate structural remedies, if there are any, in your design practice?
	Three Mile Island and Fukushima: Some Reflections on the History of Nuclear Power, Dr. J. Samuel Walker (Former USNRC Historian) 1. What are the most important lessons of Three Mile Island? 2. To what extent would a good understanding of the lessons of Three Mile Island have been helpful in the response to Fukushima? Would they have been useful in reacting promptly and as effectively as possible to the technical failures caused by the earthquake and tsunami? Would they have been helpful in responding to media questions and public fears about the effects, real and potential, of the accident? 3. Is it ever appropriate to intentionally provide information to the public about a nuclear accident that is incomplete, overly optimistic, or misleading? If so, under what conditions? 4. How do authorities deal with the problem of providing accurate and up-to-date information when their own knowledge of the situation after a nuclear plant accident is fragmentary? 5. Are the benefits of nuclear power worth the risks?

(continued)

Table 1.2 (continued)

8/4 Thu.	Engineers in Organization, in Industry and in Society: Ethical Considerations, Prof. Jun Fudano (Kanazawa Institute of Tech., Japan) 1. Compare and contrast the Code of Ethics of the American Nuclear Society (http://www.new.ans.org/about/coe/) and its counterpart in Japan, namely, the Code of Ethics of the Atomic Energy Society of Japan (http://www.aesj-ethics.org/02_/02_03_/). Also make a list of values, in order of priority, which are stipulated in each code 2. Which ethical principles have been violated in the case of the Fukushima Nuclear Accident? 3. Reflecting on the Fukushima Accident and referring to the above codes and any appropriate ones, write your own code of ethics (cite all codes you used) 4. Explain, to laypeople, why engineers, especially, nuclear engineers, have special responsibility
	Long-Term Energy and Environmental Strategy, Prof. Yasumasa Fujii (Univ. of Tokyo) 1. When should we use uranium resource in the long-term perspective of human civilization? 2. To what extent can we depend on intermittent renewable energy?
	[After-dinner Talk] from Fukushima to the World: How to learn from the experience in Japan, Dr. Tatsujiro Suzuki (Atomic Energy Commission of Japan)

Note Affiliations are as of August 2011

In addition to lectures by academic researchers, we were fortunate to have Dr. Tatsujiro Suzuki, then vice chairperson of the Atomic Energy Commission of Japan, as the after-dinner speaker on the evening of August 4. His talk was intended to deepen students' appreciation of the connection between academic research and the policy-making process (see Chap. 16 of this volume for the text of his speech).

The four days of lectures and discussions then culminated in student presentations on Friday, August 5. The self-organized student groups made presentations about their questions and answers and received feedback from lecturers and other participants.[5] The summer school closed with a session on reflections by the lecturers and organizers and a general discussion with the student participants.

1.5.3 Specific Arrangements for Educational Effectiveness

To make this educational program more focused and effective, we made several concrete arrangements before, during, and after the term of the program as listed below:

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[5] We created a "No Power Point" rule for these student presentations. Students were required to make oral presentations without projected computer slides. Although many students found this uncomfortable, we applied the rule in order to encourage them to speak concretely and, ideally, to present their ideas through dialogue with each other.

- Student applicants for this school were required to write a short essay on the root cause of the Fukushima accident[6] and to articulate what they wanted to gain from the summer school.
- The organizing committee asked lecturers to prepare five-page (at most) summaries of their lectures before the school was held. They were also asked to provide questions regarding their topics that encouraged students to think about the accident more deeply (see Table 1.2 for the questions provided). Those materials were circulated to students before the school.
- All students were required after completing the school to submit individual essays that described their own answers to the questions they chose to focus on, based on all of the discussions they participated in, including the concluding sessions. (Some of those essays are collected in Chap. 17 of this volume.)
- Students' reflections on their learning experience, as well as feedback and suggestions, were sought in an open-ended questionnaire on the concluding day of the program.
- The organizing committee asked lecturers to submit their full papers after the completion of the school. Each discussant was also asked to write a paper that summarized the main points covered in the lectures and discussions. The committee collected these papers and used them for publication of this book.

1.6 Results and Evaluation

1.6.1 Points Discussed During the Program

The PAGES 2011 program brought about very intensive and thought-provoking exchanges among the participants. Across many intriguing discussions, the following points emerged as potentially critical for post-Fukushima nuclear engineering education and societal decision-making:

- Problems centering on the social justification of nuclear utilization. In particular, utilitarian arguments—such as cost-benefit analyses—became a central point of discussion throughout the sessions. Some participants considered these justifications less compelling after the Fukushima Daiichi accident and pointed out the need for deontological considerations to think more fundamentally on this issue, while others argued that cost-benefit evaluation is still reasonable and, ultimately, necessary as a form of science-based assessment.
- In parallel with the issue above, the concept of "rationality" itself was questioned in discussions by lecturers and students. Some participants argued that

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[6] The question was the following: "Outline your current thinking about the Fukushima nuclear accident of March 11, 2011. Describe the issues you see it raising for nuclear engineering professionals and for societies pursuing nuclear power. Discuss what you see as the relevant background and fundamental causes of the accident."

the role of science (and scientists or engineers) is to provide neutral and logical conclusions based on quantifiable knowledge (and these individuals' expertise), which will render societal decision-making "rational." These participants criticized other social reactions, such as the anti-nuclear movement after the Fukushima Daiichi accident, as "irrational." However, another group of participants voiced the opinion that such social reactions embraced a different kind of "rationality" than that of technical experts. These participants argued that different types of "rationality" should be considered more intensively when society makes decisions regarding science and technology issues. This controversy is associated with the previous point, of course.

- Prof. William Kastenberg raised an issue about "safety culture" in the Japanese nuclear industry (see Chap. 9). He pointed out its weakness in light of the Fukushima Daiichi accident and its consequences, and suggested an explanation of the roots of this weakness based on cultural and historical differences between Western and Asian societies. He illustrated the importance of individualism when considering engineering ethics. This argument triggered much discussion regarding the character of social-scientific explanation and analysis of the root cause of the Fukushima Daiichi accident. Some participants questioned Prof. Kastenberg's theory. This contestation also extended the horizon of participants' perspectives on the mechanism behind the tragedy.
- Many participants also focused on the importance and difficulty of public and inter-expert communication during emergency situations (so-called "crisis communication"). They described some dilemmas: timely information vs. well-confirmed information, simple and understandable explanation vs. detailed and correct explanation, controlled disclosure vs. unlimited disclosure, and so on. Participants realized the possible tough choices for engineers posed by those dilemmas.

As we intended, no particular single conclusion was reached on these complex and difficult issues during this summer school. However, students reported that they conceptualized such dilemmas more sharply than they did before as a result of interactions with people who took different stances, brought different methodological perspectives, and held divergent opinions.

1.6.2 Evaluation of PAGES 2011

In their post-school feedback, many students strongly emphasized the importance of interaction with people of different backgrounds (for instance, Japanese and American) and different fields (engineering and social science). Many students mentioned a lack of time; specifically, they wanted to have more time for discussion with other students and lecturers. A number also requested more presentations by and discussions with social scientists. Some students regretted the absence of field trips, particularly as these had been included in our 2009 summer school. Students said they wanted to have such occasions both to expand their understanding and to strengthen relationships with other students, as well as to render their learning more concrete.

As described above, and in accord with our aim, we were able to bring about very intensive and intriguing discussions throughout the program. Every point raised in our discussions on the lessons learned from the Fukushima Daiichi accident offers an important perspective to potentially avoid similar structural failures in future. Not only did students gain knowledge from the lectures, they also broadened and deepened their perspectives on this terrible nuclear accident and nuclear utilization more generally through candid discussion. This summer school stimulated students' consciousness of various socio-technical issues that must be considered by the next generation of leading engineers.

In this sense, we believe we can evaluate the experiment of this school as successful. Our model for the impact of our efforts has been to seed new ways of thinking among rising professionals. We have seen success of this approach among the small cohort of participants in the school. We have also found our own perspectives and strategies changed by the effort, in ways that will continue to shape our own engagement on questions of nuclear technologies and society. We intend that publishing this volume and continuing to work in this area will provide stimulation for others to carry out similar efforts in their own settings and ways.

1.7 Concluding Remarks

The Fukushima Daiichi accident is not an event of the past; it is an ongoing and developing story even in 2014, when this book is being finalized. It has reminded us that nuclear technology is an extreme achievement as a man-made artifact in terms of its systematic complexity, its potential risks, and its societal, political, economic, geographic, and historical impacts. However, the PAGES project had already impressed upon us the "extremeness" of nuclear technology, although it had not been well verbalized and conceptualized by project members. All of us project members have become more conscious of the extraordinariness of this technology in the course of this interdisciplinary educational challenge. Of course, the Fukushima Daiichi accident brought definite clarity to this sort of feeling.

For the engineering side, this point might be recognized as a limit of natural-science-based (traditional) engineering scholarship. This should strengthen engineers' motivation to integrate social scientific elements with their own knowledge and skills. If this way of thinking comes to be shared more strongly and deeply by the engineering community than before the Fukushima Daiichi accident, it would mean that PAGES's original concept was a pioneering one. We can commend our own project as a forward-looking effort, though, at the same time, we deeply regret that we were not able to make a contribution to prevent the occurrence of the Fukushima Daiichi accident.

However, we do not think that this is a sufficient evaluation. The trajectory of the PAGES project and the events which have happened after the Great East

Japan Earthquake pose challenges to be addressed not only by the engineering community, but also by the social science community. Social scientists (of course, including people in the PAGES project) should realize that interdisciplinary collaboration for problem formulation and solving is much more difficult and more painful than they may have expected. Engineering places its basis not on critical analysis for its own sake but on the realization of artifacts for the client. In this sense, engineers cannot complete their mission through speeches or writings, fully protected by academic freedom. Although they enjoy the same rights in terms of scholarship, at the same time engineering is also an enterprise in society (and this fact is one of the reasons why engineering ethics is considered an essential part in which social science can/should be involved). Those who collaborate with the people who are dedicated to such an enterprise must make clear their own stance, interests, and position. They must also be required to understand the complex detail of engineering practices deeply, in order to make meaningful contributions in their collaboration.

Social scientists must realize that engineering is a profound and exacting endeavor. This observation does not mean that social scientists should be less critical of engineering or engineers. Rather, researchers should emphasize that it would be neither effective nor convincing if they simply blame engineers when they see the superficial results of engineering practice. If social scientists want to make constructive and critical relationships with engineers and to make technology even more public-interest-oriented, they must open their eyes and listen carefully to the engineers, not isolated in their offices separated from the engineering buildings in their university. PAGES might be considered as the very first step for such sometimes difficult but much more substantial and meaningful collaboration between engineers and social scientists.

Our educational program development is still in its early stages. We educators are still struggling as we take that first step in collaboration. However, we all believe it should be continued so as to supply the new generation of leading engineers with sufficient social-scientific literacy and knowledge, and significantly change the future of engineering and technology.

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References

1. Department of Nuclear Engineering and Management, The University of Tokyo (2013) The aim of the Department of Nuclear Engineering and Management. Available at: http://www.n.t.u-tokyo.ac.jp/eng/modules/contents/index.php?id=10. Accessed 20 July 2014
2. Nuclear Socio-Engineering Laboratory, Department of Nuclear Engineering & Management, The University of Tokyo (2008) Nuclear socio-engineering laboratory. Available at: http://www.n.t.u-tokyo.ac.jp/~socio/English/. Accessed 25 October 2011 (Unavailable on 20 July 2014)
3. The University of Tokyo Global COE Program Nuclear Research and Education Initiative (2007) Overview. Available at: http://www.n.t.u-tokyo.ac.jp/gcoe/eng/program/index.html. Accessed 20 July 2014
4. Kawasaki D, Ahn J (eds.) (2009) Social-science literacy for nuclear engineers and scientists in nuclear fuel cycle and radioactive waste disposal – GoNERI WIPP field trip and retreat meeting, Carlsbad and Santa Fe, New Mexico, January 15-17, 2009, Report No. UCBNE-5119 and GoNERI-0028. Available via Liaison Office for GoNERI at UCBNE GoNERI-UCBNE Collaboration in Nuclear Engineering. Available at: http://goneri.nuc.berkeley.edu/pubs/santafe-report-final.pdf. Accessed 20 July 2014

Part I
Understanding the Fukushima Daiichi Accident and Its Consequences

Chapter 2
Event Sequence of the Fukushima Daiichi Accident

Shinya Mizokami and Yuji Kumagai

Abstract On March 11, 2011, the Great East Japan Earthquake and subsequent tsunami hit Fukushima Daiichi Nuclear Power Station. Flooding by the tsunami induced loss of AC and/or DC power for reactor cooling, hence the reactor water level decreased and fuel was exposed. Water reacting with high temperature fuel metal covering resulted in hydrogen generation and hydrogen explosion of reactor buildings. This accident caused radioactive release to the environment. In this chapter, an attempt has been made to understand in detail the mechanism of the accident progression for Units 1–3 that were in operation by utilizing results of computer simulations. It should be noted that, due to limited information and capability of the state-of-the-art severe-accident simulation tools, there are still unanswered questions, which should be tackled by academic research for improving and enhancing safety for the nuclear industry now and in the future.

Keywords Fukushima Daiichi nuclear power station · Severe accident · Accident progression · Great East Japan earthquake · MAAP simulation

2.1 Overview of the Accident

The Tohoku-Chihō-Taiheiyō-Oki Earthquake[1] (the Earthquake, hereafter) and ensuing tsunami, which occurred on March 11, 2011, led the Fukushima Daiichi Nuclear Power Station (NPS) to a situation far beyond design basis accidents and was even

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[1] The earthquake is also often referred to in Japan as the Great East Japan Earthquake. In the Press Conference by Prime Minister Naoto Kan on April 1, 2011, it was announced that the Cabinet decided to officially name the disaster the Great East Japan Earthquake.

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further exacerbated by multiple failures assumed in developing accident management measures. Consequently, Units 1–3 ultimately experienced severe accidents; although they were successfully shut down, they lost functions related to cooling.

On March 11, 2011, Units 1–3 of Fukushima Daiichi NPS were in operation, while Units 4–6 had been shut down for periodic inspection outage. Due to the shock of the Earthquake that occurred at 14:46, the safety function of Units 1–3 was actuated by the seismic over-speed trip signal, which resulted in automatic shutdown of all reactors in operation at the time.

Due to the collapse of the electric tower connection to off-site, all power supply from off-site to Fukushima Daiichi NPS was lost, but the emergency diesel generators (EDGs) started up as expected, and the electric power necessary to maintain safety of the reactors was acquired.

Later, the tsunami hit the Futaba area of Fukushima Prefecture where Fukushima Daiichi NPS is located. It was one of the largest in history. Many of the power panels were inundated, and the EDGs, except for Unit 6, stopped, resulting in the loss of all alternating-current (AC) power and, consequently, loss of all the cooling functions using AC power at the site. As a consequence, core-cooling functions not utilizing AC power were put into operation, or, alternatively, attempts were made to put them into operation. These were the operation of the reactor core isolation cooling system (RCIC) in Unit 2, and the operation of the RCIC and the high-pressure injection system (HPCI) in Unit 3.

Units 1–3 had a different process, but in the end the loss of direct-current (DC) power resulted in the sequential shut down of core cooling functions that were designed to be operated without AC power supply. Then, due to water evaporation by decay heat and depressurization boiling, the reactor coolant in the reactor pressure vessel gradually decreased, which caused boil-dry of the fuel. Accordingly, water injection was attempted through an alternative water path by joining fire engines with the fire protection system and make up water condensate system (MUWC), but water could not be injected into the reactor vessels in Units 1–3 for a certain period of time.

Due to exothermic chemical reaction between steam and zirconium (Zr) included in the fuel cladding tube, $Zr + 2H_2O \rightarrow ZrO_2 + 2H_2$, massive heat was generated, causing the fuel to melt and the generation of a substantial amount of hydrogen.

Subsequently, in Units 1 and 3, explosions, which appeared to be caused by hydrogen leakage from the primary containment vessel (PCV), destroyed the upper structure of their respective reactor buildings.[2]

2.2 Unprecedented Mega-Earthquake

The Earthquake on March 11, 2011 was of the biggest scale ever observed in Japan. Kurihara City in Miyagi Prefecture observed a maximum seismic intensity of 7 on the scale ranging between 0 and 7 defined by the Japan Meteorological

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[2] Japanese BWR was designed to replace gas inside PCV with nitrogen to prevent hydrogen explosion inside PCV.

Agency (JMA),[3] and seven high tsunami waves were observed along the Pacific coastline from Hokkaido and Tohoku to the Kanto region.

It has been reported that the Earthquake occurred offshore of Miyagi Prefecture at a depth of 23.7 km where the Pacific plate sinks beneath the North American plate. The size of the source area extended from offshore Iwate Prefecture to offshore Ibaraki Prefecture, being about 500 km long (north to south), about 200 km wide (east to west), and with about 50 m in maximum slip. There was a massive slip observed in the southern trench side off the Sanriku coast and part of the trench sidel off Northern Sanriku coast to far south off the Boso Peninsula in Chiba Prefecture. Multiple regions, including offshore Central Sanriku, offshore Miyagi Prefecture, offshore Fukushima Prefecture and offshore Ibaraki Prefecture, moved simultaneously and the magnitude was 9.0 on the Richter scale at the hypocenter. A mega-earthquake of this scale was unexpected even in Japan, which is known to be seismically active.

It is worth noting that a mega-earthquake such as the Earthquake was not presumed in the national earthquake research projects engaged in by the majority of Japanese experts [1]. It was indeed a huge earthquake, the focal area of which covered a much broader area. Many unknown matters remain about the causes of such massive synchronized earthquakes. It is necessary, therefore, to monitor the research progress in Japan and overseas on the mechanism and to incorporate the latest knowledge about them in the consideration for design and operation of nuclear reactors.

The intensity of ground motions at Fukushima Daiichi NPS was at about the same level as those assumed in the seismic design, upon comparison of observed values and analysis results. Most of the frequency bands were below the values set for the seismic design, although some of the observed values for the reactor-building basement (the lowest basement floor) had exceeded the maximum acceleration corresponding to the design basis for earthquake ground motion (see Table 2.1). The reactor systems were found to be intact even with the impact of the Earthquake, from the observed plant operation status and the results of seismic

Table 2.1 Ground motion at Fukushima Daiichi NPS due to the earthquake on March 11, 2011

Unit #	Acceleration [gals]						Ratio of observed to max BDB		
	Observed			Maximum beyond design basis (BDB)					
	N–S	E–W	Vertical	N–S	E–W	Vertical	N–S	E–W	Vertical
1	460	447	258	487	489	412	0.9	0.9	0.6
2	348	550	302	441	438	420	0.8	1.3	0.7
3	322	507	231	449	441	429	0.7	1.1	0.5
4	281	319	200	447	445	422	0.6	0.7	0.5
5	311	548	256	452	452	427	0.7	1.2	0.6
6	298	444	244	445	448	415	0.7	1.0	0.6

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[3] See http://www.jma.go.jp/jma/en/Activities/inttable.html

assessment using observed ground motions; the main equipment having important functions for safety maintained its safety functions during and immediately after the Earthquake.

2.3 Tsunami

The tsunami was designated as Mw 9.1 in an index for indicating the scale of tsunami [2, 3], and was the fourth largest ever observed in the world and the largest ever in Japan.

Replication calculations [2, 3] based on a wave source model, which utilizes data for fault lengths, fault widths, locations, depths, slip scales, etc., could reproduce the Earthquake well; the simulation results for tsunami tracks, inundation heights, tsunami bore levels, submerged areas, and diastrophism in the area from Hokkaido to Chiba Prefecture agreed well with the actual observation. The simulation results indicate that an especially large slip (about 50 m at maximum) occurred near the Japan Trench.

The estimated tsunami heights based on the estimated wave source were about 13 m at Fukushima Daiichi NPS and about 9 m at Fukushima Daini NPS. It was confirmed by the simulation that multiple waves overlapped and arrived at the coast due to the wide range of the epicenter area. Therefore, the main reason for this height difference was considered to be that the peaks of tsunami waves, which were generated in regions with large slips, estimated to be off Miyagi Prefecture and off Fukushima Prefecture, overlapped at Fukushima Daiichi but not as much at Fukushima Daini.

Many unknown matters remain about the causes of such massive tsunami. It is necessary, therefore, to monitor the research progress in Japan and overseas on tsunami generation mechanisms and to incorporate the latest knowledge on massive synchronized earthquakes with accompanying tsunami in design approaches.

The tsunami waves which hit Fukushima Daiichi NPS exceeded not only the 4-m ground level above O.P.[4] (hereafter described as 4 m ground level), where seawater pumps had been installed, but also the 10 m ground level, where key buildings had been constructed, and also flowed into the buildings through openings and other routes. Consequently, motors and electrical equipment were flooded, and important systems such as emergency diesel generators and power panels were directly or indirectly affected and lost their functions.

The wave force of the tsunami appeared to be strong enough to partially destroy openings of the buildings at the ground level such as doors, shutters, etc. These damages are considered due directly to the tsunami or to floating wreckage. Parts of heavy oil tanks, which had stood on the seaside area within the Fukushima Daiichi NPS, seemed to have been pulled away from their positions by wave force and buoyancy. But no significant damage was noticed on the building structures

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[4] This stands for Onahama Peil, and means the height measured from the Onahama Port construction standard surface.

such as walls or pillars of key buildings. Furthermore, most of the breakwater and seawall banks stand as before, with no major impact having been confirmed, although part of northern breakwater with a parapet was damaged.

Regarding the arrival times of tsunami, the following findings have been concluded through analyzing continuous photographs and chronologically arranging the incidents at the time of the arrival at the site of the tsunami that accompanied the Earthquake.

- The tsunami, which affected various systems and equipment at the power plant, arrived at the Fukushima Daiichi NPS site sometime between 15:36 and 15:37, hereafter described as the 15:36 level.
- The tsunami maximum wave arrived from almost directly in front of the site with no major delay.
- Seawater system pumps located near the sea (4-m ground level) lost their functions mostly at the 15:36 level.
- Many systems and much equipment lost their functions in a limited time when there were no aftershocks,[5] indicating it was the tsunami that caused the losses of power.

2.4 Accident Progression for Units 1–3

The Modular Accident Analysis Program (MAAP) is a computer code used by nuclear utilities and various research organizations to simulate the progression of severe accidents in a light water reactor (LWR) [4]. The MAAP code cannot completely replicate the Fukushima Daiichi accident at the present time because of incomplete understanding about actual mechanisms and what the data indicate. Yet, the simulation is useful for checking the correctness of our understanding about severe accidents and constructing an integrated view of the accident; the discrepancy between simulation results and measurements gives valuable clues for further investigation. In this section, a summary of the accident progression of Fukushima Daiichi Units 1–3 is shown based on results recently obtained by validation studies for the MAAP code by comparing the simulation results with measured data. In this section as well, the accident progression is described by focusing on reactor water level and RPV/PCV pressure.

Fission-product (FP) atoms tend to have many neutrons compared to stable isotopes and are relatively unstable. Therefore, FPs decay to stable isotopes while releasing some energy. This energy liberated from FP is called decay heat. In a nuclear reactor, continuous removal of the decay heat is required even after termination of the nuclear fission reactions.

If decay heat cannot be removed, the water level in the reactor core decreases due to boiling. While it is better to maintain high pressure in RPV for sufficient

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[5] There were 9 aftershocks in the Tohoku region until 15:25 after the main shock at 14:46. However, there was no further aftershock until 16:28.

steam supply, it becomes impossible to insert water into the reactor externally at a high-pressure condition. Therefore, the pressure should be decreased sooner or later, depending on what type of the low-pressure injection system it is equipped with.

During the early stage of an accident under the situation of loss of ultimate heat sink (LUHS), because there are no measures to release the energy contained in the reactor core, PCV pressure is considered to indicate the degree of accumulation of decay heat. After the core uncovering has started, the massive pressure increase indicates hydrogen accumulation in the core, and a high degree of generation of metal water reaction, because PCV of Boiling Water Reactor (BWR) Mark-I was designed to suppress by condensing the steam released from RPV. PCV venting is the only way to release the energy to the environment in such a situation; however, this means a break in the PCV boundary, which is designed to prevent FP release. Again, there is a problem in the use of a low-pressure water injection system under high PCV pressure, so the pressure must be decreased. For this depressurization actuation, PCV venting is important, as in case of failure of the venting attempt, massive fission product might be emitted to environment.

2.4.1 Unit 1

As a result of the analysis for Unit 1 by comparing simulation results by MAAP to actual measurements, Fig. 2.1 shows the reactor water level changes, while Figs. 2.2 and 2.3 show changes of the reactor pressure and PCV pressure, respectively. In these figures, MAAP simulation results are labeled as "(analysis)." In this section, accident progression for Unit 1 is described in accordance with the following accident chronology (Table 2.2).

In Unit 1, all the cooling capability was lost due to the tsunami. Therefore, Unit 1 fell into a severe condition within 3 or 4 h after the Earthquake. It was not until the next morning (March 12) that TEPCO could inject water into RPV. And then, PCV venting was conducted at 14:30 on March 12. After that, the hydrogen explosion occurred.

2.4.1.1 From the Earthquake to Tsunami Arrival

At Unit 1, two isolation condenser (IC) systems[6] were automatically activated due to the reactor pressure increase following the scram[7] caused by the Earthquake. After that, the two IC systems were manually shut down and then IC subsystem-A was started up. The reactor pressure was controlled by manually repeating the

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[6] The isolation condenser (IC) system transfers residual and decay heat from the reactor coolant to the water in the shell side of the heat exchanger resulting in steam generation.

[7] The sudden shutting down of a nuclear reactor, usually by rapid insertion of control rods, either automatically or manually by the reactor operator. Also known as a "reactor trip".

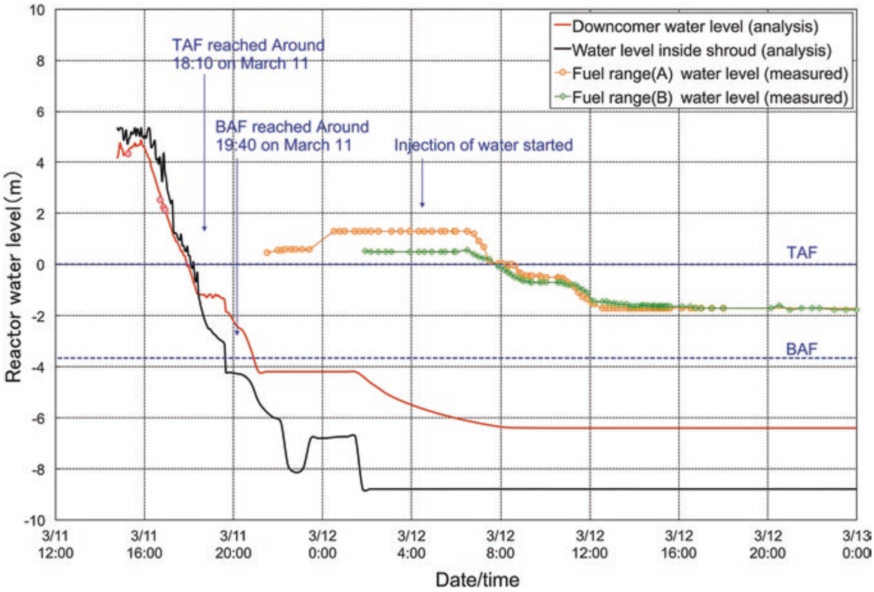

Fig. 2.1 Reactor water level change for Unit 1

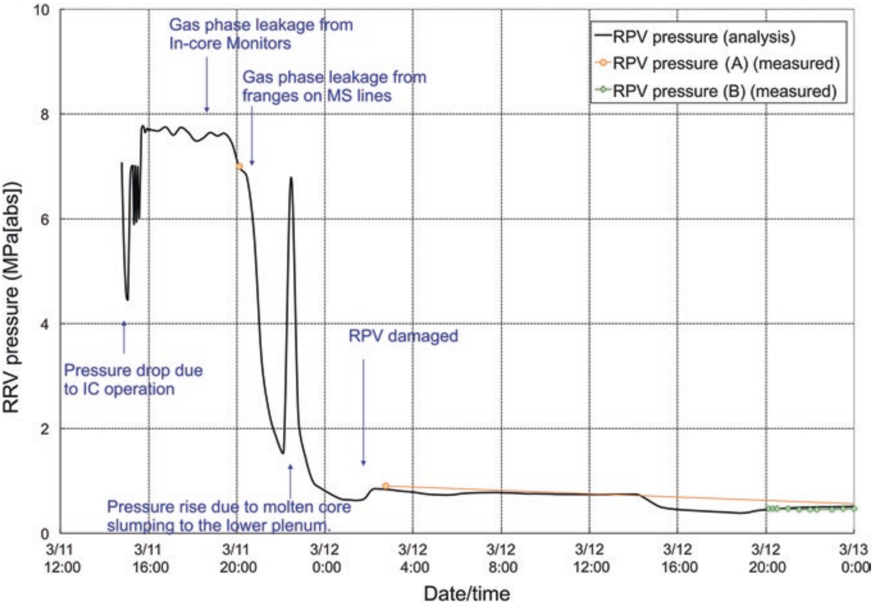

Fig. 2.2 Reactor pressure changes for Unit 1

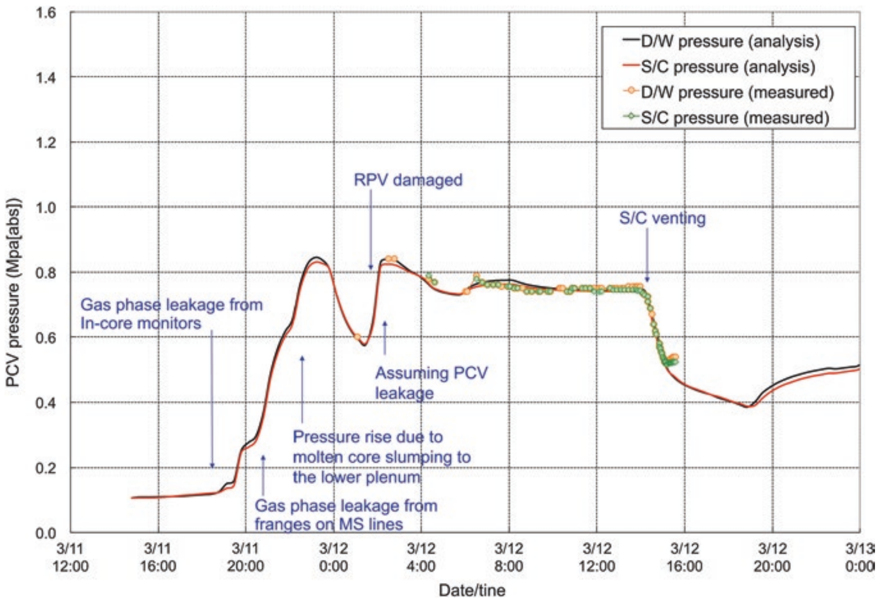

Fig. 2.3 PCV pressure changes for Unit 1

Table 2.2 Chronological accident description for Unit 1

Date	Time	Event	Section
3/11	14:46	Earthquake: reactor was automatically shutdown. Decay heat was continuously generated	2.4.1.1
		Loss of off-site power: DG was automatically started. Therefore, AC and DC power were available in this period	
	14:52–15:34	IC cooling: reactor was cooled by IC with start-stop operation so that RPV cooling down rate did not exceed 55 °C/h. Unit 1 was operated to achieve cold shutdown	2.4.1.1
	15:37	Tsunami hit: AC and DC were lost. IC was not in operation at this time	2.4.1.2
	After tsunami	RPV water inventory decrease due to no water injection	2.4.1.3
	18:10[a]	Core uncovering: Starting fuel heat up	2.4.1.3
	18:50[a]	Core damage started	2.4.1.3
	After 20:00	Containment vessel pressure increased	2.4.1.4
3/12	01:50[a]	RPV bottom damage: Corium (melted fuel) slumping to PCV pedestal	2.4.1.4
	14:30	Regarding the containment vessel vent, operation of AO valve of suppression chamber side was implemented at 10:17 am, and a pressure decrease was confirmed at 2:30 pm	2.4.1.5
	15:36	Reactor building explosions	2.4.1.6

[a] Time from MAAP calculation

start-up and shutdown of IC subsystem-A to maintain the pressure at a certain level. Maneuvering actions such as the starting up of the suppression chamber (S/C) in the cooling mode of the containment cooling system (CCS) were also being taken in parallel for a cold shutdown of the reactor. At 15:37 on March 11, 2011, however, all AC power supplies were lost due to the tsunami, followed by the loss of DC power supply.

Regarding the influence of the Earthquake, the issue of the possibility of a loss-of-coolant accident (LOCA) caused by the Earthquake was examined as described in Attachment 1–3 of Ref. [2].

2.4.1.2 From the Tsunami Arrival to Reactor Water Level Decrease

All cooling capabilities, including the steam-driven cooling system as well as motor-operated pump, were lost due to loss of control power, and all displays of monitoring instruments and various display lamps in the Main Control Room went out due to the loss of all AC and DC power. Approximately from 16:42 to 17:00 on March 11, 2011, part of the DC power supply was temporarily recovered, allowing the reactor water level to be measured for a while, which helped to confirm that it had decreased from the earlier level before the arrival of the tsunami. The level observed (by the wide range water level indicator) at 16:56 on March 11 was at the top of active fuel (TAF) +2,130 mm and had not decreased yet to TAF, although it was continuing to decrease (Fig. 2.1).

The analysis results shown in Fig. 2.1 suggest that the reactor water level reached TAF at about 18:10 on March 11, and the core damage started at about 18:50 (fuel cladding temperatures reached about 1,200 °C).

Even if the fuel starts to be uncovered, steam cooling prevents it from conspicuous temperature rises as long as sufficient steam is supplied from below. While decrease of the amount of steam generation due to decrease of water level progresses, once fuel claddings can no longer be cooled by steam cooling and their temperatures reach about 1,200 °C, large amounts of hydrogen are generated by water-zirconium reactions and the energy released from their oxidation reactions further raises fuel temperatures.

The situation continued that the IC operation could not be confirmed. When part of DC power supply was temporarily recovered, it was observed that the isolation valve outside the containment of IC subsystem-A was operable (the status display lamp was “Closed”). The shift operators took action to open the valve at 18:18 on March 11. The operators confirmed that the status display lamp changed from “Closed” to “Open,” and they heard the steam generating sounds and saw steam above the reactor building, but the amount of steam was limited and it stopped a while later. Due to the operators’ confirmation that steam generation had stopped and concern about the water inventory left in the IC shell side tank, at 18:25 the operators closed the isolation valve outside the containment on the return pipe. At 21:30 the operators took action again to open the isolation valve outside the PCV and confirmed the steam generating sounds and saw steam above the reactor building.

2.4.1.3 From the Reactor Water Level Decrease to PCV Pressure Increase

Reactor pressure of 7.0 MPa[abs] was measured at 20:07 on March 11 (Fig. 2.2), and drywell (D/W) pressure of 0.6 MPa[abs] at about 23:50; on March 12, D/W pressure of 0.84 MPa[abs] was measured at 02:30 and reactor pressure of 0.9 MPa[abs] at 02:45 (Fig. 2.3). In the meantime, although the exact timing is unknown, it was observed that at a certain time after 20:00 on March 11, the PCV pressure showed a sharp rise and the reactor pressure decreased despite no depressurization actions. BWR with MARK-I PCV is designed to suppress pressure increase by condensation at the suppression pool by steam from the reactor. Therefore, the sharp pressure rise is considered to be caused by gas leakage to the drywell.

A scenario was assumed in the analysis that steam had leaked from in-core instrumentation dry tubes or main steam pipe flanges due to temperature rise in the vessel caused by overheating of uncovered fuel and fuel melting.

When the fuel range water level indicators[8] recovered functionality at 21:19 on March 11 due to the temporary power supply, they showed that TAF was located at +200 mm, but the reactor water level indicators seemed to have already been defective. In this period, there would be no conceivable reason for an increase in water level because no water was injected to RPV. This detail is described in Attachment 1–2 of Ref. [2].

The meltdown accident progressed as follows: When heated to high temperatures, fuel melted down from the core to the lower plenum, and then further down to the bottom of the PCV by breaking through the reactor vessel.

2.4.1.4 From Containment Vessel Pressure Increase to Containment Venting Operation

At about 23:50 on March 11, the D/W pressure measured 0.6 MPa[abs]. Thereafter, the indicator continued displaying high values. At around 04:00 on March 12, the dose rate near the main gate of the NPS site started to show an upward trend, which may have resulted from radioactive materials leaked from Unit 1.

It is highly possible that the molten fuel dropped to the bottom of the reactor vessel and further to the bottom of the PCV before 19:04 on March 12, when fire engines started continuous water injection into the reactor. It is possible that the relocation of molten fuel to the PCV raised the PCV pressure and temperature even more. This scenario is related to the amount of the water injected by fire engines [2].

When the molten fuel cannot be sufficiently cooled, the concrete of the PCV floor is heated up above its melting point and core-concrete reactions start, which

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[8] Fuel range water level indicators are designed for use in LOCA condition to monitor core uncovering. Hence, it is calibrated in atmospheric pressure. Narrow and wide water level indicators are designed for use in normal operation. They are calibrated in operating pressure condition.

dissolve the concrete. The core-concrete reactions generate non-condensable gases such as hydrogen, carbon monoxide, etc., resulting in a large impact on the containment pressure change and radioactive release behavior. But it is unknown to what extent core-concrete reactions actually occurred at that moment.

The D/W pressure was being maintained at about 0.7–0.8 MPa[abs], after reaching 0.84 MPa[abs] at about 02:30 on March 12, until PCV venting was successful. This fact of constant PCV pressure gives a strong suggestion that the PCV was leaking, because the PCV pressure should rise; when steam is produced due to water injection, PCV temperature rises, and gases are generated by core-concrete reactions, etc.

Fresh water was injected by fire engines from about 04:00 to 14:53 on March 12. But, since the fire protection system and make-up water system used for water injection are separated from the interior of the plant, part of the injected water had gone to other systems and equipment, not to the reactor. The analysis could yield consistent results with actual measurement data for containment pressures by assuming that the injection had not been enough to flood the core region and that only a fairly small amount of water, compared to the actual amount of discharged water by the fire engines, had been injected to the reactor.

2.4.1.5 From the Containment Venting Operation to Reactor Building Explosion

Three times at 10:17, 10:23, and 10:24 on March 12 the operation to open the small S/C vent valve was carried out from the main control room. There was no visible response in the D/W pressure,[9] while the dose rate near the main gate increased temporarily at 10:40. A while later, when a temporary air compressor was connected to open the large S/C vent valve and it was started up at about 14:00, an up-current of steam above the stack was observed by a live camera and the D/W pressure decreased from 14:30 until about 14:50. No dose rate increase was observed near the main gate and monitoring post-8 (MP-8).

After the opening operation of the large S/C vent valve, the D/W pressure decreased from 14:30 through about 14:50. Later at 15:36, hydrogen in the reactor building exploded and the roof and outer walls of the uppermost floor were damaged.

It can be considered that hydrogen gas generated mainly by water-zirconium reactions, which leaked together with steam and finally reached the reactor building, resulted in the hydrogen explosion. But its leak path, volume, explosion aspects, and ignition source are still unknown.

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[9] S/C small vent valve is for easing the opening of S/C large vent valve while equalizing pressure by opening the small valve in case the large valve was difficult to open due to the pressure difference. Therefore, flow amount when opening the small valve is small.

2.4.1.6 From the Reactor Building Explosion to March 18

At 19:04 on March 12 after the reactor-building explosion, seawater injection was started by fire engines.

Water injection to Unit 1 and Unit 3 was halted once at 01:10 on March 14, when the water source used for these two units was depleted. Water injection to Unit 3 was resumed at 03:20 under critical conditions, when the water source was partly recovered by using an additional water supply, but water injection to Unit 1 was delayed. Water injection to Unit 1 and Unit 3 was again halted with the hydrogen explosion at Unit 3. Water injection to Unit 1 was eventually interrupted from 01:10 to 20:00.

Meanwhile, almost the whole core of Unit 1 dropped down to the lower plenum and most of that part dropped further to the containment pedestal, according to the analysis. There are many unknown matters concerning the location of debris, and the final status of accident progression.

2.4.2 Unit 2

As a result of the MAAP analysis for Unit 2, Fig. 2.4 shows the reactor water level changes, while Fig. 2.5 shows the reactor pressure changes, and Fig. 2.6 shows the PCV pressure changes. In this section, accident progression for Unit 2 is described in accordance with the following accident chronology (Table 2.3).

In Unit 2, despite the fact that both AC and DC power were lost due to the tsunami, RCIC continued operation without control for almost 70 h. However, Unit 2 fell into severe accident mode because of lack of water injection. PCV venting was never successful. Hydrogen explosion had not occurred, but FPs were released to the environment.

2.4.2.1 From the Earthquake to Tsunami Arrival

At Unit 2, the following operation steps were taken towards cold shutdown: start-up and shutdown of the reactor core isolation cooling (RCIC) system,[10] start-up of the residual heat removal (RHR) system[11] in the S/C cooling mode, etc. Unit 2 lost all power supplies due to damage by the tsunami at 15:41 on March 11. At Unit 2, as the RCIC system had been manually started up at 15:39 just before the DC power for control was lost, water injection to the reactor could continue after the tsunami arrival. This was the major difference between the situations of Unit 1 and Unit 2, i.e., at Unit 1 the IC had been shut down before the tsunami arrived, and therefore the IC could not be restarted upon loss of the control power supply, which resulted in a rapidly deteriorating situation.

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[10] The RCIC system is a single train standby system for safe shutdown of the plant.

[11] The residual heat removal (RHR) system is typically a multiple-use system with modes of operation for low-pressure injection, shutdown cooling, suppression pool or containment sump cooling, and/or containment spray.

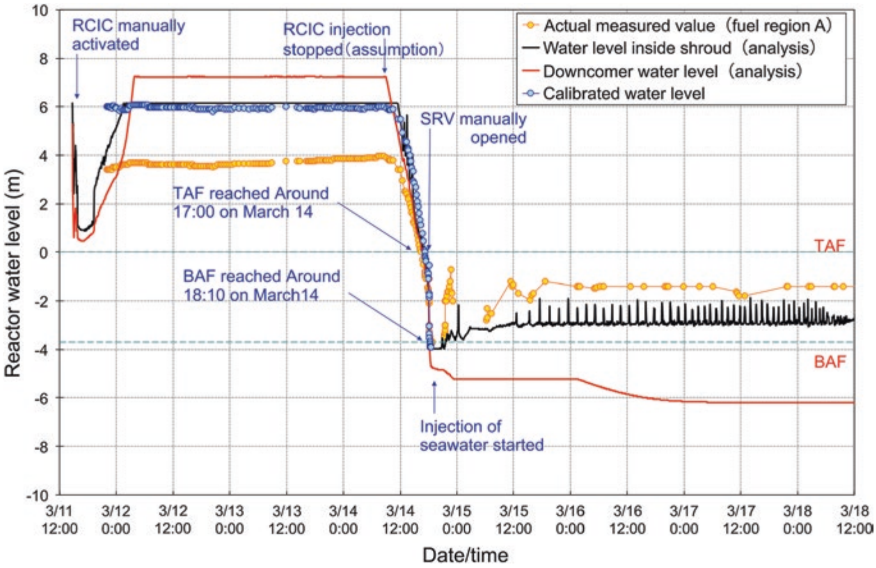

Fig. 2.4 Reactor water level change for Unit 2

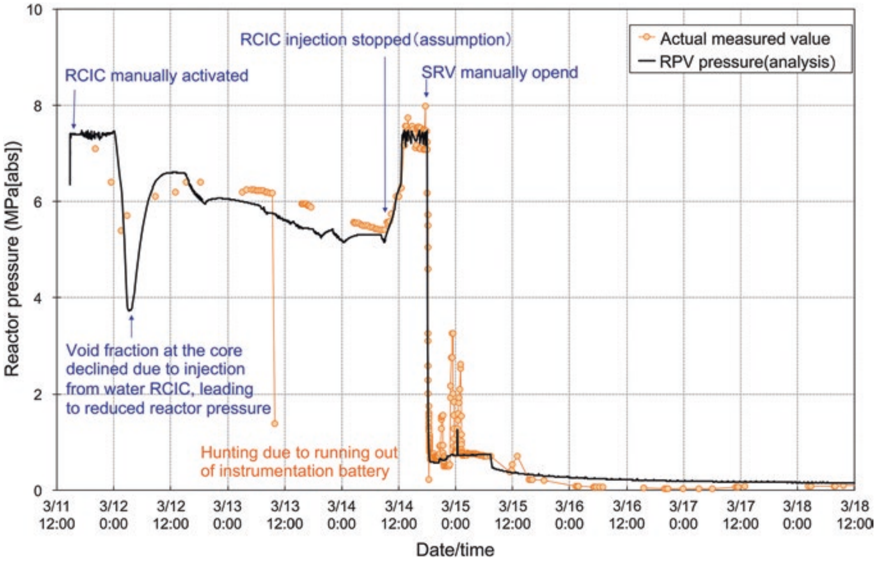

Fig. 2.5 Reactor pressure change for Unit 2

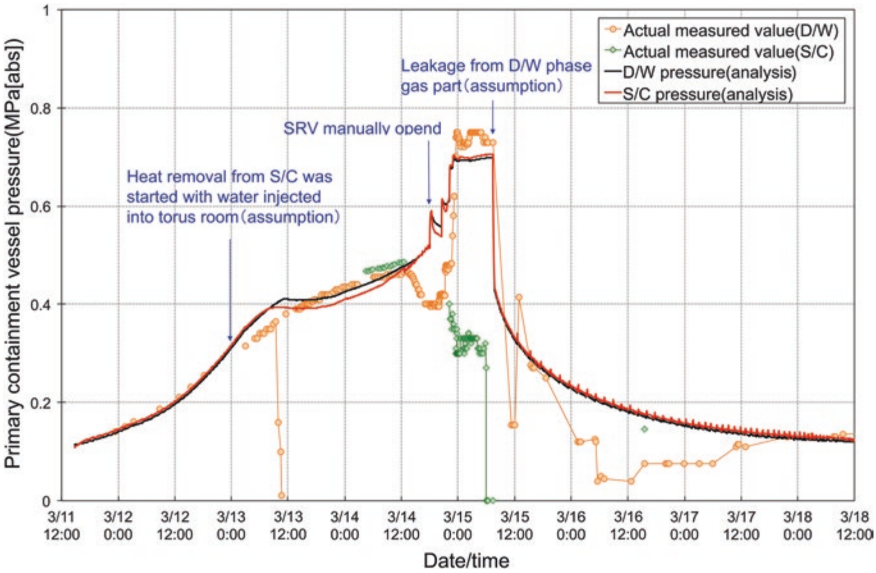

Fig. 2.6 PRC pressure changes for Unit 2

Table 2.3 Chronological accident description for Unit 2

Date	Time	Event	Section
3/11	14:46	Earthquake	2.4.2.1
		Loss of off-site power	
	14:50–15:41	RCIC injection: reactor was cooled by RCIC, even though RCIC was tripped several times due to RPV water level being too high	2.4.2.1
	15:37	Tsunami hit: AC and DC were lost. RCIC had been in operation for 2 min	2.4.2.2
	After tsunami	Reactor water level was increased and maintained by RCIC manual operation	2.4.2.3
3/14	9:00	RCIC operation was terminated due to some reason	2.4.2.4
	After RCIC termination	RPV water inventory decreased due to boiling	2.4.2.4
	17:00[a]	Core uncovering: starting fuel heat up	2.4.2.4
	18:02	Forced depressurization by SRV	2.4.2.5
	19:20[a]	Core damage started	2.4.2.5
3/15	After 7:20	PCV pressure deceased	2.4.2.6

[a] Time from MAAP calculation

2.4.2.2 From Tsunami Arrival to Reactor Water Level Increase

A possibility was hinted that the RCIC system was in operation, with no control power supply due to the tsunami, being driven by water-steam mixture, i.e., two-phase flow, which had been generated when the reactor water level increased to a level above the main steam line since water started being injected more than the amount of loss by steam; thus water was flowing into the steam piping, as in Attachment 2–1 of Ref. [2]. But no detailed behavior prior to the water level increase to the main steam line has been confirmed.

Reactor pressure was not at the level expected from normal RCIC operation during this period. In normal RCIC operation, reactor pressure would be maintained within the safety relief valve (SRV) activation and reset pressure, because the RCIC turbine cannot consume enough energy generated by decay heat; the rest of the steam should be released through SRV. Although the density of energy contained in water is less than steam, the density of mass is much larger than steam. Therefore, all of the decay heat was removed through the RCIC turbine line without SRV activation. This is the reason why reactor pressure varied in the range between 5 and 7 MPa. The changes in the reactor pressure in Unit 2 is further described in Attachment 2–1 of progress report [2].

In the analysis, the water injection rate was assumed to be 30 % of the rated value, which replicated the measured reactor pressure changes during the period while the RCIC was considered to be driven by two-phase flow. According to the results under this condition, the reactor pressure levels calculated during the time period prior to the water level increase up to the main steam line rose more slowly than the measured values. This raises the need to investigate the RCIC behavior after loss of power supply due to the tsunami (see Attachment 2–4 of progress report [2]).

2.4.2.3 From Reactor Water Level Increase to Loss of RCIC Functions

After the reactor water level increased by the consecutive operation of RCIC, no accurate water levels could be estimated, because the fuel range reactor water level indicators had reached their maximum limit of measurement. The reactor pressure, however, started to decrease after the RCIC started up. When it reached 5.4 MPa[abs] at 01:30 on March 12, the reactor pressure began to rise again (Fig. 2.5). In the time sequence, this pressure change had no relation to the switchover of water sources from 04:20 through about 05:00 on March 12, but can be explained by the (general) relationship between saturation temperature and pressure. It is expected that the accident progression can be better explained by identifying the amount of water injected by RCIC with which MAAP simulation reproduces the pressure rise observed at 1:30 on March 12.

Incidentally, the reactor water levels measured were higher than the “reactor water level high (L-8)” (upper limit of water level measurement) after correction of the reactor pressure increase and containment temperature increase (Fig. 2.4).

While the RCIC operation was continued with no control power supply, the reactor pressure is considered to have remained at lower levels than the level at normal operation for the following reasons:

- The reactor water level rose above L-8 because of no control of the RCIC valve apertures for adjusting steam flow rates.
- Decay heat energy was removed from the reactor by low quality two-phase flows.
- The water was injected by the RCIC at a lower flow rate than the rated value, because the RCIC turbine was operated by low quality two-phase flows.
- Thus, the energy in the reactor vessel was kept balanced without steam release by SRV operation required in the original design.

The reactor pressure varied in a downward trend again from about 06:00 on March 13 (Fig. 2.5). This can be understood as the effect of decreased decay heat with time. Thereafter, the pressure increased again after it was measured as 5.4 MPa[abs] at 09:00 on March 14 and reached 5.6 MPa[abs] at 09:35. MAAP could reproduce the gradual reactor pressure increase, assuming interruption of water injection by the RCIC system (but steam supply to its turbine continued) at 09:00 on March 14. The sharp change in the trend of the reactor pressure was considered to be a reflection of the change in the status of water injection by RCIC.

The containment pressure varied at lower levels than anticipated (Fig. 2.6), despite the fact that all the decay heat was stored in the S/C, because of the loss of the ultimate heat sink (LUHS). In the process of Unit 2's accident progression, it is considered that the SRV located in the transfer path of energy from RPV to PCV did not operate when the RCIC was in operation. This means the RCIC exhausted two-phase steam that had flowed into the S/C, accompanied by the energy equivalent to the decay heat energy. Therefore, the energy stored in the S/C must have raised the containment pressure. Some energy flow-out is required for lower than expected PCV pressure. As the scenario of this energy flow-out, tsunami-induced seawater inundating the reactor building is assumed to transmit energy and heat to the exterior from PCV through the S/C wall. Further investigation is discussed in Attachment 2–6 of progress report [2].

2.4.2.4 From Loss of RCIC Functions to Forced Depressurization by SRV Operation

Although it has not been clarified at what time the RCIC system shut down, the reactor water level started to decrease gradually after RCIC stopped, uncovering the core, and then it rapidly decreased due to depressurization boiling by opening the SRV. The core was completely uncovered and core damage started. After the reactor pressure increased due to RCIC system shutdown, it was maintained at about 7.5 MPa[abs] due to the SRV relief valve mode (Fig. 2.5) (the SRV(A) had been connected to temporary batteries and 7.5 MPa corresponds the actuation pressure). Thereafter, the reactor pressure sharply dropped upon opening the SRV manually and finally approached ambient pressure.

The reactor pressures and water levels were measured once the water level had gone below the maximum range of the fuel region reactor water level indicator, following the RCIC shutdown. Further, the reactor water levels and pressures could be reproduced with good accuracy. In the analysis, this was done by appropriate processing of the energy balance and property changes over the time span until the forced depressurization by the SRV, because the water in the reactor decreased monotonously, although it was being accompanied by pressure changes.

The measured values of PCV pressure changed downward from about 13:00 on March 14 after the RCIC system had stopped (Fig. 2.6). It can be considered to be a complex phenomenon due to heat continuing to be removed from the S/C by the seawater that flowed into the torus room, although no more energy was transferred to the S/C through the RCIC turbine.

2.4.2.5 From Forced Depressurization by SRV to PCV Pressure Decrease Initiation

About the same time when depressurization by the SRV was completed, water injection was started by fire engines. But the amount of water assumed in the present analysis turned out to be insufficient to correctly simulate the core water level (Fig. 2.4). Sufficient data on reactor water levels were not available, but their increasing trend after 21:00 on March 14 could be confirmed. This reactor water level increase, however, could have been caused by overestimating the real level due to water evaporation inside the reference water level side piping during the accident progression, as in Unit 1. The water level indicator became unable to show accurate values after all, although the timing when this happened is unknown. Therefore, the actual amount of injected water is considered to have been less, too, including its possible leakage from the injection lines of the fire engines.

The PCV pressure increased to 0.75 MPa[abs], thereafter, due to hydrogen generation and SRV opening, etc. The D/W pressure increases were observed at about 20:00, 21:00, and 23:00 on March 14, probably the effects of hydrogen generation.

At Unit 2 preparation was underway for the S/C venting and for attempting to release the valve several times, but no decisive evidence exists whether or not the rupture disc was opened. But it was at about 23:00 (measured pressure at 23:00 was 540 kPa[abs]) on March 14 when the D/W pressure exceeded the preset rupture disc operating pressure (528 kPa[abs]), even if the measured S/C pressure was not correct. In the meantime, a radiation monitoring car did record a sharp rise in dose rates at about 21:20 when the SRV opening operation was recorded. The occasional increase in reactor pressure around this time was at most about 1.5 MPa[abs] and non-condensable hydrogen gas is considered to have mixed with the discharged steam upon pressure decrease, because core damage is thought to have developed by this time.

2.4.2.6 From PCV Pressure Decrease Initiation to March 18

The measured PCV pressure was 0.73 MPa[abs] at about 07:20 on March 15, and then it decreased to 0.155 MPa[abs] at 11:25 on March 15. It is not clear when the pressure started to decrease, because the measured data are limited around this time period due to the temporary reduction in the workforce at Fukushima Daiichi NPS. Still, it is highly possible that this pressure decrease occurred during the morning, as suggested by the facts that (1) steam release from the Unit 2 blowout panel was confirmed in the morning on March 15, and (2) the dose rates measured by monitoring cars increased. The FPs released at this time are believed to have resulted in radioactive contamination in Iitate Village, etc., due to the effect of wind and rainy weather.

The containment atmospheric monitoring system (CAMS (D/W)) in the meantime showed a monotonous increase until around 06:00 on March 15 (63 Sv/h at 06:20) and then a lowered value (46 Sv/h at 11:25) after an interruption of data recording for about 6 h. The PCV pressure decrease would explain the dose rate decrease in the PCV, by the FP release from it. The CAMS (D/W) recorded a sharp rise to 135 Sv/h later at 15:25 on March 15. This indicates the possibility of drastic change inside the RPC and PCV.

The reasons for no hydrogen explosion at Unit 2 could possibly be hydrogen leakage from a blowout panel or ceiling holes, or a lower hydrogen generation rate at Unit 2 as compared to Units 1 and 3.

2.4.3 Unit 3

As a result of the MAAP analysis for Unit 3, Fig. 2.7 shows the reactor water level changes, while Fig. 2.8 shows the reactor pressure changes, and Fig. 2.9 shows the PCV pressure changes. In this section, the accident progression for Unit 3 is described in accord with the following accident chronology (Table 2.4). In Unit 3, owing to the survival of DC power, decay heat was removed by RCIC and HPCI. However, it fell into severe accident mode because of lack of water injection by HPCI. PCV venting was conducted by interoperation with reactor depressurization. Hydrogen explosion occurred about 1 day after depressurization.

2.4.3.1 From the Earthquake to Tsunami Arrival

Unit 3 was moving towards cold shutdown after the Earthquake by controlling the reactor pressure and water level, etc., through SRV and RCIC operations. But at 15:38 on March 11 all its AC power supplies were lost due to the tsunami. The DC power supply could maintain its function until the batteries were depleted though the function of the AC power supply was lost.

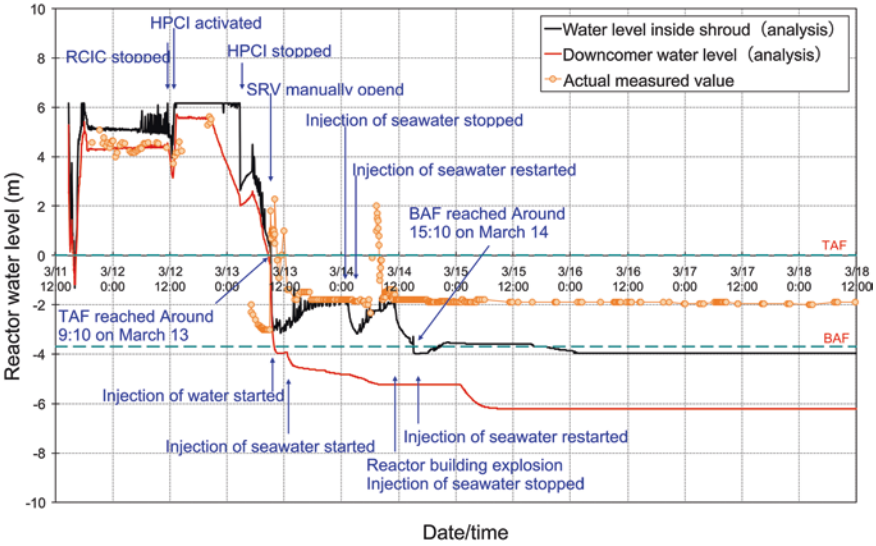

Fig. 2.7 Reactor water level changes for Unit 3

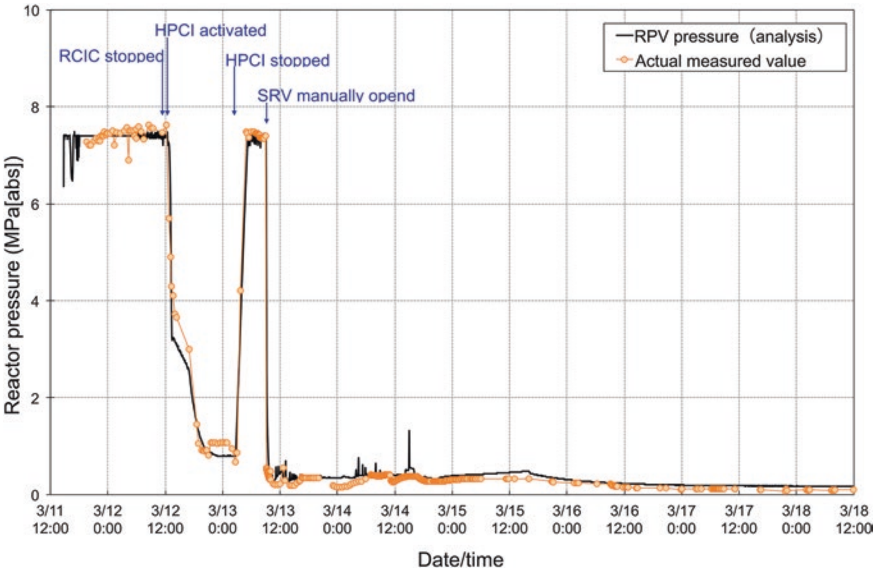

Fig. 2.8 Reactor pressure changes for Unit 3

2.4.3.2 From the Tsunami Arrival to RCIC Shutdown

The RCIC had stopped automatically at 15:25 on March 11 due to the high reactor water level before the tsunami arrived. As DC power supply was available at Unit 3,

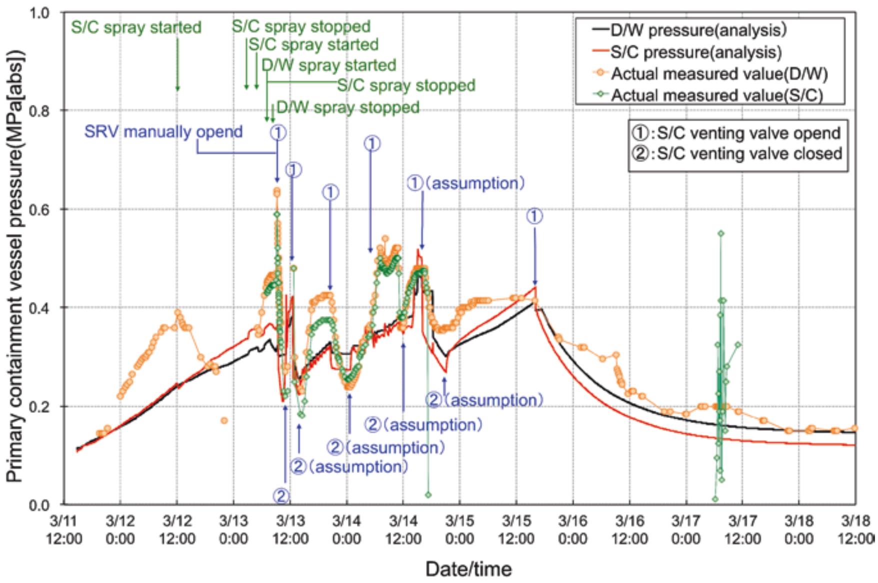

Fig. 2.9 PCV pressure changes for Unit 3

Table 2.4 Chronological accident description for Unit 3

Date	Time	Event	Section
3/11	14:46	Earthquake	2.4.3.1
		Loss of off-site power	
	14:50–15:37	RCIC injection: reactor was cooled by RCIC, even though RCIC was tripped several times due to RPV water level too high	2.4.3.1
	15:37	Tsunami hit: AC power was lost but DC power was available. RCIC was kept in operation with operator's control	2.4.3.2
	11:36	RCIC operation was terminated due to some reason	2.4.3.3
3/14	12:35	HPCI was automatically started due to RPV water level too low. RPV pressure decreased because HPCI consumed much steam	2.4.3.3
	2:42	HPCI manual shutdown: HPCI could not inject enough water due to lack of RPV pressure to drive turbine	2.4.3.4
	9:00	Reactor pressure sharp decrease by SRV manual open	2.4.3.5
	10:40[a]	Core damage started	
	11:01	Reactor building explosion	2.4.3.6

[a] Time from MAAP calculation

the RCIC was manually started at 16:03. The reactor pressure and water level were thus controlled by the SRV and RCIC. Since RCIC was designed for making up water loss by decay heat 15 min after shutdown, most of the time during plant operation, the amount of water injection was too large compared to decay heat. Hence, actuation and stop of RCIC was designed by increase and decrease of water level. Operators maintained reactor water levels by adjusting the flow rate set for flow controllers to allow gradual reactor water level changes. This was done by using the line configuration where water would pass through both the reactor injection and test lines so that part of the water could be returned to the condensate storage tank (CST) (water source for RCIC) in order to decrease the amount of water injection to the reactor even by consecutive operation. This would prevent automatic shutdown due to high reactor water levels, avoid battery depletion due to RCIC re-activation, and also ensure stable reactor water levels.

During this period the D/W pressure was increasing but the analysis results provided lower values of increase contrary to the situation of Unit 2; therefore the pressure behavior is assumed as follows.

- The RCIC turbine exhaust steam heated up the S/C pool water near the turbine exhaust pipe exit.
- The high temperature pool water was dispersed horizontally on the pool surface, thus producing thermal stratification in the pool water.
- This stratification caused a larger PCV pressure increase than the analysis (which assumed a uniform temperature increase of the pool water).

The RCIC stopped automatically at 11:36 on March 12 and thereafter its status of shutdown was confirmed on-site but its restart-up failed.

2.4.3.3 From RCIC Shutdown to HPCI Shutdown

The RCIC stopped automatically at 11:36 on March 12 and the reactor water level started to decrease. The High Pressure Coolant Injection System (HPCI)[12] started up automatically at 12:35 when the water level reached the low reactor water level (L-2). In addition, the diesel-driven fire pump (DDFP) was started up at 12:06 on March 12 for the S/C spray, since the S/C pressure had risen due to the exhaust steam from the SRV and RCIC.

Operators controlled the HPCI water flows by flow controllers using, as with the RCIC, the line configuration where water would pass through both the reactor injection and test lines so that part of the water was returned to the CST (water source of HPCI), which would prevent automatic shutdown due to high reactor water levels and avoid battery depletion due to re-activation, and also ensure stable reactor water levels. After the HPCI was started up, the reactor pressure started decreasing because the driving turbine consumed the steam.

The HPCI has a larger flow capacity than that of RCIC since the HPCI was designed to make up coolant flowing out from broken part in case of LOCA and consumes more reactor steam to actuate the HPCI turbine. As a result of these

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[12] The HPCI system is a single-train system that provides a reliable source of high-pressure coolant for cases when there is a loss of normal core coolant inventory.

two facts, the reactor pressure decreased by operating the HPCI and reached about 1 MPa[abs] at about 19:00 on March 12. This reduced reactor pressure lowered the HPCI turbine rotation speed and the status continued so that it could stop anytime.

In addition, monitoring of the reactor water level became impossible at 20:36 on March 12 due to loss of the power supply for the reactor level indicators.

The reactor pressure, which had been stable at about 1 MPa[abs], started to decrease at about 02:00 on March 13. It became lower than the allowable HPCI operation limit and reached a situation in which the HPCI could stop anytime. The operator, therefore, manually shut it down at 02:42 in consideration of the preparation underway for reactor water injection using the DDFP.

2.4.3.4 From HPCI Shutdown to Reactor Depressurization

The DDFP was switched over from the S/C spray mode to reactor water injection mode, and the injection of water to the reactor was prepared, so that the main control room operators were notified of the information at 03:05 on March 13, shortly after the HPCI shutdown. The reactor pressure reversed to an increasing trend after the HPCI had been shut down, but the depressurization attempt by SRV manual open operation failed after all. The reactor pressure further increased and exceeded the DDFP discharge head, thus disabling the alternative water injection to the reactor. An attempt was made on-site to supply nitrogen gas to drive the SRV via the supply line, but it failed, because the valve on the supply line was an air-driven type and it could not be manually operated due to structural limitations. Further operation attempts also failed to start up the HPCI and RCIC: the HPCI failed due to battery depletion, and the RCIC failed because the turbine trip throttle valve was closed again by its trip mechanism.

The measurement of reactor water level was interrupted at 20:36 on March 12 due to loss of power supply. When it was resumed upon recovery of power supply at about 04:00 on March 13, the fuel range water level indicators showed about TAF-2 m.

Water injection by S/C spray was resumed by switching over the DDFP from the reactor water injection mode at 05:08 on March 13 in order to prevent pressure increases of the D/W and S/C. At 07:39 the spray lines were switched over from S/C to D/W and the S/C spray was terminated at 07:43.

At 08:41 on March 13, the large S/C vent valve (air-operated) was opened and the configuration of the venting line was completed except for the rupture disc.

At about 08:40 through 09:10 on March 13, the DDFP stopped the D/W spray and waited for the reactor depressurization by SRV manual open, and then switched to water injection to the reactor again.

The reactor pressure, in the meantime, reversed to increase by the HPCI manual shutdown at 02:42 on March 13 and reached about 7 MPa[abs] at about 04:30, and stayed thereafter for about 5 h at about 7.0–7.3 MPa[abs]. When battery connection work was ongoing for depressurization regardless of the manual operation of depressurization by operator, the reactor pressure decreased abruptly at about 09:00 on March 13 down to below 1 MPa[abs]. This depressurization might have occurred due to the actuation of ADS in accord with depletion of DC power and investigation of RPV and PRV pressure behavior. Further investigation related to this depressurization is discussed in Attachment 3–3 and 3–4 of progress report [2].

2.4.3.5 From Reactor Depressurization to Reactor Building Explosion

Following this rapid reactor depressurization, fire engines started freshwater injection from 09:25 through 12:20 on March 13, and later at 13:12 fire engines started seawater injection. The DDFP was also being operated in parallel, but water injection was considered mostly not to be working due to the pressure balance relation between the pump discharge pressure and reactor pressure.

Because of rapid reactor depressurization, the PCV pressure increased, the S/C pressure exceeded the rupture disc working pressure, and the D/W pressure was confirmed at 09:24 on March 13 to have decreased. This led to the conclusion that the PCV had been vented.

The reactor water level indicators showed hunting oscillatory behavior after the rapid depressurization at about 09:00 on March 13 and a certain constant level after 12:00 regardless of the amount of water injection. Similar to other units, it can be understood that the correct water level could not be shown due to water evaporation in the water level instrumentation tube.

The reactor water level which was kept at around the top of active fuel level following the HPCI shutdown at 02:42 on March 13 decreased, and fuel was overheated by the decrease in the amount of steam following the water level drop as in Unit 1, which resulted in the start of core damage. A large amount of hydrogen was generated by water-zirconium reactions when the core became uncovered and fuel cladding temperatures started to rise. The reason for the PCV pressure increase during rapid depressurization of RPV is assumed to be the effect of the accumulation of large amounts of hydrogen inside RPV. Therefore, it is considered that the core damage at Unit 3 had mostly progressed before the depressurization.

According to the chart records, the reactor pressure after the rapid depressurization at about 09:00 on March 13 showed a sharp rise to several MPa[abs] first at about 10:00 and again at 12:00, followed by a gradual decrease.

This pressure behavior may have some correlation to the SRV opening/closing operation for connecting batteries to the SRV for opening. But the pressure rise is steep for the value due to steam generation. The pressure increase can be confirmed to be considerably faster when compared with the pressure increase upon HPCI shutdown. Therefore, it is possible that the molten fuel dropping into the water pool at the bottom of RPV contributed to the pressure increase due to massive steam generation.

2.4.3.6 From the Reactor Building Explosion to Late March

Water injection by fire engines was continued after being interrupted at the time of the explosion at 11:01 on March 14 in the Unit 3 reactor building.

Water injection by fire engines was resumed at 15:30 on March 14 after the explosion. It was found that water injection to Unit 3 was interrupted again at 21:14 on March 14 in order to secure water injection to Unit 2 and that it was resumed at 02:30 on March 15.

Efforts were continued to keep the PCV vent valve open since it had been opened at about 09:00 on March 13 when the rupture disc opened upon reactor depressurization. But it was closed thereafter due to failure of the temporary generator for power supply, and the opening operation of PCV vent valve had to be repeated until March 20 to keep it open.

Unclear features remain concerning the D/W pressure: its changes when no PCV venting was recorded; and no pressure decrease when the PCV vent valve was confirmed to have been opened at 06:10 on March 14.

Steam was observed on several occasions, which might have leaked from the PCV: black smoke rising up at about 16:00 on March 21; and steam rising up from the west side of the building and above the building on March 29.

2.5 Present Situation of Cores and PCVs of Units 1–3

2.5.1 Unit 1

Water is being injected to Unit 1 from the Core Spray (CS) and feedwater system, as shown in Fig. 2.10. Water from the CS system is directly sent to the core and water from the feedwater system is sent to the lower plenum via the outer side of the core shroud. The reactor level is confirmed to be below TAF-5 m, based on the calibrated results of the water level indicators, that is, no sufficient water exists in the core region.

The status of Unit 1's core was estimated based on the above facts and aforementioned examination results, and is illustrated in Fig. 2.10. As can be seen in the figure, most of the molten fuel generated by the accident fell down to the lower plenum below the reactor pressure vessel and only a little fuel remains in the original core location. Most debris, which had fallen to the lower plenum, is believed to have reached the PCV pedestal. It is estimated that, after causing core-concrete interactions, the debris was cooled by injected water, decrease of its decay heat terminated the core-concrete interactions, and it now remains in the PCV.

At the in-containment investigation in October 2012, the level of residual water in the D/W was checked by cameras. It was about 2.8 m above the D/W floor (as of October 10, 2012).

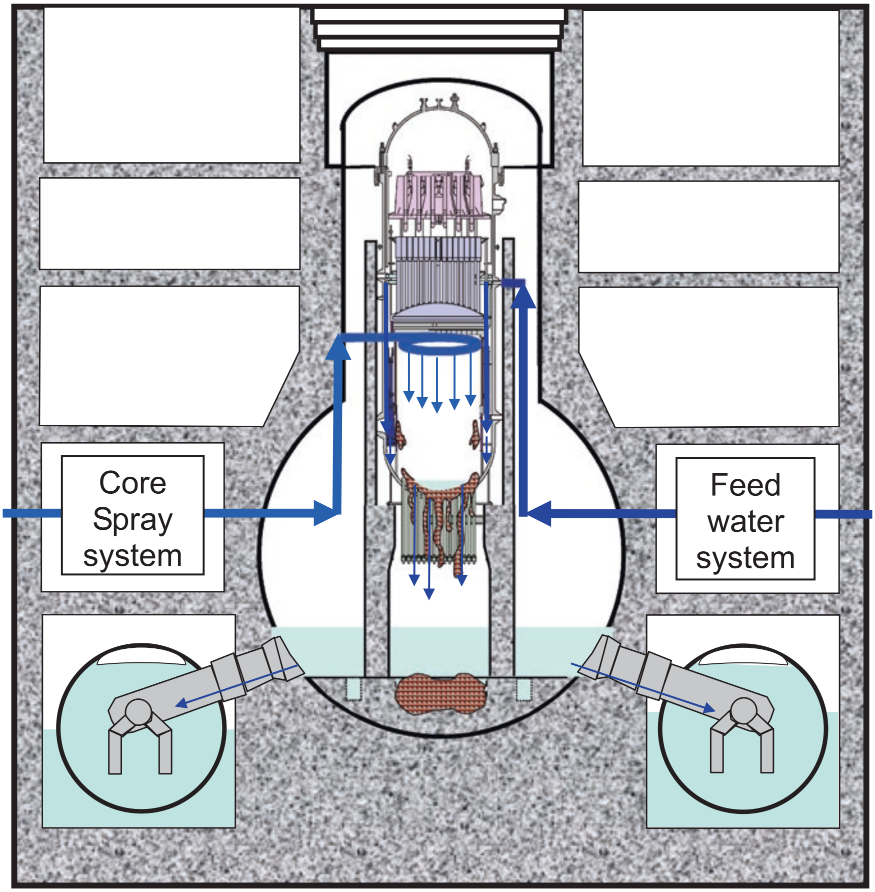

Fig. 2.10 Estimated conditions of the core and PCV of Unit 1

Concerning the status in the S/C, the nitrogen gas injection experiment in September 2012 demonstrated a mechanism that Kr-85 and hydrogen generated at an early stage of the accident had remained in the upper space of the S/C and they were discharged to the D/W via vacuum breakers when the S/C water level was pushed down. This means that the S/C is currently filled with water.

The location of liquid phase leakage was confirmed at the D/W bottom and vacuum breaker valve line due to the following evidence:

- Water flow from suction drainpipe which exhausted accumulated water to outside the D/W in November 2013.
- Water flow from vacuum breaker valve line connected for reducing the pressure difference between S/C and D/W in May 2014.

2.5.2 Unit 2

Water is being injected to Unit 2 from the CS and feedwater system, as shown in Fig. 2.11. Water from the CS system is directly sent to the core and water from the feedwater system is sent to the lower plenum via the outer side of the core shroud. Based on water filling to the condensing chamber on reference water level side piping shown by the water level indicators, the reactor water level is estimated to be below TAF-5 m, meaning there is not sufficient water for covering the core.

The estimated situation of the Unit 2 core, based on the above facts and aforementioned examination results, is illustrated in Fig. 2.11. As can been seen in the figure, part of the melted fuel generated in the accident fell down to the lower plenum below the reactor pressure vessel or to the PCV pedestal. Some of the fuel may remain in the original core location.

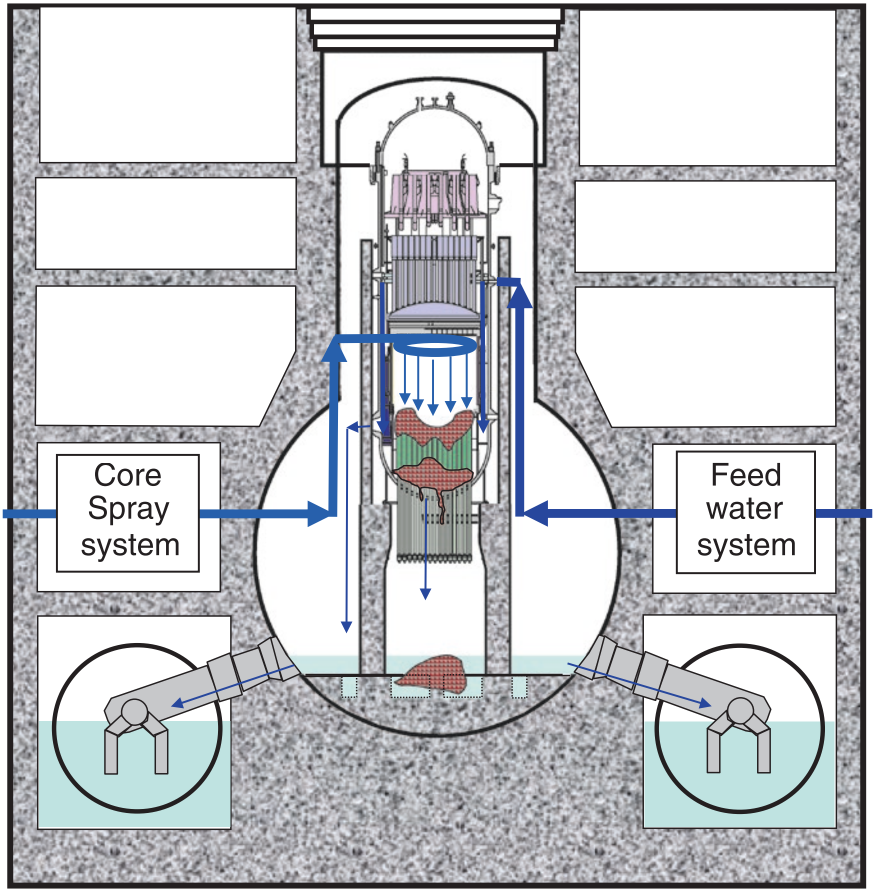

Fig. 2.11 Estimated conditions of the core and PCV of Unit 2

At the in-containment investigation in March 2013, the level of residual water in the D/W was checked by cameras. It was about 60 cm above the D/W floor (as of March 26, 2013).

The nitrogen gas injection experiment to the S/C conducted in May 2013 showed the S/C pressure of 3 kPag (as of May 14, 2013). This meant the S/C water level was at around the nitrogen gas injection inlet (O.P. 3,780 mm), because a certain water head should appear if the S/C was close to being full. When considered together with the low water level in the D/W, the water injected to the reactor is estimated to have flowed into the S/C via the vent lines from the D/W and leaked out to the reactor building from the bottom of the S/C, i.e., the current S/C water level can be estimated to be about the same level as the residual water level in the torus room.

The water leak paths from the S/C have not been located yet. But at least no leakage was confirmed at the S/C manholes, etc., when, for the internal investigation in the torus room in April 2012, robots accessed the corridor for visual checks; or at the lower ends of the vent tube, when they were checked at the internal investigation of the torus room in December 2012 and March 2013. Due to no damage at S/C top and low water level of D/W, leakage location of PCV is assumed to be at the S/C bottom.

2.5.3 Unit 3

Water is being injected to Unit 3 from the CS and feedwater system, as shown in Fig. 2.12. Water from the CS system is directly sent to the core and water from the feedwater system is sent to the lower plenum via the outer side of the core shroud. The reactor temperature was lowered to 70 °C as of November 11, 2011, which had been achieved by water injection from the CS system conducted from September 1, 2011 and the fuel debris in the CS water injection path, i.e., in the core, could be cooled.

The estimated situation of the Unit 3 core based on the above facts and aforementioned examination results is illustrated in Fig. 2.12. As can been seen in the figure, part of the melted fuel generated in the accident fell down to the lower plenum below the reactor pressure vessel or to the PCV pedestal. Some of the fuel may remain in the original core location.

No measured values are available so far concerning the D/W water level. But it could be estimated to be about 5.5–7.5 m above the floor by converting the S/C pressure to water head. The S/C pressure was obtained from its existing pressure indicators, not calibrated since the accident, so they are not highly accurate but they could be reliable as a trend to a certain extent because they have followed the pressure changes according to the water injection. In addition, leakage from around the expansion joint of PCV penetration of the main steam line D was confirmed. The elevation of this leakage is the same as the presumed water level inside the PCV, so most of the leakage from the PCV is assumed to be from this location.

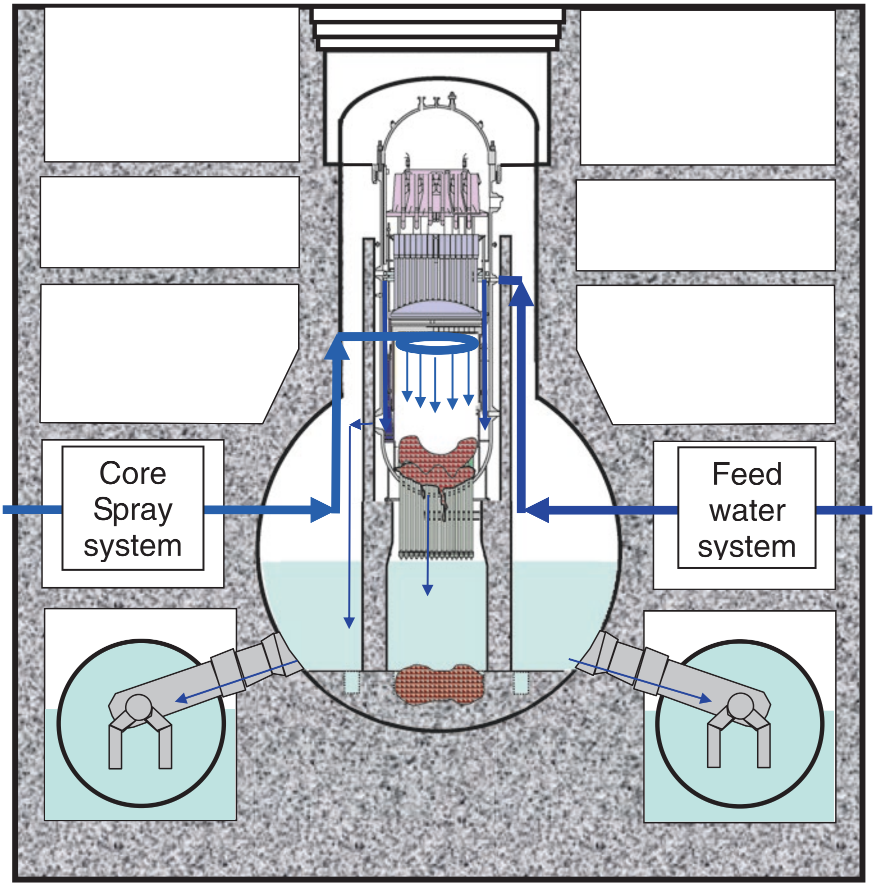

Fig. 2.12 Estimated conditions of the core and PCV for Unit 3

2.6 Spent Fuel Pool Cooling

Due to the impact of the tsunami, Units 1–6 and the common spent fuel pool (SFP) all lost cooling capacity. There was no emergency situation with the reactors, but the fuel energy deposition was large, and there was concern about the condition of the Unit 4 SFP that eventually led to the hydrogen explosion.[13] The day after the explosion (March 16), a TEPCO employee accompanied a Self-Defense Force (SDF) helicopter pilot, and according to the employee, the pool water level was maintained.

SDF helicopters sprayed water onto Unit 4, while firefighting units from the SDF, Tokyo Fire Department, and the National Police Agency hosed it down. Later, as

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[13] SFP generally has fuels with small decay heat, therefore rapid accident progression is not considered. However, fission product released in case of fuel damage is large since there is no containment vessel for SFP.

a long-term stable measure for injecting cooling water, a large size concrete pump vehicle was used. (Cooling water injection into Unit 4 began on March 22.)

Dealing with the Unit 4 SFP was an extremely important turning point in preventing the spread of the disaster.

2.7 Plant Explosion

2.7.1 Units 1 and 3

It is assumed that when the fuel inside the reactor was damaged, hydrogen was generated as a result of zirconium-water reaction, which then leaked out and remained in the reactor building, finally resulting in hydrogen explosion.

The exact route by which the hydrogen escaped into the reactor building is unknown, but it is assumed that leak-proof seals on the head of the PCV and hatch joints where machinery and personnel enter and exit were exposed to high temperatures and may have lost their functionality.

Another possibility is that it may have escaped from the PCV vent line via the standby gas treatment system (SGTS) line into the reactor building, but the results of investigating the condition of the Unit 2 SGTS show that the volume of hydrogen that could travel this route is limited, and therefore, the major source of hydrogen for the explosion must have leaked directly from the PCV into the reactor building.

2.7.2 Unit 4

There are no indications of damage to the fuel in the SFP, and as the process of radiolysis of the water in the pool can only generate small amounts of hydrogen, the fuel inside the SFP is not being considered as a possible cause of the explosion.

The results of investigating conditions of the Unit 4 SGTS and the field investigation of conditions inside the Unit 4 reactor building lead to the hypothesis that the hydrogen that caused the explosion was the Unit 3 PCV vent gas that traveled through the SGTS pipes into Unit 4.

2.8 Concluding Remarks

There are still unclear issues and some observed phenomena that cannot be confidently interpreted. For example, the reason why the reactor core isolation cooling (RCIC) system of Unit 2 lost its function still remains unknown. Also, concerning earthquakes and tsunami, there are some issues for academic researchers to tackle, such as the mechanism of earthquakes of this historically huge scale occurring in the same district and causing massive tsunami.

Discovering root causes for loss of the safety equipment function improves knowledge about existing system functionality and thus enhances safety. Fuel removal and prevention of generating contaminated water are crucial for decommissioning Fukushima Daiichi NPS.

In order to cope with these issues, it is essential to grasp the damage mechanisms as well as the current situation of debris in the reactors and containment vessels (PCV). Even the issues not directly related to accident progression may provide clues to enhancing safety as a result of examining them.

References

1. Matsuzawa T, Iio Y (2012) The reasons why we failed to anticipate M9 earthquake in northeast Japan. In: Proceedings of the international symposium on engineering lessons learned from the 2011 Great East Japan Earthquake: One Year after the 2011 Great East Japan Earthquake, 1-4 March 2012, Tokyo
2. The Tsunami Evaluation Subcommittee, The Nuclear Civil Engineering Committee (Feb 2002) Tsunami assessment method for nuclear power plants in Japan. Japan Society of Civil Engineers, Tokyo. Available at: http://committees.jsce.or.jp/ceofnp/system/files/JSCE_Tsunami_060519.pdf. Accessed 20 July 2014
3. Kanamori H (July 1977) The energy release in great earthquakes. Journal of Geophysical Research 82: 2981-2987
4. Tokyo Electric Power Company (13 Dec 2013) Evaluation of the situation of cores and containment vessels of Fukushima Daiichi Nuclear Power Station Units 1 to 3 and examination into unsolved issues in the accident progression, Progress Report No. 1. Tokyo Electric Power Company, Tokyo

Bibliography

5. Tokyo Electric Power Company (Jun 2012) Fukushima nuclear accident analysis report
6. Yamanaka Y, Mizokami S, Watanabe M, Honda T (2014) Update of the first TEPCO MAAP accident analysis of units 1, 2, and 3 at Fukushima Daiichi Nuclear Power Station. Nuclear Technology 186(2): 263-279
7. Tokyo Electric Power Company (6 Aug 2014) Evaluation of the situation of cores and containment vessels of Fukushima Daiichi Nuclear Power Station Units 1 to 3 and examination into unsolved issues in the accident progression, Progress Report No. 2. Tokyo Electric Power Company, Tokyo

Chapter 3
Analysis of Radioactive Release from the Fukushima Daiichi Nuclear Power Station

Satoru Tanaka and Shinichiro Kado

Abstract Basic schemes and databases necessary to assess the radioactive release in severe accidents at nuclear power plants are presented. The approaches include one based on the physical and chemical properties of the core fuel, and another based on the radiation monitor. Trials of the rough evaluation for the severe accident at Fukushima Daiichi nuclear power station are made using both approaches without relying on specialized computer simulations for educational purposes, even though the exact values will be less reliable. The results were compared with the official statements by the authorities for both cases, and confirmed to be nevertheless fairly consistent with each other. This fact implies that these "manual calculation-based" approaches are practically useful, especially for accidents where detailed simulation results have not yet come out, or are still unavailable or ambiguous. Background of the database, such as atmospheric diffusion, flash boiling, and radiological equivalence including dose factor, are described in the appendixes.

Keywords Core inventory · Severe accident progression · Radioactive release · Dose assessment · Ground shine · Radiological equivalence

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3.1 Introduction

Located at the Fukushima Daiichi (1F) nuclear power station (NPS) are six nuclear power plants. Among them, Units 1, 2, and 3 (referred to hereafter as 1F1, 1F2, and 1F3, respectively) had major accidents resulting from the earthquake and tsunami on March 11, 2011. Units 1, 2, and 3 encountered station blackout (SBO), i.e., loss of all alternating current (AC) power including emergency diesel generator, back-up battery depletion, and emergency cooling system failure. Response to the accident faced severe difficulties in removing the decay heat of the fuel and oxidization heat of the fuel rods made by Zircaloy (see Chap. 2 of this volume). Finally, core melt of the fuel rods occurred. What was worse, the fuel materials further melted through the reactor pressure vessels (RPVs), which led to a considerable amount of leakage of the radioactive materials to the environment.

Information necessary to evaluate (or even to speculate) the degree of seriousness of the accident seemed to be insufficient, since it was limited, undisclosed, or uncertain, especially in the early stage of the accident. Even under such circumstances, one could only rely on the inventory calculated from the operation history of each unit, together with the physical and chemical properties of the materials, and ambient dose rate monitored by the government, electric power companies, or nuclear facilities in research institutes or in universities.[1]

The purpose of this chapter is thus to introduce some background information for scientific analysis of the release of radioactive materials from the Fukushima Daiichi NPS based on their inventory in the reactor core, mechanisms of the release, and the behavior of the released radionuclide. The state of contamination and decontamination of the area is also briefly mentioned.

3.2 Methods of Analysis

3.2.1 General Concepts for Various Models

The image of the damage and the pathways of the radioactive materials are shown schematically in Fig. 3.1. These events, together with the leakage of the primary containment vessels (PCVs), caused significant release of radionuclides to the environment.

The real situation was far more complicated. Thermally damaged top-head flanges, cracks in pipe inlets in the PCV, and vent pipes between the PCV and the

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[1] Note that the data evaluated here have considerable ambiguities; thus the authors would like to suggest that readers take them as examples for study of methodology of the analysis from the limited availability of information and data. Indeed, up to now (as of 2014), the data reported by the government, TEPCO, etc., have been frequently updated.

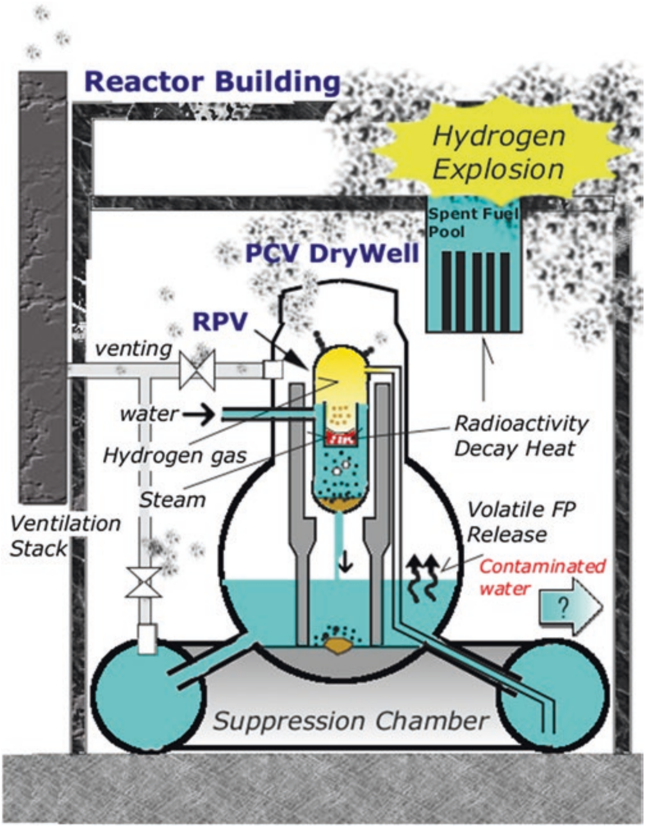


Fig. 3.1 Schematic drawing of the reactor damage and behavior of radioactive materials

suppression chamber (SC) have been regarded as possible leak paths. Indeed, three units exhibited different features of cooling failure (see Chap. 2 of this volume).

Figure 3.2 shows schematically the behavior of radioactive materials in the environment after their release from the reactor facility. In order to assess the direct effects of the radioactive release to the environment, we must make use of the inventory of radionuclides and chemical elements in the fuel just before the accident; release from the fuel at the accident; existence states of radionuclides in the RPV, PCV, and reactor building; release from the stack or reactor building; migration in the atmosphere; contamination of soil; and ambient dose rate from radionuclides in the soil and in the atmosphere.

There are basically two approaches to evaluating the amount of environmental release of radionuclides. One is based on analysis of the physical and chemical conditions of the core fuel. In this approach, a fraction of the released amount is approximated with certain plausible values. The other is based on "radiation mapping" made by monitoring the excess ambient dose rate and/or radioactivity measurement of the contaminated soils. The former is an indirect method because

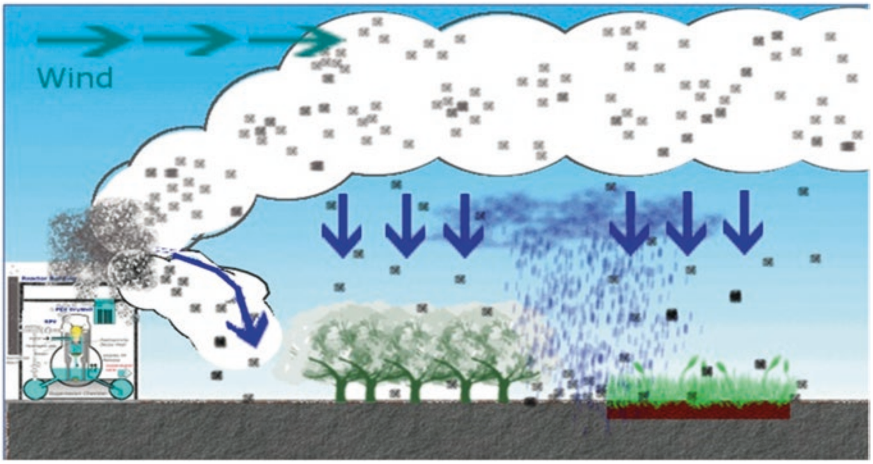


Fig. 3.2 Radioactive materials in the environment

the radioactive species need to be assumed from other information or knowledge. However, in the early stages of the accident it is more convenient than the latter.

3.2.2 *Model 1: Release from Fuel with Known/Assumed Inventory*

Amounts of radionuclides, such as fission products (FPs), uranium (U), plutonium (Pu), and minor actinides (MAs) in the reactor fuel need to be evaluated. Information about the chemical elements is also important for the stoichiometric estimation of the chemical forms of released fission products. This can be calculated with the help of the ORIGEN code [1], which is based on the theory of production and the following radioactive decay of FPs and MAs.

A cause for release of radioactive materials at all reactors was that decay heat of fission products had not been eliminated due to loss of the cooling function. Consequently, the fuel rods were exposed to steam and the fuel and cladding were heated up, which resulted in generation of hydrogen gas by chemical reaction between zirconium and steam above 900 °C. The reaction $Zr + 2H_2O \rightarrow ZrO_2 + 2H_2$ produces hydrogen, which caused the subsequent hydrogen explosions. It also produces heat because this reaction is exothermic. This heat accelerates the heating of the fuel combined with decay heat. At high temperatures uranium made an eutectic compound with zirconium. The melting point of this eutectic is lower than uranium oxide. Figure 3.3 shows high temperature phenomena of the fuel relating to the core-melt progression [2, 3]. Some radioactive materials in the fuel soluble in UO_2 were released following heating and melting of the fuel. The fraction of released radioactive materials from the heated

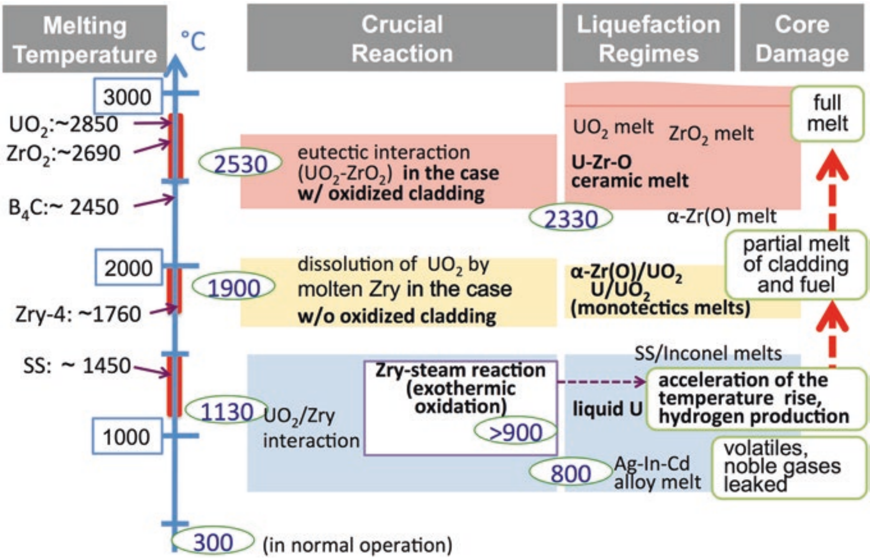


Fig. 3.3 High temperature phenomena in the core [2, 3]

fuel depends on the vapor pressure (i.e., melting point) and diffusivity in the fuel. These behaviors are strongly dependent on the temperature. A release rate constant k [min^{-1}] as a function of the temperature T [K] is given by

$$k = k_0 \exp(-Q/RT), \tag{3.1}$$

where Q is the activation energy [kcal/mol], and $R = 0.001987$ kcal/mol K the universal gas constant.

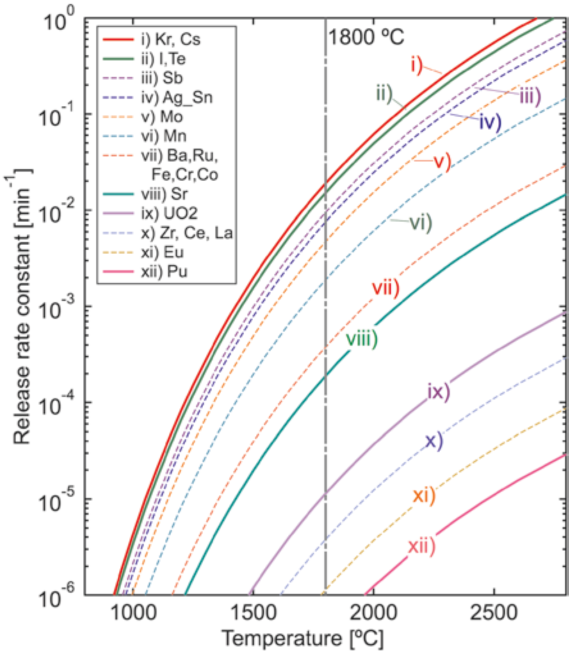
Although Q depends on the chemical species, Oak Ridge National Laboratory (ORNL) and others proposed, in their CORSOR-O model [4], to use the common Q of 55 kcal/mol for all species and the dependence on the species is represented by the empirically corrected k_0. For example, $k_0 = 12{,}000\ \mathrm{min}^{-1}$ for Cs and Kr while it is 9,600 min^{-1}[$= 0.8 \times k_0$ (Cs)] for I and Te. The results are shown in Fig. 3.4.

Using the CORSOR-O model, the fraction of inventory released from the fuel at time t is obtainable. Taking Cs as an example for calculation, the fractions of inventory released at 1,800 °C are: F = 90 % at $t = 2$ h; and $F = 100$ % at $t = 4$ h.

3.2.3 Model 2: Codes for Severe Accident Progression Analysis

Computer codes have been developed to analyze or predict the progression of severe accidents. Modular Accident Analysis Program (MAAP) was developed

Fig. 3.4 Temperature dependence of release rate constants from UO_2 fuel



by U.S. industries while MELCOR was developed by the United States Nuclear Regulatory Commission (US NRC) [5].

These codes basically calculate the thermal response of the core, dealing with the entire progression from the initiating event to the radionuclide releases to the environment, which is called the "source term." Therefore, the initial inventory and the release properties for each nuclide are required as input parameters. These values are usually calculated by a burn-up code, such as ORIGEN or CORSOR. The entire progression from the initial event includes damage in the RPV and PCV and consequent leakage of water and steam.

After the accident, another code named "Severe Accident analysis code with Mechanistic, Parallelized Simulations Oriented towards Nuclear fields (SAMPSON)" [6], developed by Nuclear Power Engineering Corporation (NUPEC), has been improved by Institute of Applied Energy in Japan. The merit of the SAMPSON code is the fact that there is no factor adjusted by the user.

3.2.4 Model 3: Atmospheric Transport Model

Behavior of the radioactive materials released from a nuclear facility differs depending on their chemical properties, weather conditions (e.g., wind direction, wind speed, rainfall, snowfall), and the geography around the plant. Noble gases such as Kr or Xe are transported and dispersed by wind. If upward wind is predominant, the gases will be transported to the stratosphere and delivered across the entire earth by the wind. Gases of volatile radioactive materials such as I_2 are also transported by the wind. CsI or Cs oxides can be transported by the wind if these nuclides float in the air as dust particles or attach to aerosols. This is called the "plume" as schematically shown in Fig. 3.2.

If rain or snow falls, some particles will fall to the surface of the earth together with raindrops (wash-out or rain-out) and contaminate the land. Therefore, prediction of the transport of radionuclides, i.e., evolution of the plume, is crucial for protecting local residents from radiation. Note, in contrast, that relatively large particles such as fuel grains are rather difficult to be transported far by the wind, so they tend to fall out by gravity near the NPS.

The time-integrated concentration of the released nuclides in the atmosphere, $\chi(x, y, z)$ [Bq/m^3], can be formulated by the Gaussian model as:

$$\chi(x, y, z) = \frac{\Gamma}{2\pi U\sigma_y\sigma_z}\exp\left(-\frac{y^2}{2\sigma_y^2}\right)\left\{\exp\left(-\frac{(z-h)^2}{2\sigma_z^2}\right) + \exp\left(-\frac{(z+h)^2}{2\sigma_z^2}\right)\right\} \tag{3.2}$$

where Γ is the release rate at source [Bq/s], U the mean wind speed in the x direction [m/s], h the physical height where the plume comes out [7]. The diffusion parameters, σ_y and σ_z, represent the broadening in the transverse and vertical direction, respectively. Their values can be found in the data chart known as the Pasquill-Gifford diagram shown in Fig. 3.5, which categorizes air-stability into 6 classes, A-F, depending on local solar radiation and surface wind speed [7]. One can see from this figure that the lateral spread of the plume is only 1/10–1/100 the

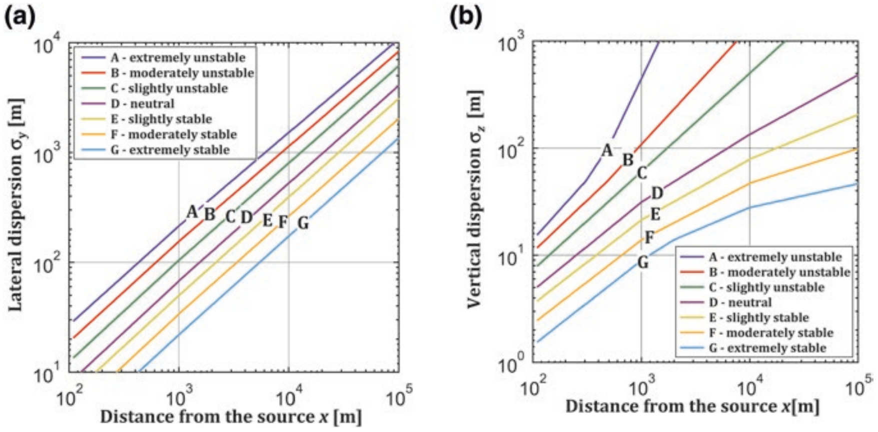


Fig. 3.5 Pasquill-Gifford dispersion diagrams: **a** horizontal dispersion, ground sources; **b** vertical dispersion, ground sources. In Japan, an extremely stable class G is added to classes A–F (see Appendix A of this chapter)

travel distance necessary to deliver local effects to the environment. Nevertheless, the atmospheric diffusions are larger than that deduced from molecular collisional diffusion, since the turbulent flows enhance the net diffusion.

Because Eq. (3.2) is only applicable to the simple condition, i.e., flat topography and temporally and spatially constant wind, it is not suitable for the real-time simulation of atmospheric dispersion of radionuclides during emergency. Thus, more sophisticated model is used for this purpose. The System for Prediction of Environmental Emergency Dose Information (SPEEDI) [8] predicts the atmospheric dispersion and deposition of released radionuclides in the local and regional areas by solving the transport and diffusion equation numerically in which three-dimensional meteorological fields and topography are considered explicitly. A worldwide version of SPEEDI (WSPEEDI) [9] can predict in detail the process of the atmospheric dispersion and deposition of released radioactive materials over the world for overseas accident.

The behavior of radioactive materials released to the ocean is evaluated from transportation and dispersion along the ocean current, dispersion by the tidal stream and wind, precipitation to the bottom of the sea, and intake by fishes and their migration. The compartment model is used for evaluation of the contamination in the ocean. The amount of release directly to the ocean as contaminated water is not included in the assessment of the accident scale.

3.2.5 Model 4: Ambient Dose Rate from the Contaminated Ground

The total release of the radioactive material, that is the integral of the source term with respect to the period of release, can be roughly evaluated from the ground contamination caused by the fallout/rainout/washout after the radiation plume has passed through, based on the following equations.

$$D_j(t_{obs}) = \left[A_j^{'}(t_{com})\right]\left(\frac{1}{2}\right)^{(t_{obs}-t_{com})/\tau_j} CF_{grd,j} \tag{3.3}$$

$$\hat{D}_j(t_{obs}) = D_j(t_{obs})/\sum_j D_j(t_{obs}) \tag{3.4}$$

$$A_j(t_s) = \hat{D}_j(t_{obs})\left(\frac{1}{2}\right)^{(t_s-t_{obs})/\tau_j} CF_{grd,j}^{-1} \cdot SF^{-1} \tag{3.5}$$

$$s_i = A_j(t_s)\frac{Land + ocean}{Land} \tag{3.6}$$

where D and A represent the dose rate [Sv/h] and the radio activity of the surface area [Bq/m^2], respectively.

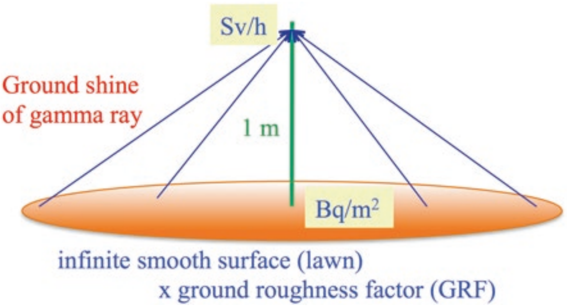


Fig. 3.6 Schematic drawing of evaluation of dose rate based on the ground shine

CF_{grd} is the conversion factor from ground contamination to the ambient dose rate at 1 m above the ground, [(Sv/h)/(Bq/m^2)] shown in Fig. 3.6, while SF is the shielding factor depending on the ground condition, location, or buildings. We determined that $SF = 0.7$ is a plausible value to be applied in the present situation (see Appendix C). τ is the half life of the radioactivity. t_{com}, t_{obs} and t_{s} are the times when the species ratio is determined, when the dose rate was measured, and when the radioactive species are released, respectively. Note that the subscript j is the label of the species and ^{131}I ($\tau = 8.02$ d), ^{134}Cs ($\tau = 752.4$ d), and ^{137}Cs ($\tau = 11019.3$ d) in the present case.

3.3 Occurrence of the Accident and Release, Transport, and Washout of the Radiation Plume

From the severe-accident analysis based on the MAAP or MELCOR code, it is reported that the core damage incident for each unit happened approximately at the period listed in Table 3.1.

Figure 3.7 shows the temporal evolution of the ambient dose rate observed inside the 1F site, in nearby and distant cities, together with the wind conditions

Table 3.1 Core damage progression simulated by MAAP and MELCOR codes

Simulation analysis	Unit	1F1	1F2	1F3
MAAP code (TEPCO)	Core exposure	3 h	75 h	40 h
	Core damage	4 h	77 h	42 h
	RPV melt-through	15 h	109 h	66 h
MELCOR code (NISA)	Core exposure	2 h	75 h	41 h
	Core damage	3 h	77 h	44 h
	RPV melt-through	5 h	80 h	79 h
Actual events	IC/RCIC stopped	2 h 50	70 h 39	35 h 56
	Vent (AO valve)	23 h 44	Failed?	42 h 30
	Explosion/rupture	24 h 50	77 h	68 h 12

Hours from scram (March 11, 2011, 14:46 JST)

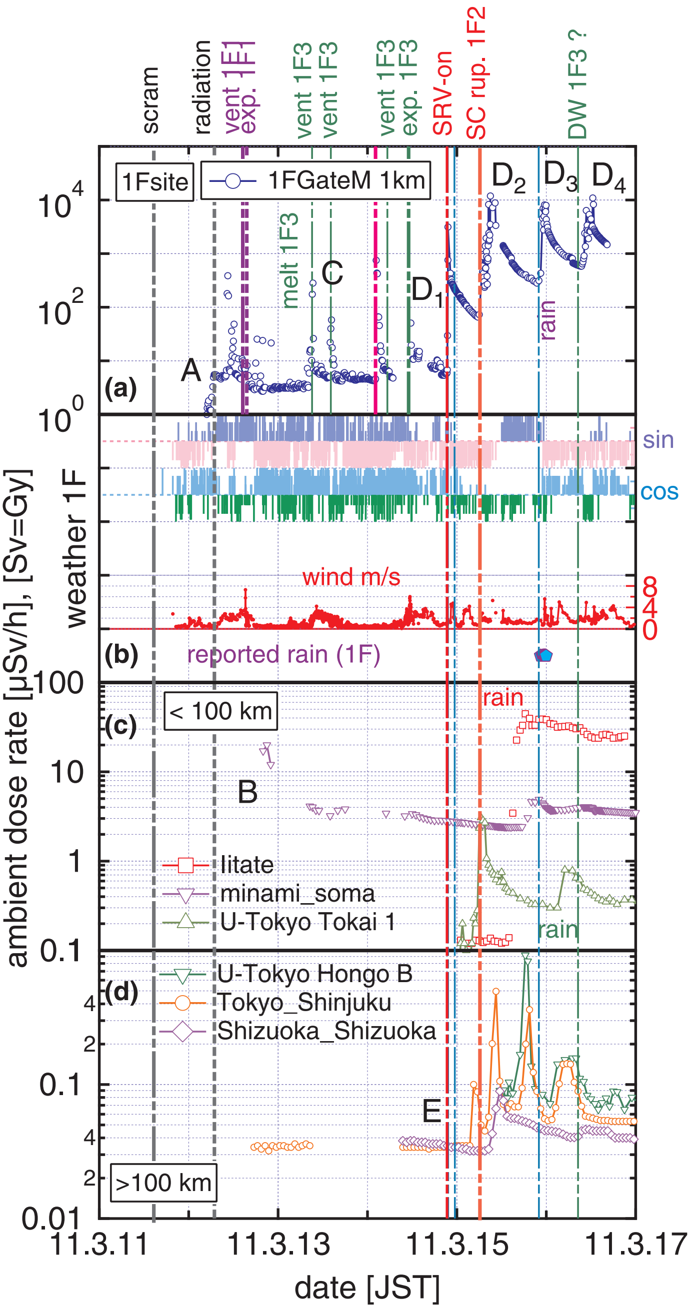


Fig. 3.7 Temporal evolution of the ambient dose rate at **a** 1F monitoring post, **c** nearby, and **d** distant, **b** wind direction indicated by sine and cosine components (data from the University Tokyo and those publicly released by TEPCO and MEXT)

at the 1F monitoring posts (MPs). Note that in 1F, a monitoring car was used because the MPs were not working due to the power failure. The direction and speed of the wind were recorded with a 16 point compass, e.g. north (N), north-northwest (NNW), northwest (NW), west-northwest (WNW), south (S), east (E), etc., at the same time as the radiation dose rate at the monitoring posts/car in 1F. In order to compare the temporal evolution of the wind vector with other events, we represented the wind direction θ as the sine and cosine components of the direction (orienting to the east being 0°, while orienting to the north being 90°). In the present analysis, $\sin(\theta) > 0$ corresponds to the direction from the land to the ocean, while $\cos(\theta) < 0$ corresponds to the direction to the south (toward Tokyo).

At the 1F site, the dose rate began to increase from 4:04 on March 12 (13 h after scram), which presumably coincides with the incidents in 1F1 (Fig. 3.7, A). First, venting and the following hydrogen explosion was presumed to be the cause of the increase in the dose rate in Minami-sōma, 26 km north of 1F, on March 12 (Fig. 3.7, B). Note, however, that precise data recorded every 20 s (telemeter system) disclosed in November 2013 revealed that the rapid increase of dose rate at Kamihatori 6 km north west of 1F coincided with the attempt to vent around 14:30 while the hydrogen explosion at 15:36 did not cause apparent increase in the dose rate around 1F.

The core damage incident in 1F3 occurred on March 13. The venting of the PCV of 1F3 was operated several times in the depressurizing procedure of the RPV during March 13 and 14, and the hydrogen explosion occurred at 11:01 on March 14 (68 h after scram). The fact that the wind was directed to the east (sea direction) during this period was, so to say, one consolation in the disaster (Fig. 3.7, C). However, the release of the radioactive materials in this event was considerably smaller than the following incident in 1F2.

The incident at 1F2 caused the most serious release of radioactive nuclides. The suspected leakage of the PCV caused the release of radioactive gases around 21:30 on March 14 (Fig. 3.7, D_1), which was several hours before detection of the sound of the explosion or rupture at the suppression chamber (SC) of 1F2 (at 6:10) (Fig. 3.7, D_2). Note that for that time, we have not enough evidence to tell whether the event was an explosion or a rupture. On October 2, 2011, it was reported that the accident investigation commission of Tokyo Electric Power Company (TEPCO) determined from the signals recorded on a quake meter that the hydrogen explosion might not have occurred in 1F2. It is more likely that the sound was delivered from the hydrogen explosion at 1F4, presumably caused by the escaped hydrogen from 1F3 through a duct.

The radioactive leakage from 1F2 in this period (Fig. 3.7, D_1), presumably caused by opening the safety relief valves (SRVs) followed by the leakage through the damaged PCV, initiated the radiation plume toward the South direction, and the increase in ambient dose was observed as the plume propagated and passed through the locations at a speed of about 10 km/h (Fig. 3.7, E). The radiation plume was observed even in Tokyo (SW 230 km of 1F) and Shizuoka (SW 360 km).

Note that by using SRVs to depressurize the RPV, external water injection becomes possible. However, flash boiling (see Appendix B) can accelerate the core exposure. SRV operation after core damage can therefore cause a significant transport of radioactive materials out of the RPV into the SC.

Figure 3.8 shows the temporal evolution of the ambient dose observed at different locations after the initial prominent radioactive release on March 15.

[**North <50 km from 1F**]

The plume on March 15 (Fig. 3.7, D_1) soon passed and the ambient dose rate decreased rapidly, particularly in distant locations. However, the plume initiated by the SC rupture (Fig. 3.7, D_2), propagated to the Northwest direction and caused fallout/washout/rainout due to rainfall and/or snowfall. This contributed to the significant increase in dose rates in these areas, such as Iitate-mura (NW 40 km) (Fig. 3.8, F).

Although the origin of the later peaks at the main gate (Gate M) of 1F, indicated in Fig. 3.7 as D_3 and D_4, has not yet been rigorously identified, the release of radioactive materials still continued even after March 16. As a result, rainfall over a wide area to the south washed out the plume into the soil, leading to a significant increase in the ambient dose rate. This time the decrease in the dose rate was dominated by the radiation decay of the radioactive nuclides. On March 18 and 19, the wind blew toward the North direction, and several dose rate peaks were observed in Minami-sōma (N 30 km). However, presumably because there was no rainfall, these plumes did not deposit material onto the ground (Fig. 3.8, G).

On March 21, although rain fell in Fukushima, the plume did not deposit material onto Minami-sōma, because the wind was heading south (Fig. 3.8, H).

This suggests that ground contamination occurred due to both the plume and rainfall.

[**South 50–100 km from 1F**]

Ibaraki prefecture, located south of Fukushima, was subjected to a considerable degree of washout/rainout on March 16 and 20, that can be seen from the increase of the baseline of the ambient dose rate, having a decay timescale of ^{131}I, 8.02 d (Fig. 3.8, I).

Just after the delivery of the plume, the decay of the short-lifetime radioactive nucleus was also observed, such as ^{135}I (6.7 h), or ^{132}I in radiative equilibrium with ^{132}Te (78 h) (Fig. 3.8, J).

[**South >100 km from 1F**]

In Tokyo, rain on March 21 washed out the plume and increased the radiation dose rate, which led to a minor panic when ^{131}I was detected from the tap water source (Fig. 3.8, K).

In Shizuoka, at 360 km from 1F, one can see from the time difference between the rain and the increase in the dose rate that the plume arrived during rainy weather (Fig. 3.8, L).

This suggests that the plume remains no longer than a few days when new plumes are not delivered.

This speculation agrees with the observation of the radioactive material level of fallout in Tokyo per day [10]. Usually the fallout lasted around 3–4 days in

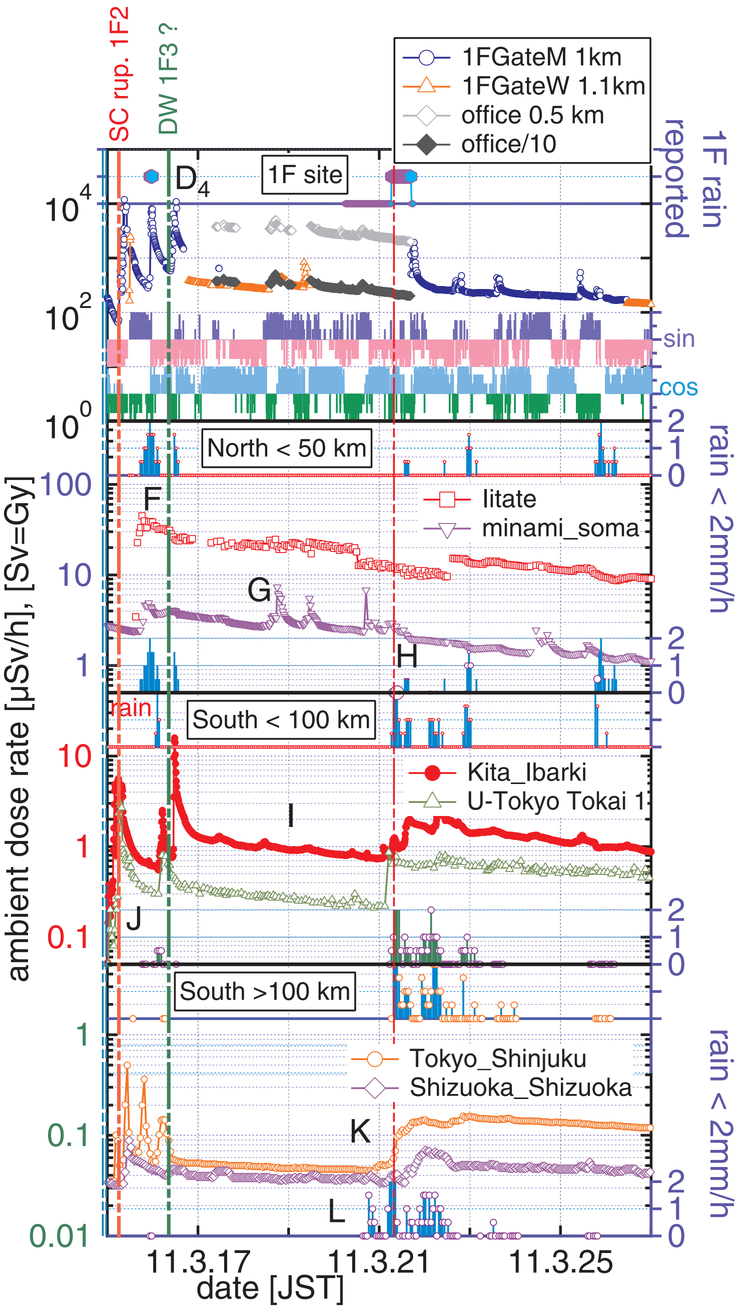


Fig. 3.8 Temporal evolution of the ambient dose rate of distant locations. Right axis corresponds to rain. *Note* Data for office 0.5 km from 1F divided by 10 to scale its temporal behavior consistent with that of main gate (GateM) and west gate (GateW)

March and April. For the purpose of protection from the radioactive exposure, it is preferable to watch the dose rate near one's location and the rain for a few days after passage of the plume. In particular, the rain causes cesium deposition onto soils, while removal of the deposited cesium is difficult. Therefore, we think that covering playgrounds with plastic sheets before it rains might be effective as an emergency protection against ground contamination—even a mattress or blanket is better than nothing. Some prefectural offices and nuclear power plants provide real-time dose rates. It might be preferable if one could watch these data together with rain and wind speed given in weather forecasts. At the same time, it might be required that not only the government but also scientists provide appropriate information about how to interpret the monitored data.

3.4 Evaluations

3.4.1 *Approach Based on Radionuclide Release Analysis: Model 1*

The behavior of released radioactive nuclides is complicated because it is closely related to the evolution of the accident. However, we made a rough evaluation, assuming that a certain proportion was released from the inventory in the fuel existing one day after the scram.

Figure 3.9 is an illustrative image of the behavior of radioactive materials in the reactor and their release to the environment. Release to the environment is basically composed of two steps: release from fuel (A) and release to the environment after release from the fuel (B). The latter release mechanism is complicated because detailed information of reactor damage and RI behavior in the damaged reactor is not simple. Radionuclides exist in various chemical forms in the RPV, PCV, and reactor building, such as gas, dissolved in water, aerosol, and

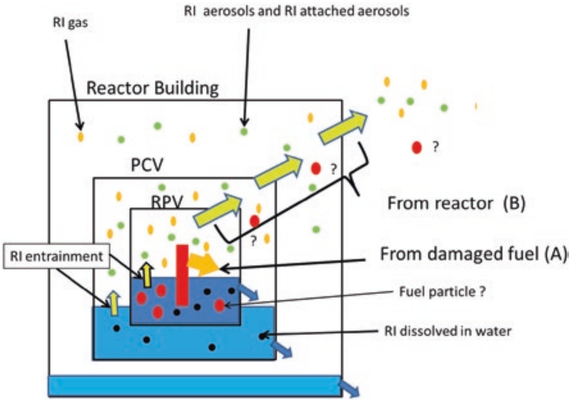


Fig. 3.9 Release fraction of leakage from reactor

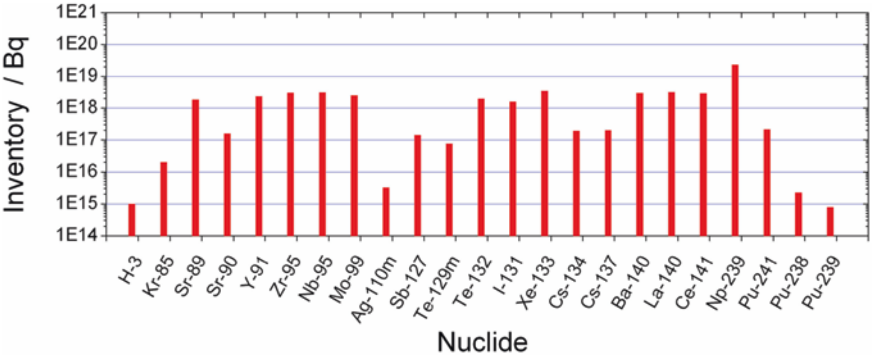


Fig. 3.10 The inventories of radionuclide at 1F1 at one day after scram

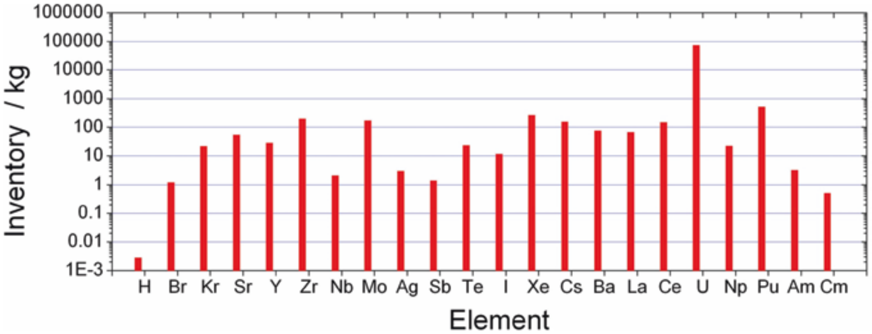


Fig. 3.11 Inventories of chemical elements in 1F1 at one day after scram

solid particle. Entrainment of the species to the gas phase is also important in the dynamic or boiling state.

The electric power output, the number of fuel assemblies, and the average burn-up at the scram of 1F1, 1F2, and 1F3 are (460 MWe, 400, 26 GWd/t), (784 MWe, 548, 23 GWd/t), and (784 MWe, 548, 22 GWd/t), respectively. Using these data, amounts of radionuclides and chemical elements for FP and MA at one day after the scram were calculated using the ORIGEN code.[2] Figures 3.10 and 3.11 show the inventories of radionuclide and chemical elements in 1F1 at one day after the scram, respectively.

Inventories in 1F2 and 1F3 at one day after the scram are about 1.5 times those for 1F1. The following nuclides were found to be significant based on the produced amount and half-life: ^{239}Np (2.36 d), ^{133}Xe (5.25 d), ^{140}La (1.68 d), ^{141}Ce

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[2] We made a rough estimate of inventory data on July 2011 with use of ORIGEN 2.2, assuming conditions about core and operation of the reactor, which might be considered similar to those of 1F1.

(32.51 d), ^{131}I (8.04 d), ^{137}Cs (30.17 y), ^{134}Cs (2.06 y), ^{89}Sr (50.5 d), ^{90}Sr (28.8 y), ^{132}Te (3.20 d), ^{129m}Te (33.6 d), ^{238}Pu (87.7 y), ^{239}Pu (24,000 y), ^{241}Pu (14.4 y), ^{140}Ba (12.75 d), ^{95}Zr (64.03 d), ^{91}Y (58.51 d), ^{127}Sb (3.85 d), ^{99}Mo (65.94 h), ^{3}H (12.3 y), and ^{85}Kr (10.7 y). The chemical inventory shown in Fig. 3.11 gives us important information. For example the inventory of Cs is about ten times larger than that of I.

The chemical state can typically be categorized into noble gases (Kr, Xe), volatile materials (I, Cs, Te, H), and low volatile materials (Sr, Y, Pu). The degree of volatilization is a key to understanding the release during the accident.

The chemical forms and the location of radioactive materials released from the fuel depend on their chemical properties. Noble gases such as Kr and Xe exist in the gas phase and were released to the atmosphere by the venting operation. Iodine was released as CsI and dissolved in water. However, some chemicals exist in the gas phase as I attached to aerosol, I_2, and organic iodine. Cs takes the chemical forms of CsOH and oxide as well as CsI in the gas phases or in water. Te exists as oxide in the gas phase or is dissolved in water. Sr is dissolved in water as a cation or exists as oxide in the gas phase or in water. Therefore, aerosols in the gas phase might carry these kinds of species.

In order to evaluate the radionuclide release from the fuel, we assumed the two cases of the temperature and the duration time as (i) 2,800 °C and 1 h, and (ii) 2,000 °C and 4 h. We used source terms based on the inventory at 1 h after scram for 1F1, 1F2, and 1F3 for simplicity. The fraction of inventory released from the fuel is calculated by the release rate constants as shown for these two cases in Table 3.2. As can be seen from the comparison, all noble gases and volatile materials were released in both cases. However, the difference in the fraction is remarkable for Ba, Sr, La, and Pu.

Table 3.2 The fraction of inventory released from the fuel

2,800 °C 1 h		2,000 °C 4 h	
Xe, Kr	100 (%)	Xe, Kr	100 (%)
H	100	H	100
Cs	100	Cs	100
I	100	I	100
Te	100	Te	100
Ba	83	Ba	29
Sr	58	Sr	16
Zr	1.7	Zr	0.34
Np	1	Np	0.5
Mo	100	Mo	99
La	1.7	La	0.34
Pu	0.17	Pu	0.034
Am	1	Am	0.5

Chemical properties such as the vapor pressure of each element must be taken into account in the release rate from RPV and PCV as shown in Fig. 3.9. Some appropriate assumptions must be made for estimates of released amounts by the accident, except for noble gases (fully released). Released radioactive materials exist in the water or steam of the RVP and PCV due to their chemical properties and damage to the RPV and PCV. Particles in the fuel generated by rapid cooling after melting might be dispersed in the water. Some parts of the radionuclide in the gas phase were released in the accident. Some part of the species in the liquid phase is considered to have been transported to the gas phase by the entrainment. The release fraction to the environment from the reactor is very complicated because it reflects various events causing RI release, such as seat leakage from the flanges or bulbs (including SRV release to a leaking vessel), venting, hydrogen explosion, and damage to the suppression chamber. Therefore, we tentatively assumed the release fraction [(B) in Fig. 3.9] from the RPV + PCV + Reactor Building to the atmosphere considering the vapor pressure of the elements: Xe 100 %; Kr 100%; Cs 1 %; I 1 %; Te 0.1 %; Sr 10^{-4}; Ba 10^{-4}; Zr 10^{-4}; Np 10^{-4}; Pu 10^{-5}; ^{3}H 25 %; etc. In this evaluation we also assumed these releases occurred at one day after the scram by the earthquake. Although these assumptions are different from the actual accident scheme, our estimation can give us a fundamental understanding of RI release.[3]

We calculated released amounts to the environment by multiplying the inventory by the release fraction from the fuel [(A) in Fig. 3.9] and by that from the reactor [(B) in Fig. 3.9]. The calculation results of amounts released are: ^{3}H 9.4×10^{14}Bq; ^{85}Kr 7.6×10^{16}Bq; ^{89} Sr 3.9×10^{14}Bq; ^{90}Sr 3.5×10^{13}Bq; $^{129\mathrm{m}}$Te 2.9×10^{14}Bq; ^{131}I 6.0×10^{16}Bq; ^{133}Xe 1.3×10^{19}Bq; ^{137}Cs 7.6×10^{15}Bq; ^{134}Cs 7.4×10^{15}Bq; ^{249}Np 8.8×10^{13}Bq; ^{241}Pu 1.4×10^{10}Bq; ^{241}Am 8.9×10^{7}Bq for fuel damage at 2,800 °C for 1 h. The ^{131}I equivalent amount of radionuclide is evaluated as 4.9×10^{17}Bq using the conversion factor in the INES manual (Table 3.3).

The Nuclear and Industrial Safety Agency (NISA) reported it as 7.7×10^{17}Bq calculated by the MELCOR code [10].

As to the release points of radioactive materials, they are released from the venting stack in accidents without severe damage. However, in the 1F accident, these were also released from the disrupted points of the PCV, duct pipes, and the reactor building. Moreover, contaminated water was released into the sea through the tunnel of 1F2 from a crack in the concrete pit.

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[3] Facts to provide evidence about what actually occurred are not fully confirmed. The facts and the radionuclide behavior will be made clear within the decommissioning. Therefore, we provide assumptions considering those chemical properties.

Table 3.3 The multiplication factors based on the ^{131}I equivalence which are calculated by effective dose from external radiation and inhalation following the INES manual

Radionuclide	Multiplication factor based on ^{131}I
^{3}H	0.02
^{85}Kr	0.001
^{89}Sr	0.50
^{90}Sr	20
^{106}Ru	6
^{111}Ag	0.10
^{115}Cd	0.07
^{125}Sb	0.8
^{127}Sb	0.1
^{129m}Te	0.6
^{132}Te	0.3
^{131}I	1
^{133}Xe	0.008
^{134}Cs	3([a]20)
^{137}Cs	40
^{140}Ba	1
^{237}U	0.1
^{239}Np	0.07
^{241}Pu	70
^{242}Cm	400

[a] See in detail Appendix C

3.4.2 *Approach Based on Radiation Monitor*

3.4.2.1 Result of the Standard Method Based on SPEEDI Simulation: Model 3

The Nuclear Safety Commission of Japan (NSC) reported the source term of ^{131}I and ^{137}Cs released between March 12 and April 5 based on atmospheric dispersion simulations, such as SPEEDI or WSPEEDI. The simulation result for the unit release rate (1 Bq h^{-1}) was compared to that obtained by the dust-sampler to normalize the absolute value. They obtained: 150 PBq for ^{131}I, and 12 PBq for ^{137}Cs (1 PBq $= 10^{15}$Bq). In order to obtain the radiological equivalence to ^{131}I release, the value for ^{137}Cs was multiplied by 40, yielding the total ^{131}I equivalent release of 630 PBq [11, 12]. Minor corrections were made to these data to equal 570 PBq (^{131}I: 130 PBq and ^{137}Cs: 11 PBq) on August 22. Note that the *reverse estimation* based on the SPEEDI simulation has been further improved by including the radiation data.

However, the results of the SPEEDI calculation were only disclosed on March 23, and on April 11. The government finally admitted that more than 5,000 evaluation results had existed from the beginning of the accident, which had not been disclosed for fear of public panic.

Because these evaluations rely on simulation codes and detailed weather data inaccessible to the public, we proposed a simple but straightforward estimation from the ambient dose rate data, or radiation map, available at many locations.

3.4.2.2 Alternative Method Based on Ground Shine: Model 4

The ratio of the radioactivity A' in Eq. (3.3) can be determined at the specific time when all species of interest can be commonly determined from measurements, such as dust sampling, soil analysis, or simulations.

We adopted the Becquerel ratio $[^{131}\mathrm{I}]:[^{134}\mathrm{Cs}]:[^{137}\mathrm{Cs}] = 1:1:1$ on t_{com} = April 10 from air sampling data at the Comprehensive Nuclear-Test-Ban Treaty (CTBT) National Operation System of Japan in Takasaki, Gunma prefecture [13].

In this case, taking t_{obs} = April 5 for instance, the normalized dose ratio can be calculated to be 0.21:0.57:0.22 from Eq. (3.3) followed by normalization using Eq. (3.4). This ratio agrees with the species-sensitive dose monitoring in Ichihara, Chiba prefecture, reported by Japan Chemical Analysis Center [14].

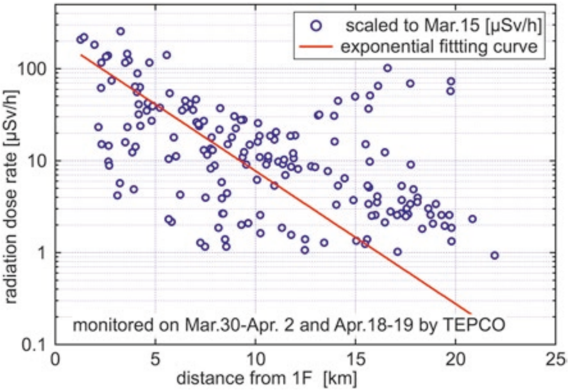
For Eq. (3.5), we corrected data from the dose rate, of locations categorized into the following groups.

(i) Inside 20 km no-go zone:

For inside the 20 km no-go zone, TEPCO monitored the dose rate during March 30–April 2 and April 18–19, the results of which are listed with the distance from 1F [15]. The data are shown in Fig. 3.12 as a function of the distance from the 1F site. Although the scattering of the data showed significant directional dependence, the general trend exhibited the decaying property. Therefore, we performed an exponential decay fitting to determine the rough integral of the dose rate in this area based on the following equation,

$$D_j(0)\int_0^{\infty} 4\pi r\,\exp(-\frac{r}{L})dr = 4\pi D_j(0)L^2 \tag{3.7}$$

Fig. 3.12 Dose rates at locations inside 20 km no-go zone, scaled to that on March 15 when dominant radioactive release occurred



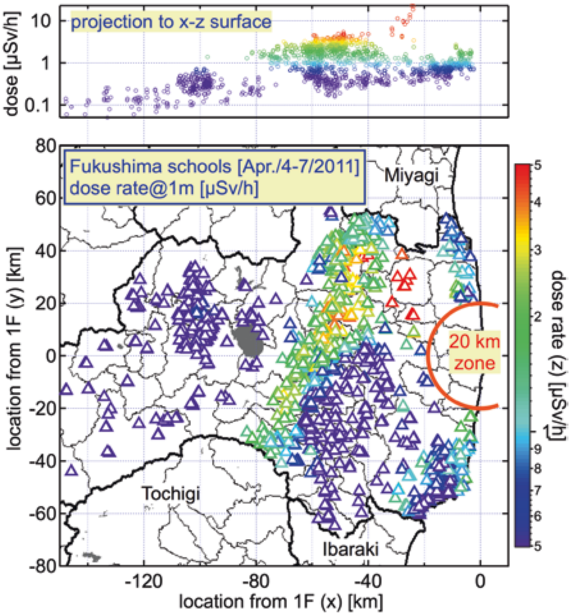


Fig. 3.13 Dose rate mapping of schools in Fukushima performed in April. Upper diagram is the projection along the latitude

where, L is the characteristic length of the spatial decay while $D_j(0)$ is the dose rate extrapolated to the origin, namely the 1F plant.

(ii) **East part of Fukushima prefecture outside the 20 km no-go zone, and** (iii) **West part of Fukushima prefecture**:

The administrative authority of Fukushima prefecture conducted gamma dose rate monitoring at more than 1,600 schools all over Fukushima except inside the 20 km circle from 1F during April 4–7, 2011 [16]. In this period, the contribution of ^{131}I to the dose rate was still obvious, so it can be used to evaluate the radioactive release. A dose rate map of these data is shown in Fig. 3.13[4] together with the 1-dimensional distribution projected along the latitude direction.

It may safely be said that Fukushima Prefecture outside the 20 km no-go zone was divided into two parts, East (ii) and West (iii) areas, which are approximately equal in size. We distributed 1,370 points to (ii) and 267 points to (iii) depending on their location. As a result, one data point in (ii) and (iii) can be regarded as representing an area of around 4.57 and 28.6 km^2, respectively [area of the half disk 20 km in radius was removed from the area of half of the prefecture in (ii)].

(iv) **Ibaraki prefecture**:

Ibaraki Prefecture, located south of Fukushima prefecture, exhibited a relatively higher dose rate among the adjacent prefectures. We assumed the excess dose

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[4] Fukushima map from "National Land numerical information (Administrative Divisions, 2011), Ministry of Land, Infrastructure, Transport and Tourism, file: japan_ver71, processed by ESRI Japan".

rate of Mito City on April 10, 0.17 μSv/h, as representing the averaged values for Ibaraki prefecture.

(v) **Tochigi, Chiba, Gunma prefectures, and others**:

For a minor correction of the evaluation, the area of these three prefectures was regarded as representing ground contamination in distant places. The excess dose rate was assumed to be 0.07 μSv/h on April 10.

The largest ambiguity in evaluating the released radioactive materials is in the fraction of the ground deposition against the total release. Atmospheric simulations also have a considerable amount of error depending on the modeling.

We had first approximated the fraction at about half. Actually, Ref. [17] reported from the atmospheric dispersion model GEARN in WSPEEDI-II that these fractions for ^{131}I and ^{137}Cs are 0.44 and 0.46, respectively—i.e., it can be suspected that the fraction for ^{134}Cs is also 0.46. However, Ref. [18] implies, from a three-dimensional chemical transport model, Models 3 Community Multiscale Air Quality (CMAQ), that the fractions for ^{131}I, ^{134}Cs, and ^{137}Cs deposits on land were 0.13, 0.22, and 0.22, respectively. We have updated the evaluation using these value ranges. The results are shown in Table 3.4. Smaller values are the result of adopting Ref. [17] as the fraction for the land deposition, while larger values are those adopting Ref. [18].

From these results, the ^{131}I equivalent released radioactive nucleus was evaluated to be 337–782 PBq.

The databases necessary to evaluate the ground contamination are compiled in Appendix C. Note that the ambiguity in ^{137}Cs has a large effect on the ^{131}I equivalent value, since the multiplying factor is as large as 40.

In this rough evaluation, different from that of NSC, we did not address the daily changes in the release rate, based on the assumption that almost all released species had been fallout/rainout/washout and the fraction of those on the land

Table 3.4 Evaluated ground contamination and source terms in PBq

	^{131}I	^{134}Cs	^{137}Cs
(i)	8.03	0.95	0.93
(ii)	12.5	1.47	1.44
(iii)	2.33	0.27	0.27
(iv)	1.35	0.16	0.16
(v)	1.63	0.19	0.19
Total on land	25.8	3.05	2.98
Land fraction	0.13/0.44	0.22/0.46	0.22/0.46
Source term	199/59	13.8/6.6	13.6/6.5
(factor)	(1)	(3)	(40)
I-eq.	199/59	41.6/20	542/258
(factor[a])	(1)	(20)[a]	(40)
I-eq.[a]	199/59	277/132	542/258

[a] Multiplication factor for ^{131}I equivalent for ^{134}Cs was corrected from 3 to 20 (see Appendix C)

had contributed to the dose rate. Ambiguity in the fraction that was deposited on land also has a direct effect on the evaluation of the source terms. One needs to be reminded that this is also true for the other method based on atmospheric transport simulation.

3.4.2.3 Crosscheck of the Evaluation

The result in the previous subsection was compared to the June 14 cesium radiation map of Fukushima and adjacent prefectures and was presented by the Ministry of Education, Culture, Sports, Science and Technology (MEXT) on September 30. There were 1,732 data points located in Fukushima prefecture [19, 20].

By correcting the data to that on March 15, using Eq. (3.5), total ground contamination values scaled on March 15 of Fukushima prefecture of ^{134}Cs and ^{137}Cs are 2.5 and 2.6 PBq, yielding source terms of 32 and 470 PBq, respectively, which agree well with the sum of our evaluations (i), (ii), and (iii).

Fallout of ^{131}I, ^{134}Cs, and ^{137}Cs has been monitored at specific cities in every prefecture in Japan except Fukushima and Miyagi [21]. We summed up the monthly fallout in Bq/m^2 in each prefecture multiplied by the area of each prefecture in m^2, yielding 0.4 PBq for ^{137}Cs. This value roughly agrees with our evaluation for areas in (iv) and (v).

Moreover, we would like to emphasize that these different methods lead to results consistent with each other for source term, release rate, dust sampling, fallout, and dose rate by ground shine with $SF = 0.7$ (see Appendix C for detail).

3.4.3 Comparison Between Approaches

Evaluation results based on these approaches are compared in Table 3.5. All of them exceeded the criteria of INES accident level 7 ($>10^{16}$Bq). For comparison, results for the Chernobyl accident are also listed. These rough evaluations, calculations practically done by hand, were able to obtain approximated release amounts of radioactive materials.

It is worthwhile to mention that the total amounts of radionuclides of the Chernobyl accident were 1,800 PBq for ^{131}I, and 85 PBq for ^{137}Cs, yielding the radiological equivalence of ^{131}I of 5,200 PBq. This is considerably larger than that of the Fukushima Daiichi accident. The reason for this fact is not only because the PCV covers the RPV in the Fukushima case, but also because in the Chernobyl case, a massive amount of Cs, I, Sr, and Pu was released to the environment by steam explosion of the melted fuel.

The accident level assessment based on INES (see Appendix C) has been performed by the radiological equivalence to ^{131}I for ^{131}I and ^{137}Cs release. The release of ^{134}Cs has not been included. Indeed, the effect of ^{134}Cs is small *if* one

Table 3.5 Comparison between different approaches to evaluate the total release in PBq

		Method	^{131}I equivalent	^{131}I	^{134}Cs	^{137}Cs
				x 1	x 3	x 40
Radionuclide release analysis	Model 1 (this study)	ORIGEN CORSOR-O chemical analysis	490	60	7.4	7.6
	Model 2 by NISA	MAAP/MELCOR	370 (770)	130 (160)	–	6.1 (15)
Radiation monitor	Model 3 by NSC	SPEEDI dust sampling	630 (570)	150 (130)	–	12 (11)
	Model 4 (this study)	Radiation map (ground shine)	337–782	59–199	6.6–13.8	6.5–13.6
Chernobyl		Core inventory analysis code	5,200	1,800	–	85

Some data have been updated from the initial publication, indicated in parentheses. We kept ^{131}I equivalent multiplication factor for ^{134}Cs to be 3 in spite of the fact that the correct one is 20 (see Appendix C)

uses the wrong radiological equivalence multiplication factor of 3. If one applies, however, the correct multiplication factor of 20 instead, the effect of the ^{134}Cs release contributes 50 % of that of ^{137}Cs and contributes more than ^{131}I itself. Therefore, the (second) author would like to recommend re-evaluating the past accident including ^{134}Cs.

3.4.4 Contamination and Environmental Cleanup

The ambient dose rate, surface dose rate, and radioactivity in the soil have been measured around the site after the accident. The detailed distribution maps of the radiation dose are made with a smaller mesh on June 6–14, and June 27–July 8, 2011 [22]. Figure 3.14 indicates that massive amounts of radiation fell to the surface of the ground by snowfall after the plume, which contained radioactive materials released by the rupture at 1F2 (suspected), and had been transported to the northwest by wind from the southeast. Although ^{131}I with a half-life of 8 days was predominant in the early stage, ^{134}Cs (2.06 y), ^{137}Cs (30 y), and ^{129m}Te (33.6 d) are now the main reactive materials. ^{137}Cs with a half-life of 30 years will be a major target for cleanup in the future.

The radioactive materials absorbed by particles in the air are detected by dust sampling at various points in and out of the site. ^{89}Sr (50.5 d) and ^{90}Sr (29 y) are detected in the soil within a range of 20 km from the site. These elements have a value range between 1/10 and 1/10,000 that of Cs. These elements may be evidence of the fact that they were released in this accident because the half-life of ^{89}Sr is as short as 50.5 days. Moreover, ^{140}La, ^{95}Nb, and ^{110m}Ag have been detected slightly in the soil toward the northwest at a distance of 30 km from the site. A small amount of

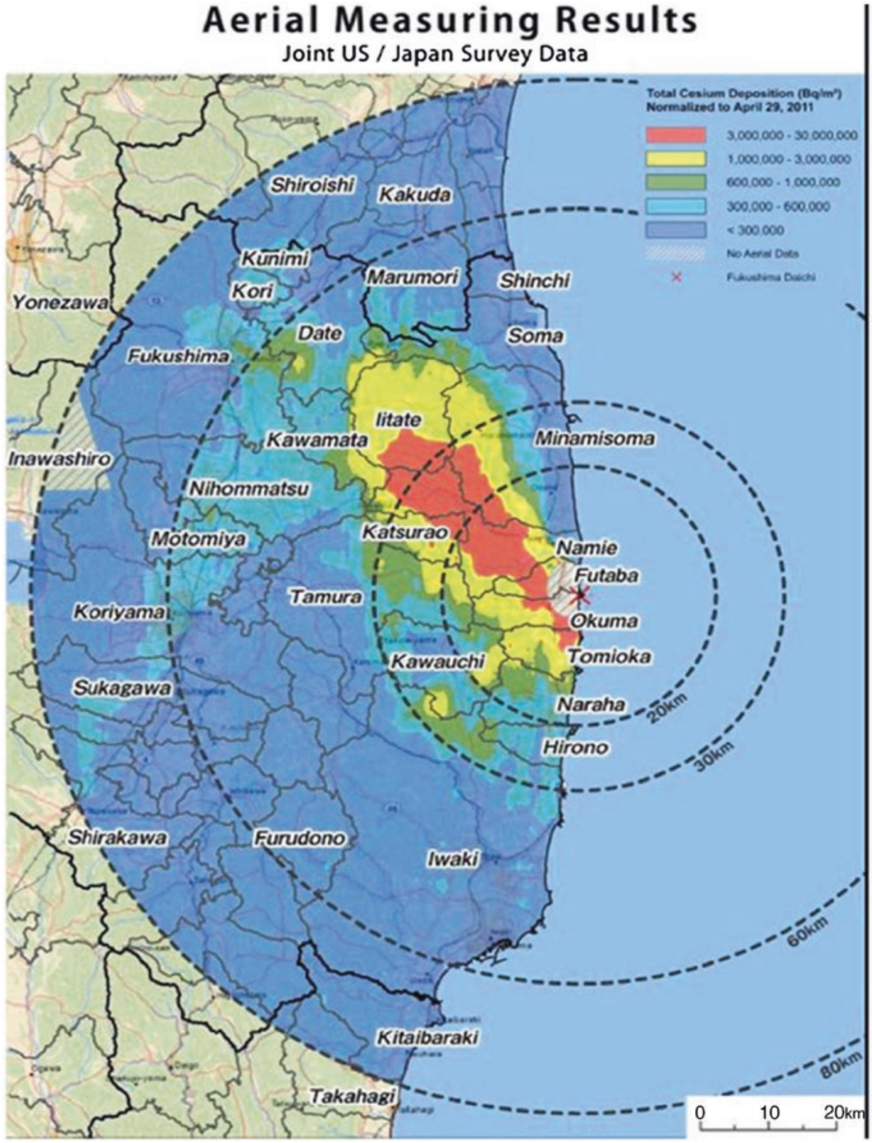

Fig. 3.14 Map of deposition of radioactive cesium (sum of ^{134}Cs and ^{137}Cs) for the land area within 80 km of the Fukushima Daiichi plant, reported by MEXT [22]

Pu isotopes was detected and the evaluation of the isotope ratio ^{238}Pu/(^{239}Pu+^{240}Pu) indicated that some samples contained released Pu by this accident. MEXT reports that the difference in behavior of these elements might account for the wide range of detected values and suggests that more detailed investigation is needed.

The amount of released Sr and Pu is estimated to be much less than that of the Chernobyl accident in which contamination by Sr and Pu was a severe problem.

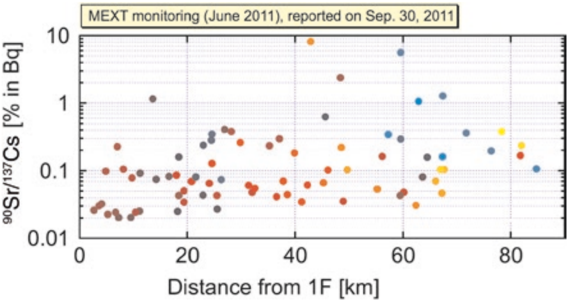

Fig. 3.15 Becquerel Ratio of ^{90}Sr/^{137}Cs [%] as a function of the distance from 1F. Color of dots corresponds to the latitude, but no clear tendency has been observed. Data from [23]

Specifically, the highest value of ^{90}Sr/^{137}Cs was 8.2 % for the sample obtained at Sōma City, but on average, it was about 0.37 % regardless of the location [23], as shown in Fig. 3.15. Simple scaling of the radiological equivalence of averaged ^{90}Sr release yields about 0.7 PBq from analysis in both Sects. 3.1 and 3.2.2 (=10 PBq × 0.37 % × 20), that is much smaller than that for the Chernobyl accident of 160 PBq (^{131}I-eq.), where ^{90}Sr/^{137}Cs was 1/10.

Monitoring of radioactivity under the sea has been executed. Although concentration of radioactivity at a sampling point within the harbor of the nuclear power plant was high because highly concentrated radioactive water was released from the concrete near the sluice gate of 1F2 (i.e., ^{131}I 2.8×10^{15}Bq, ^{134}Cs 9.4×10^{14}Bq, ^{137}Cs 9.4×10^{14}Bq), concentrations outside the plant, especially in the area at a distance of more than 30 km from the plant, was low [11].

The mechanism of soil contamination by Cs depends on the fraction of it absorbed on the outer surface of minerals or on the layer structure of clay. While an effective method for desorption of Cs from clay has not yet been found, it is expected in the future. Various ways of cleanup of paddy soils should be taken depending on the level of contamination: stripping surface soil, elimination of clay particles by plowing, and removal of vegetation. Effective decontamination methods for soil, which includes methods for disposal of secondary waste, are essential for allowing the return of evacuated residents to their homes if the evacuation zone is to be reopened. For secondary waste from decontamination, temporary keeping, interim storage, and final disposal are required depending on the radiation level. Communication among stakeholders, residents, local governments, and the central government is crucial in the process of determining sites to locate this waste. Academic societies should play an important role by supplying scientific information on RI behavior and safety evaluation for storage and disposal.

3.5 Summary and Conclusion

We have seen that the release of radionuclides is subject to the physical and chemical properties and composition of the fuel core, which is highly dependent on its temperature. The source term can be evaluated by the fraction of the release to the environment. The integrated source term can also be evaluated alternatively based on radiation monitoring by assuming the fraction of the land deposition, or by making use of atmospheric simulation. Although the exact value of the radioactive release has considerable ambiguity, the amount of the release derived from these methods is roughly consistent, and is considerably less than that released by the Chernobyl accident.

The atmospheric diffusion/transport mechanism of each nuclide has not yet been fully understood. However, in the present situation, Cs is considered to be the most serious radionuclide while the other nuclides may have minor effects on the environment. The environmental behavior of each species must still be investigated from both scientific and political points of view to find a better roadmap for decontamination procedures.

Acknowledgments The authors wish to acknowledge Dr. Takuji Oda for providing data based on the ORIGEN code, and Ms. Ayumi Ito for support in compiling data.

Appendix A: Pasquill-Gifford Dispersion Diagrams

The diffusion parameters in Eq. (3.2), σ_y and σ_z, are functions of distance from the source in the x direction. The Pasquill-Gifford curves (Fig. 3.5) are constructed from observations over smooth terrain and represent averages over a few minutes [7]. In practical calculation, the parameter σ_i ($i = y, z$) can be approximated as a function of the distance x[m],

$$\sigma_i = \gamma_i \cdot x^{\alpha_i} \tag{3.8}$$

where γ_i and α_i are the constants indicated for the stability classes and x [24]. Figure 3.5 is plotted using Eq. (3.8). The stability is classified (as shown in Tables 3.6 and 3.7) by tendency of diffusion into unstable (A–C), neutral (D) and stable (E–F). In Japan, stability class G, which means extremely stable, is added to the existing classes A–F.

Appendix B: Flash Boiling of Water

Water tends to condense more at higher pressures. The saturated vapor P_sat [atm] above 1 atm can be empirically approximated as a function of the temperature T [°C] by the Antoine equation proposed in 1888,

$$\log P_{sat} = C_0 - C_1/(C_2 + T) \tag{3.9}$$

where $\{c_0, c_1, c_2\}$ are {8.07131, 1,730.63, 233.426} for $1 < T < 100$, while {8.14019, 1,810.94, 244.485} for $99 < \mathrm{T} < 374$.

Table 3.6 Approximation constant for σ_y

Stability	α_y	γ_y	x (m)
A	0.901	0.426	0–1,000
	0.851	0.602	1,000–
B	0.914	0.282	0–1,000
	0.865	0.396	1,000–
C	0.924	0.1772	0–1,000
	0.885	0.232	1,000–
D	0.929	0.1107	0–1,000
	0.889	0.1467	1,000–
E	0.921	0.0864	0–1,000
	0.897	0.1019	1,000–
F	0.929	0.0554	0–1,000
	0.889	0.0733	1,000–
G	0.921	0.0380	0–1,000
	0.896	0.0452	1,000–

Table 3.7 Approximation constant for σ_z

Stability	α_z	γ_z	x (m)
A	1.122	0.0800	0–300
	1.514	0.00855	300–500
	2.109	0.000212	500–
B	0.964	0.1272	0–500
	1.094	0.0570	500–
C	0.918	0.1068	0–
D	0.826	0.1046	0–1,000
	0.632	0.400	1,000–10,000
	0.555	0.811	10,000–
E	0.788	0.0928	0–1,000
	0.565	0.433	1,000–10,000
	0.415	1.732	10,000–
F	0.784	0.0621	0–1,000
	0.526	0.370	1,000–10,000
	0.323	2.41	10,000–
G	0.794	0.0373	0–1,000
	0.637	0.1105	1,000–2,000
	0.431	0.529	2,000–10,000
	0.222	3.62	10,000–

In 1993, Wagner and Pruss [25] proposed the equation that is valid for $0.01 \leq T < 374$ °C as:

$$\log P_{\mathrm{sat}} = 217.755 \times (c_0\tau^1 + c_1\tau^{1.5} + c_2\tau^{1.5} + c_3\tau^3 + c_4\tau^{3.5} + c_4\tau^4 + c_6\tau^{7.5})/(1 - \tau) \tag{3.10}$$

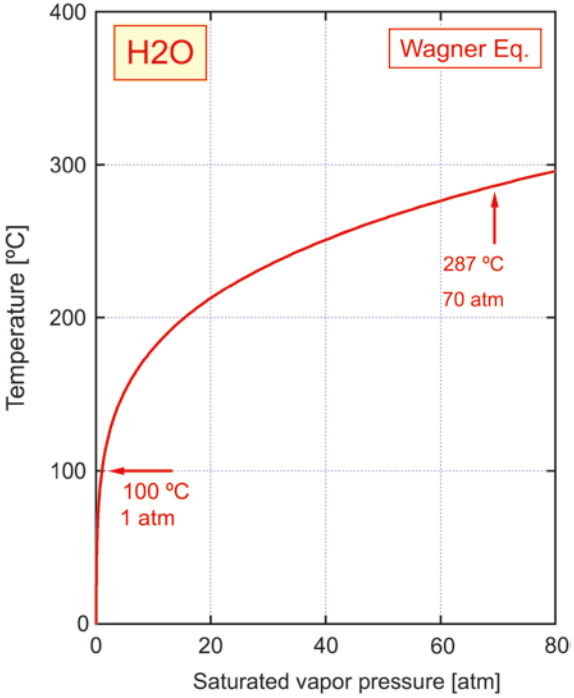

Fig. 3.16 Saturated vapor pressure by Wagner's equation

where $\tau = 1 - (T + 273.15)/647.096$ and $\{c_0, c_1, c_2, c_3, c_4\, c_5, c_6\}$ are {−7.85951783, 1.84408259, −11.7866497, 22.6807411, −15.9618719, 1.80122502}.

This function form is more useful in that the coefficients are usable over the range from the experimentally given triple point and the critical point, and that this form also copes well with its derivatives. Thus, it has been approved by the International Association for the Properties of Water and Steam. Other various formulas can be found in Ref. [26].

The calculated result of T as a function of P_{sat} is shown in Fig. 3.16. For example, the sudden decrease of pressure, say from 70 to 1 atm, by valving on the SRV, leads to a sudden drop in the vaporization temperature from 290 to 100 °C. As a result, quite rapid evaporation of the water, called "flash boiling," in the RPV might occur. Therefore, water injection needs to be started at the same time as, or at least as soon as, the SRV is opened.

Appendix C: Ground Shine of Gamma Ray Radiation

C.1 Half-Value Layer

External exposure from the contaminated ground is called "ground shine." The required database is compiled in [27]. Due to absorption/scattering by air, the radiation was attenuated. The characteristic lengths at which the radiation becomes half, the half-value layer (HVL), of lead, iron, aluminum, water, air, and concrete are compiled in Table E2 of Ref. [27].

Roughly speaking, the dose rate from ground shine reflects the area inside the circle of several times the air HVL in the radius. Each point of Figs. 3.12 and 3.15 represents at least 4.57 or 4 km^2, respectively. Therefore, the influence of one area on adjacent points in the MEXT monitoring that could cause a double-counting of the dose rate are eliminated.

C.2 Dose Factor

Conversion factors from [Bq/m^2] to [Sv/h] listed in Table E3 [27] include effective dose rate for external dose and committed inhalation due to resuspension resulting from remaining on contaminated ground. However, since the inhalation dose for the present situation is considerably small, this database can also be used for the pure external dose.

The shielding factor (*SF*) needs to be considered, since the evaluation above is the ideal case where the ground is smoothly spread over the infinite disk. For ordinary ground cases, Ref. [27] proposed using *SF* of 0.47–0.85 (representative of 0.7). In addition, the dose factors for plume submersion, crucial in the early stage of accidents, is calculated in Table 3.1 of Ref. [28].

C.3 Radiological Equivalence

Radiological equivalence is the ratio of the activity released of a specified radionuclide to the case for ^{131}I. This value is used to classify the scale of the accident as described in [29]. It considers the above mentioned ground contamination and plume submersion. The database for the total effect on the public is given in Table 15 in Appendix I of Ref. [29].

Data are listed in Table 3.8 for species of interest. Although ^{134}Cs is the present leading radiator, ^{137}Cs is the most crucial nucleus in the evaluation of the rating of the accident. Evaluation of ^{90}Sr is less effective due to both its low concentration (approximately below 1 % of ^{137}Cs) and its low radiological equivalence (half of ^{137}Cs).

It should be noted that the official data of ^{131}I eq. of ^{134}Cs has significant error. This is caused by the significant error of the 50 years dose factor for ^{134}Cs tabulated in Table E3 in [27]. The correct value is 5.1E-02 rather than 5.1E-03.

This error has been taken into account in the International Nuclear and Radiological Event Scale (INES) defined in [29]. As a result, the radiological equivalence to ^{131}I summarized in Table 2 of the INES user guide, I-eq, for ^{134}Cs has been under-estimated to 2.8 (~3) which, in reality, should be 16.2 (~20).

Table 3.8 Dataset to assess radiological equivalence to ^{131}I

Nucleus	τ	Air HVL (m)	(Sv/h)/(Bq/m^2)	^{131}I eq.
^{131}I	8.0 d	55.9	1.30E−12	1
^{134}Cs	2.06 y	71.9	5.40E−12	3 → 20
^{137}Cs	50 y	69.2	2.10E−12	40
^{89}Sr	50.5 d	80.5	8.0E−15	0.5
^{90}Sr	29.1 y	–	1.0E−15	20

Note: The second author noticed this mistake and sent a letter to MEXT and to the Nuclear Regulation Authority in October 2012 [30]. MEXT sent it to the IAEA through diplomatic channels. Finally, after several reminders, the IAEA issued the corrigendum of Refs. [27, 29] in March 2013. Now I-eq for ^{134}Cs has been corrected to 17 in Table 2 of [29]. Tables 15 and 16 have yet to be corrected; they should be 17 and 20 (1 digit), respectively.

C.4 Experimental Determination of the Shielding Factor (SF)

Assessment of the relationship between the ground contamination and the resultant ambient dose rate needs careful consideration of the definition of the quantity used in the database.

In order to clarify the definition, we described the relation in the Eq. (3.11) as:

$$\frac{D}{H^*(10)/K} = A \cdot CF_{grd}(w/oGRE) \cdot SF_{tot} \cdot \frac{1}{H^*(10)/K} \tag{3.11}$$

The dose factor CF_{grd} represents the ambient dose rate at 1 m above ground level per unit of deposition for a radionuclide. In the most commonly used database [27], this factor is calculated using the RASCAL code (ver. 3.0.5), considering a ground roughness factor (GRF) of 0.7, considering ordinary ground (Eq. 3.12). Note that GRF = 1 corresponds to the case for a smooth infinite field of lawn. Shielding factor is defined by the Kerma in the shielding material divided by the Kerma for the infinite smooth surface (Eq. 3.13).

$$CF_{grd}(w/GRF) = CF_{grd}(w/oGRF) \cdot GRF \tag{3.12}$$

$$SF_{tot} = GRF \cdot SF_{BLG} \tag{3.13}$$

Therefore, the practical formula to be used can be written as

$$\frac{D}{H^*(10)/K} = A \cdot CF_{grd}(w/GRE) \cdot SF_{BLG} \cdot \frac{1}{H^*(10)/K} \tag{3.14}$$

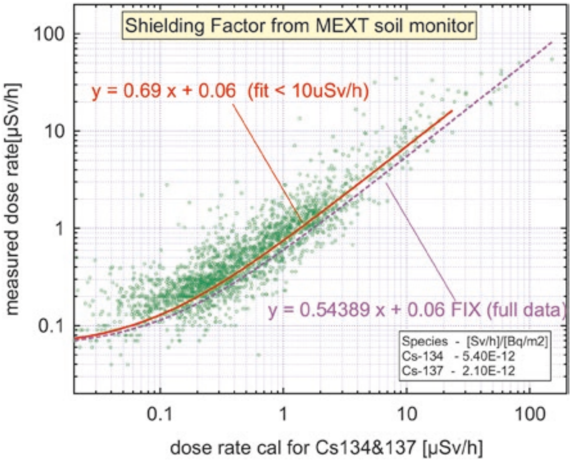

Fig. 3.17 Measured dose rates assuming 1 Sv/h = 1 Gy/h versus those evaluated from the ground shine with GRF = 0.7. Background dose rate of 0.06 μSv/h was assumed

$H^{*}(10)/K$ is the conversion factor from Kerma [Gy] to 1 cm ambient dose equivalent [Sv], for which a typical value of 1.3 following the data tabulated in Ref. [31] might be a plausible approximation for sub-MeV photon.

Note that for the emergency situation, 1 Gy/h ≈ 1 Sv/h, is usually proposed and the data provided for the accident has been provided in this approximation. Therefore, it is necessary to treat the measured dose rate as the form of $(D/1.3)$ (Gy/h).

$$\left(\frac{D}{1.3}\right) = A \cdot CF_{grd} \cdot \frac{SF_{BLG}}{1.3} \tag{3.15}$$

The shielding factor can also be evaluated by comparing the dose rate calculated from the measured ground contamination using Eq. (3.14) with the measured dose rate, as shown in Fig. 3.17. In the fitting procedure, we fixed the baseline corresponding to the background natural radiation dose.

One can see that the $(SF_{BLD}/1.3) = 0.7$, by fitting where dose rate <10 μSv/h (adopted because of the large number of data points), is a plausible value in the general discussion, which corresponds to $SF_{BLD} = 0.9$. Because the scattering of data is considerably large, it may be misleading if one calculates external exposure from the local ground contamination. The dose rate used was the averaged, namely effective, value around the measurement point.

The inverse determination of the ground contamination from the measured dose rate can be evaluated as

$$A = \left(\frac{D}{1.3}\right) \cdot CF_{grd}^{-1} \cdot \left(\frac{SF_{BLG}}{1.3}\right)^{-1} \tag{3.16}$$

where the experimental value of $(SF_{BLD}/1.3) = 0.7$ can be used.

References

1. Groff A (1983) OriGEN-2: a versatile computer code for calculating the nuclear compositions and characteristics of nuclear materials. Nuclear Technology 62:335-352
2. Lewis BJ, Dickson R, Iglesias FC, Ducros G, Kudo T (2008) Overview of experimental programs on core melt progression and fission product release behavior. J Nucl Mater 380:126-143
3. Nuclear Safety Research Association (2013) The behaviors of the light water reactor fuel 5th ed. (in Japanese). Nuclear Safety Research Association, Tokyo
4. Lorenz RA, Osborne MF (1995) A summary of ORNL fission product release test with recommended release rates and diffusion coefficients. NUREG/CR-6261. Oak Ridge National Laboratory, Oak Ridge
5. Vierow K, Liao Y, Johnson J, Kenton M, Gauntt R (2004) Severe accident analysis of a PWR station blackout with the MELCOR, MAAP4 and SCDAP/RELAP5 codes. Nuclear Engineering and Design 234: 129–145
6. Ujita H, Satoh N, M. Naitoh M, Hidaka M, Shirakawa N, Yamagishi M (1999) Development of severe accident analysis code SAMPSON in IMPACT project. J Nucl Sci and Tech 36:1076-1088
7. Panofsky HA, Dutton JA (1984) Atmospheric turbulence—Models and methods for engineering applications. John Wiley & Sons Inc, New York
8. Chino M, Ishikawa H, and Yamazawa H (1993) SPEEDI and WSPEEDI: Japanese emergency response systems to predict radiological impacts in local and workplace areas due to a nuclear accident. Radiat Prot Dosimetry 50:145-152
9. Terada H, Chino M (2008) Development of an atmospheric dispersion model for accidental discharge of radionuclides with the function of simultaneous prediction for multiple domains and its evaluation by application to the Chernobyl nuclear accident. J Nucl Sci and Tech 45:920-931
10. Tokyo Metropolitan Institute of Public Health (2011) Radioactive material level of fallout in Tokyo (in Japanese). Available at: http://monitoring.tokyo-eiken.go.jp/monitoring/f-past_data.html. Accessed July 2011
11. Nuclear Emergency Response Headquarters, Government of Japan (2011) Report of the Japanese government to the IAEA ministerial conference on nuclear safety—The accident at TEPCO's Fukushima Nuclear Power Stations—. Available at: http://www.kantei.go.jp/foreign/kan/topics/201106/iaea_houkokusho_e.html. Accessed 11 June 2011
12. Chino M, Nakayama H, Nagai H, Terada H, Katata G Yamazawa H (2011) Preliminary estimation of release amounts of ^{131}I and ^{137}Cs accidentally discharged from the Fukushima Daiichi Nuclear Power Plant into the atmosphere. J Nucl Sci and Tech 48:1129-1134
13. Japan Institute of International Affairs (2011) Center for the Promotion of Disarmament and Non-Proliferation. Available at: http://www.cpdnp.jp/eng/English/. Accessed July 2011
14. Survey results by Japan Chemical Analysis Center (2011) Dose rate report by Japan Chemical Analysis Center (in Japanese). Available at: http://www.jcac.or.jp/site/senryo/senryo-kakushu.html. Accessed 11 July 2011
15. Nuclear Regulation Authority (2011) Dose rate report within a radius of 20 km from Fukushima Daiichi Nuclear Power Station (in Japanese). Available at: http://radioactivity.nsr.go.jp/ja/contents/4000/3633/24/1305284_0421.pdf. Accessed 11 July 2011.
16. Fukushima Prefecture (2011) Dose rate report by Fukushima prefecture 5-7 April 2011 (in Japanese). Available at: http://www.pref.fukushima.jp/j/schoolmonitamatome.pdf. Accessed July 2011

17. Kawamura H, Kobayashi T, Furuno A, In T, Ishikawa Y, Nakayama T, Shima S, Awaji T (2011) Preliminary numerical experiments on oceanic dispersion of ^{131}I and ^{137}Cs discharged into the ocean because of the Fukushima Daiichi Nuclear Power Plant Disaster. J Nucl Sci and Tech 48:1349-1356
18. Morino Y, Ohara T, Nishizawa M (2011) Atmospheric behavior, deposition, and budget of radioactive materials from the Fukushima Daiichi nuclear power plant in March 2011. Geophysical Research Letters 38:L00G11
19. Ministry of Education, Culture, Sports, Science and Technology (2011) Analysis report of soil radionuclide (Cs-134 and Cs-137) (in Japanese). Available at: http://www.mext.go.jp/b_menu/shingi/chousa/gijyutu/017/shiryo/__icsFiles/afieldfile/2011/09/02/1310688_1.pdf. Accessed 11 July 2011
20. Ministry of Education, Culture, Sports, Science and Technology (2011) On the mapping of radiocesium concentration in soil (in Japanese). Available at: http://www.mext.go.jp/b_menu/shingi/chousa/gijyutu/017/shiryo/__icsFiles/afieldfile/2011/09/02/1310688_2.pdf, and http://radioactivity.nsr.go.jp/ja/contents/6000/5047/24/5600_110921_rev130701.pdf. Accessed Sept 2011
21. Tokyo Metropolitan Institute of Public Health (2011) Radioactive material level of fallout in Tokyo (in Japanese). Available at: http://monitoring.tokyo-eiken.go.jp/monitoring/f-past_data.html. Accessed July 2011
22. Nuclear Regulation Authority (2011) Results of airborne monitoring by the Ministry of Education, Culture, Sports, Science and Technology and the U.S. Department of Energy (in Japanese). Available at: http://radioactivity.nsr.go.jp/en/contents/4000/3180/24/1304797_0506.pdf. Accessed July 2011
23. Ministry of Education, Culture, Sports, Science and Technology in Japan (2011) Radionuclide analysis for plutonium and strontium by MEXT (in Japanese). Available at: http://radioactivity.nsr.go.jp/ja/contents/6000/5048/24/5600_110930_rev130701.pdf. Accessed Oct 2011
24. The Environment Agency of Japan (1993) Manual for total volume control of nitrogen oxide (in Japanese)
25. Wagner W, Pruss A (1993) International equations for the saturation properties of ordinary water substance. Revised according to the international temperature scale of 1990. Addendum to Journal of Physical and Chemical Reference Data 16, 893 (1987). J. Phys. Chem. Ref. Data 22: 783-787
26. Murphy DM, Koop T (2005) Review of the vapour pressures of ice and supercooled water for atmospheric applications. Quarterly Journal of the Royal Meteorological Society 131:1539–1565
27. International Atomic Energy Agency (2000) Generic procedures for assessment and response during a radiological emergency, IAEA-TECDOC-1162. http://www-pub.iaea.org/mtcd/publications/pdf/te_1162_prn.pdf. Accessed July 2011
28. Eckerman KF, Ryman JC (1993) External exposure to radionuclides in air, water, and soil. Federal Guidance Report No. 12, EPA-402-R-93-081, Oak Ridge National Laboratory. http://nnsa.energy.gov/sites/default/files/seis/fgr12.pdf. Accessed July 2011
29. International Atomic Energy Agency (2009) The international nuclear and radiological event scale user's manual 2008 edition. http://www-pub.iaea.org/MTCD/publications/PDF/INES-2009_web.pdf. Accessed July 2011
30. Kado S, Endo T (2012) Report on the mistakes in the dose factor in IAEA-TECDOC-1162 and its impact on the assessment for the Fukushima Nuclear Power Plant accident, letter to MEXT (Oct. 24, 2012, in Japanese; Nov. 7, 2012 English translation)
31. International Commission on Radiological Protection (1997) Conversion coefficients for use in radiological protection against external radiation 74. Elsevier

Chapter 4
Environmental Contamination and Decontamination After Fukushima Daiichi Accident

Joonhong Ahn

Abstract In this chapter, effectiveness of the environmental decontamination is discussed from the point of view of waste management. First, the relation between the environmental contamination and the radiation dose rate to the resident is summarized. Then, a model has been developed to understand effectiveness of artificial decontamination measures to achieve the goals set by the Japanese law. The analysis revealed the importance of waste volume reduction by strategic selection of areas for decontamination and development of volume reduction technologies. Decontamination can effectively contribute to reduction of the air dose rate if it is applied in areas where natural dispersion is slow, and thus strategic prioritization of areas for decontamination is highly recommended. Because of high heterogeneity of the natural environment, an adaptive, staged approach with feedbacks from actual decontamination should be taken. Instead of constructive feedback loop, however, we observe a vicious cycle consisting of a lack of integrated scientific knowledge base about environmental contamination and deterioration in trust among stakeholders in society. To halt this vicious cycle, we need to establish a fundamental scientific basis, both natural and social, for enabling in-depth analysis about what has been the most crucial damage resulting from the accident and why that occurred, and how radiological risk can or should be compared with other risks in society.

Keywords Decontamination · Natural dispersion · Cost · Feedback from stakeholders

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4.1 Prologue

On September 11, 2012, 18 months after the Great East Japan Earthquake and tsunami hit Japan, I visited the towns of Kawamata, Namie, Okuma, and Minami-Soma in Fukushima Prefecture. It was a bright, sunny day.

Ever since the accident, I had been feeling that I must visit the scene of the accident and see for myself what had happened. At the same time, I did not want to create more work for those who bore the heavy responsibility of dealing with its aftermath. After some vacillation, I gingerly asked Dr. Shinichi Nakayama, a close friend of mine, if I could have an opportunity to observe the restricted areas. Before the accident, he had worked for many years at the Japan Atomic Energy Agency (JAEA) on basic research in the geochemistry of radionuclides. After the accident, JAEA established an office in Fukushima to give scientific advice on environmental decontamination to the Prefectural government and local communities. Dr. Nakayama was then the deputy head of this new office. He willingly agreed to my request, saying that he had already welcomed such visitors several times, including those from overseas, and arranged a 1-day tour for me with six other researchers from JAEA (Fig. 4.1). The inside of our car was fully covered with plastic sheeting to protect the vehicle from being contaminated by dirt tracked in on our shoes. Each of us had a pocket dosimeter.

Fig. 4.1 Researchers of JAEA Fukushima, who accompanied me during the 1-day tour, taken in front of Okuma Town Hall on September 11, 2012. Dr. Nakayama is second from *left*

Fig. 4.2 Plastic bags containing waste from decontamination, or *josen*, piled up in the schoolyard in the Town of Namie, Fukushima Prefecture; taken on September 11, 2012

I was nearly speechless during the day. The mountains, forests, fields, farms, school buildings, playgrounds and houses looked peaceful and intact, though unnaturally quiet (Fig. 4.2). Police cars often passed by, breaking the silence. They were patrolling empty houses to protect them from theft by intruders. Then, we stepped into the coastal area in the town of Okuma, which was inundated by the tsunami. Because the area was within a mile of the Fukushima Daiichi Nuclear Power Station and the radiation level was high, it had been left untouched since the accident. All that was displayed in front of my eyes was emptiness covered by dense summer grasses.

This view was completely different from what I had seen in Kobe in February 1995, a month after the Great Hanshin-Awaji Earthquake, when I went there to visit my late brother and his family. In Kobe I saw many heavily destroyed buildings and roads, and through my brother's work [1] as a psychiatrist, the difficulties and agony of survivors. But in Fukushima, it took me some time to comprehend those scenes of silence and disappearance, although they continued to gnaw on my mind long after. That night I had a late supper by myself after parting from the JAEA researchers, profoundly unsettled by the emptiness I had witnessed.

The full impact of the Fukushima nuclear disaster on Japanese society goes far beyond matters directly related to what happened within the nuclear power plant itself. From among dozens of critical issues that should be taken up, I have limited my focus in this chapter to decontamination of the environment and its consequences from the point of view of waste management.

4.2 Environmental Contamination

We first need to grasp the degree and nature of contamination of the environment due to the release of radioactive materials from the Fukushima Daiichi site, which could cause people to receive radiation doses (potential health hazard) through various pathways. Readers are referred to Chap. 3, which gives in-depth analysis about the sources of environmental contamination.

4.2.1 Surface Radioactivity Concentrations

4.2.1.1 Areal Extension of Contamination

The map (Fig. 4.3) shows the parts of Japan that were affected by radioactive fallout from the Fukushima Daiichi Nuclear Power Station. More precisely stated, Fig. 4.3 shows where and to what extent the land has been contaminated by two isotopes[1] of cesium (Cs), Cs-134 and Cs-137. Eight prefectures are shaded in brown, from Yamagata and Miyagi prefectures at the top, Fukushima Prefecture directly below them, followed by Gunma, Tochigi, Ibaraki, and Saitama, and then Chiba at the very bottom. The Tokyo metropolis is nestled at the junction of the southeastern border of Saitama and the northwestern border of Chiba.

4.2.1.2 Radionuclides of Concern

Any consideration of decontamination options must begin with a basic understanding of the properties of the radioactive isotopes involved. As Chap. 3 discusses, during the 1st week of the accident, iodine isotopes (mostly iodine-131, with a half-life of 8 days) were released and dispersed into the environment, and then diminished fairly soon through a process of spontaneous radioactive decay. Cs-134 and Cs-137 were also released from the damaged reactors and widely dispersed into the environment, settling on the surfaces of soil, trees, water, roads, and buildings. But unlike iodine contamination, which had diminished before it was measured, the level of cesium contamination, still present owing to their much longer half-lives, can be measured and expressed by radioactivity, as the number of becquerels (Bq), per square meter of surface (Fig. 4.3).

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[1] Isotopes are variants of a particular chemical element. While all isotopes of a given element have the same number of protons in each atom, they differ in neutron number. All cesium isotopes have 55 protons.

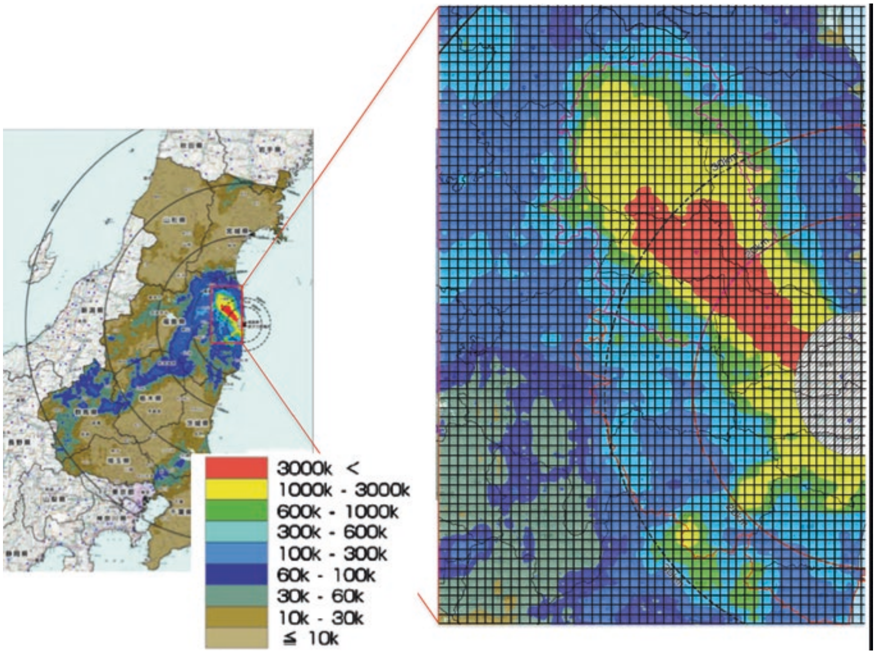

Fig. 4.3 Surface radioactivity concentrations of Cs-134 and Cs-137 as of September 18, 2011 [2]. The *right* figure is an enlargement of the most contaminated area. The *grid lines* overlapped on the map are drawn 1 km apart. Thus, one small rectangle covers an area of 1 km^2

4.2.1.3 Radioactivity Concentrations

The radioactivity of a radioisotope is proportional to its mass. For example, 1 g of the radioisotope Cs-134 is equivalent to 1 (g)/134 (g/mol) = 0.00746 mol.[2] Because 1 mol includes the Avogadro number, 6.02×10^{23}, of atoms, 1 g of Cs-134 includes 4.5×10^{21} atoms. The second step in calculating becquerel is that it is known that an atom decays with a certain probability in unit time. This probability is expressed by the decay constant, usually denoted with the symbol "lambda" (the eleventh letter of the Greek alphabet) λ (1/s). For Cs-134, lambda (λ) is known to be 1.06×10^{-8} (1/s). The radioactivity of 1 g of Cs-134 can then be calculated as 4.5×10^{21} (i.e. the total number of atoms) $\times$ 1.06×10^{-8} (i.e. the rate of decay per unit time) = 4.8×10^{13} atoms decayed per second, or 48 trillion becquerels.

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[2] According to International Bureau of Weights and Measures (IBWM), the mole is defined to be the amount of substance of a system which contains as many elementary entities (e.g. atoms, molecules, ions, electrons) as there are atoms in 0.012 kg of carbon-12 (^{12}C), the isotope of carbon with relative atomic mass 12. Thus, by definition, one mole of pure ^{12}C has a mass of *exactly* 12 g.

Let us now return to Fig. 4.3. The surface concentration is shown in units of Bq/m^2, or the number of atoms decayed per second per square meter. For example, the red-colored region is contaminated at a concentration of "3,000 kBq/m^2 or greater," which means more than 3 million becquerels per square meter. As will be explained later (also shown in Chap. 3 of this volume), half of this contamination is due to Cs-134. So if the surface concentration at a location of interest is 3 million becquerels per square meter (Bq/m^2), then 1.5 million becquerels of Cs-134 exists per square meter at that location. To express this level of contamination in terms of mass (grams) rather than radioactivity (becquerels), we can divide the number of becquerels just calculated (1.5 million per square meter) by the number of atoms decayed per second, as calculated in the preceding paragraph (4.8×10^{13}), as follows: $1.5 \times 10^6 / 4.8 \times 10^{13} = 0.031 \times 10^{-6}$ g/m^2, or 0.031 $\mu g/m^2$. In other words, in Fig. 4.3, the Cs-134 contamination of the red-colored region is about three-hundredths of a microgram of Cs-134 spread over the area of 1 m^2.

4.2.2 Radiation Doses Due to Contamination

4.2.2.1 Sievert

Besides becquerels and grams, there is one other unit of measurement—sievert—that we must understand in order to comprehend effects of radiation on human bodies resulting from radioactive contamination such as the data presented in Fig. 4.3. When nuclei decay, they emit energized particle(s), such as electrons, neutrons, protons, photons, and helium nuclei. These particles lose their energy while in motion whenever they interact with and transfer kinetic energy to other matter that exists along their trajectory, such as air, concrete, paper, water, and human tissue. When an energized particle hits a human body, it transfers its energy to human tissue, and in some cases causes irrecoverable damage (see Chap. 13). The severity of damage is dependent on the energy and type of particle, and on part of the body hit by the particle. While the first two factors are physical, the third is biological. Sievert (Sv) is a unit of measurement for a radiation dose that takes into account these three factors. Sievert expresses the combined effects (i.e., severity) of emitted energetic particles on a human body.

4.2.2.2 Pathways that Cause Radiation Dose

To estimate how much radiation dose (Sv) would be caused by the observed contamination of Cs-134 and Cs-137 in the environment, various pathways need to be taken into account. A report [3] published by the International Atomic Energy Agency (IAEA) shows a generic model for radiation dose evaluation.

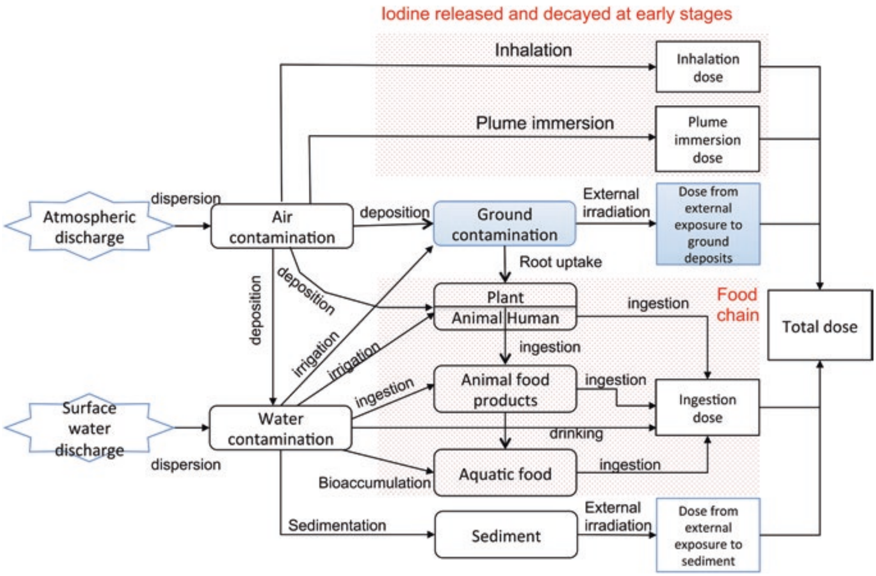

Fig. 4.4 Generic models for assessing the impact of discharges of radioactive substances to the environment [3]

Figure 4.4 depicts multiple pathways that affect radiation dose to a resident in a contaminated area. The box labeled as "Total dose" at the right of Fig. 4.4 indicates that the total dose results from various causes, such as inhalation of radionuclides floating in the atmosphere, external radiation due to immersion in the radionuclide plume in the atmosphere, external radiation exposure to radionuclides deposited on the ground surface, ingestion of foodstuffs contaminated by radionuclides, etc.

Among those, the first two pathways, i.e., inhalation and plume immersion, occurred within a few weeks after the initial accident. Due to failure in conducting systematic measurement at the early stage of the accident, however, only an indirect way is now possible for dose evaluation for these pathways.[3] The ingestion pathway through contaminated foodstuffs can be avoided by applying stringent inspection for foodstuffs before they enter the commercial market. Thus, in this analysis, we focus on the external radiation due to exposure to radionuclides deposited on the ground surface.

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[3] In such indirect estimates, first, evolution of radioactivity plumes with time is simulated by utilizing detailed information on the source term, i.e., how much radioactivity was released from the Fukushima Daiichi site, and on the meteorological data. Then, information on traces of people's movements during the first few weeks needs to be collected. Finally, the radiation dose can be estimated for individual evacuees.

4.2.2.3 Hourly Dose

For radiation due to exposure to radionuclides deposited on the ground surface, the relation between the surface concentration and the hourly radiation dose to a resident is given in the IAEA report by the conversion factor 2.1×10^{-3} (μSv/h)/(kBq/m^2) for Cs-137, and the factor 5.6×10^{-3} (μSv/h)/(kBq/m^2) for Cs-134. A study in Fukushima [4] indicates that the radioactivity of Cs-137 and Cs-134 observed in the environment was approximately the same soon after the accident. Therefore, for example, at a location with contamination of 1,000 kBq/m^2, 500 kBq/m^2 is due to Cs-137 and 500 kBq/m^2 is due to Cs-134. Using these values, we can calculate the total hourly radiation dose to a resident located at a point with 1,000 kBq/m^2 of contamination in the following way: 2.1×10^{-3} (μSv/h)/(kBq/m^2) × 500 (kBq/m^2) + 5.6×10^{-3} (μSv/h)/(kBq/m^2) × 500 (kBq/m^2) = 3.8 μSv/h. This means that if you stay at a location contaminated by these two cesium isotopes with a total concentration of 1,000 kBq/m^2, then you will get 3.8 μSv of radiation dose every hour. It should be noted that 2.8 μSv/h is contributed by Cs-134 because of the greater conversion factor. With the shorter half-life for Cs-134, this contribution decreases faster than that by Cs-137.

4.2.2.4 Annual Dose

The guidelines of the decontamination measures announced by the government are expressed in terms of the annual dose, as shown in the next section. To obtain the conversion relation between the annual dose and the hourly dose, we need to make assumptions about people's daily life and living conditions. Suppose that (1) a person stays outside of buildings for 8 h and inside for 16 h a day, and (2) while inside, because of shielding effects by the building's walls, the radiation dose is reduced to 40 % of that observed outside. In such a scenario, 3.8 μSv/h for example can be converted as follows: [3.8 (μSv/h) × 8 (hours-outside/day) + 3.8 × 0.4 (μSv/h) × 16 (hours-inside/day)] × 365 (days/year) = 20,000 μSv/year or 20 mSv/year.[4] In this manner, the surface radioactivity concentration of Cs-134 and Cs-137 can be related to an annual dose of radiation.

4.2.3 Regulatory Guidelines

The Japanese government enacted a law on special measures on August 30, 2011 [5]. It stated that (1) the annual dose is to be made less than 20 mSv/year within 2 years, and (2) 1 mSv/year or lower at any location in the long term.

Returning again to Fig. 4.3, the surface concentrations of cesium in the yellow and red regions exceed the 1,000 kBq/m^2 level, in which case, as the calculation

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[4] 1 mSv (milli sievert) is equal to 1,000 μSv.

above illustrates, annual doses exceed the 20 mSv/year level. This fact indicates that efforts to reduce the surface concentration of cesium should be focused in these regions to achieve the first guideline. To achieve the second guideline requires decontamination of a much broader area. With the proportionality between the surface concentration and the annual dose, the target area of decontamination would be all places with a surface contamination greater than 50 kBq/m^2, in other words the areas corresponding to the first through the seventh bars in the legend for Fig. 4.3.

4.3 Modeling of Decontamination to Help Decision Making

4.3.1 Purpose of Modeling

With the two decontamination guidelines defined by the law, more practical and burning questions arise immediately as to how soon these goals can actually be achieved, how much it will cost, and what the parameters are that could significantly affect effectiveness of a decontamination job. In the 3 years since the accident, a tremendous amount of effort has already been devoted to decontamination, but little information was shared in the public domain, which is what enables Japanese citizens to have informed discussions for determining national and local policies and procedures for decontamination.

To help answer these questions, let us consider an abstracted model (Fig. 4.5) by taking into account three major mechanisms that would affect the surface

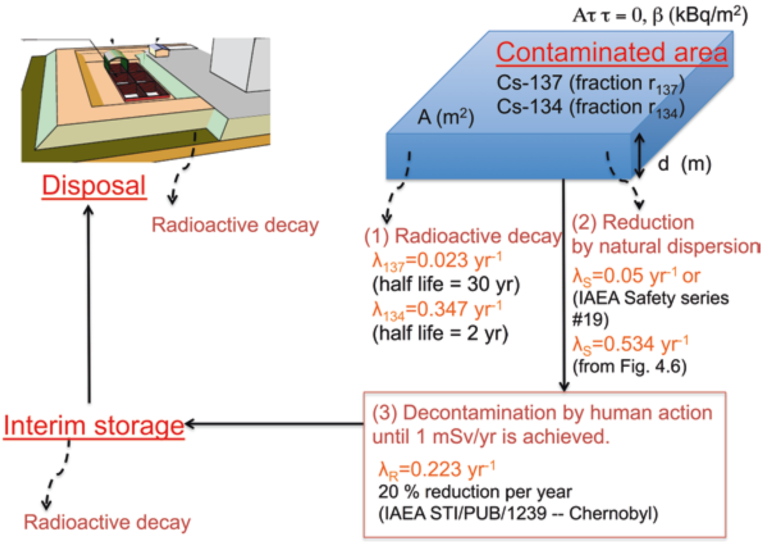

Fig. 4.5 Model for decontamination and waste management

radioactivity concentration: (1) spontaneous radioactive decay, (2) natural dispersion, and (3) artificial decontamination actions, i.e., decontamination by human action. See Appendix for mathematical formulations.

4.3.2 Mechanisms Considered in the Model

4.3.2.1 Radioactive Decay

The first mechanism, spontaneous radioactive decay, is purely a physical process and one that is well understood. Nuclei of Cs-134 and Cs-137 decay with half-lives of 2 years and 30 years, respectively, to Ba-134 and Ba-137. Because these barium isotopes are stable (i.e., not radioactive), it means that there is always some lessening of radioactivity occurring through this physical process.

4.3.2.2 Natural Dispersion

The second mechanism, natural dispersion, refers to the fact that cesium isotopes can move through the natural environment as a result of rainfall, wind, and the flow of water in surface and subsurface regions. To understand this mechanism, we need to know about the behavior of cesium in the environment, ranging from microscopic levels (such as the interaction of cesium with soil particles and microorganisms) to macroscopic levels (such as transport of cesium by groundwater, rivers, and off-shore ocean currents). The behavior of cesium in the environment is highly site-specific, heterogeneous at different scales, and evolves over time. Despite such complexity, the IAEA recommends a provisional value of 0.05 year^{-1} [3] for the rate constant of this process. This value asserts that the radioactivity observed at a location of interest will be halved every 15 years, if only natural dispersion mechanisms are in play.

Recent measurements have revealed that natural dispersion mechanisms in Fukushima could be faster than the rate of 0.05 year^{-1} IAEA recommends. Figure 4.6 indicates that the dose rates at various locations measured in December 2011 were about 70 % of those measured in June 2011. In other words, during this 6-month period, radioactivity decreased by about 30 % through spontaneous radioactive decay and natural dispersion. Note that no artificial decontamination activities were done during that period. With this data, the rate of natural dispersion is calculated to be 0.534 year^{-1}, which is about 10 times greater than the IAEA-recommended value. We consider two cases in the following analysis: fast (0.534 year^{-1}) and slow (0.05 year^{-1}) natural dispersion.

4.3.2.3 Artificial Decontamination

As for the third mechanism, artificial decontamination, the IAEA recommends a value of 0.223 year^{-1} [7], based on its observations of decontamination done at Chernobyl. This value means that every year, 20 % of the remaining radioactivity

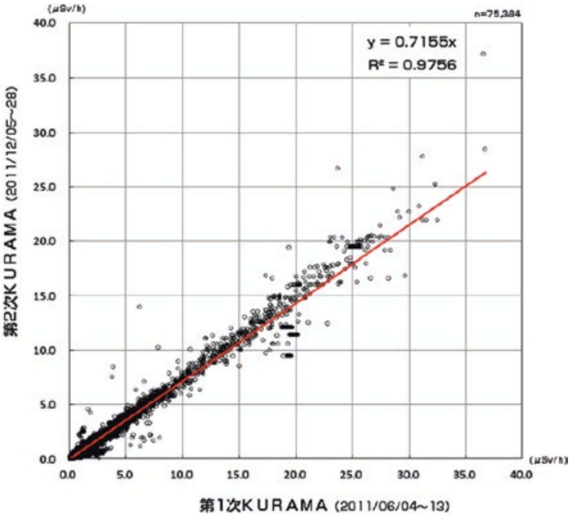

Fig. 4.6 Correlation between 2011/06 data and 2011/12 data for the air dose rate at various locations [6]

is removed from that location. Taking into account the second guideline defined by the law, we assume in the present modeling that artificial decontamination will continue until the annual dose of the area has become 1 mSv/year or lower. We consider two cases in the following analysis: with or without decontamination, for which the values of the rate constant are assumed to be 0.223 year^{-1} or zero, respectively. As discussed below, the rate constant of artificial decontamination also varies significantly from place to place, because of different contamination conditions and, consequently, different techniques applied.

4.3.3 Results

Figure 4.7 and Table 4.1 show the results of numerical evaluation for four cases as combinations of with or without artificial decontamination and slow or fast natural dispersion. The chart at the left in Fig. 4.7 shows the results for the case with no artificial decontamination. Radioactivity in the environment decreases by the first and second mechanisms described above. Note that in this case, no waste is generated. The chart at the right shows the results for the case with artificial decontamination, which generates waste.

Two questions are addressed in relation to the two goals defined in the law: (1) Can the annual dose be made smaller than 20 mSv/year within 2 years? and (2) How long will it take for annual doses to become 1 mSv/year or lower at any location?

Can the annual dose be made smaller than 20 mSv/year within 2 years? It should be noted that the dose rate exceeds 20 mSv/year if the initial contamination was 1,000 kBq/m2 or higher. Table 4.1 indicates that for the area with 1,000–3,000 kBq/m2 contamination, the dose rate would become below 20 mSv/year within at most 2.52 years. For the area with >3,000 kBq/m2, the time for the dose to become below 20 mSv/year is longer than that, but artificial decontamination can effectively shorten the time, particularly if the natural dispersion is slow (0.05 year−1). The results of actual measurement shown in Fig. 4.8 are consistent with this observation. In Fig. 4.8, it is observed that the dose rate comparison between September 18, 2011 (Fig. 4.8a) and September 28, 2013 (Fig. 4.8b) shows that the yellow zone, which corresponds to 1,000–3,000 kBq/m2 initial contamination, actually decreased to below 20 mSv/year, as indicated by the arrow in the figure. Similarly, the red zone shrank while the orange zone increased.

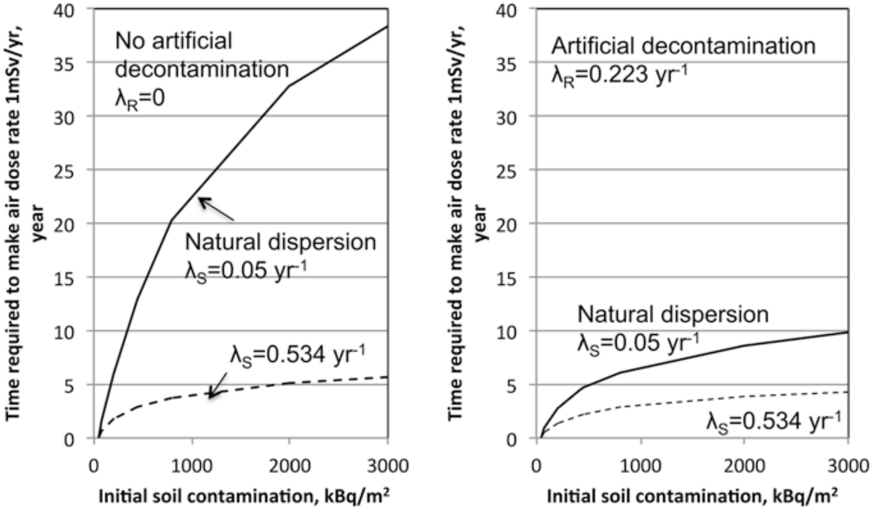

Fig. 4.7 Time required to make the air dose rate 1 mSv/year or lower as a function of initial surface soil contamination with (*right*) or without (*left*) artificial decontamination for the natural dispersion rate of 0.05 year^{-1} (IAEA recommended) or 0.534 year^{-1} (from Fig. 4.6)

Table 4.1 Effects of decontamination and natural dispersion

Initial contamination, β (kBq/m^2)	Years to reach 20 mSv/year				Years to reach 1 mSv/year			
	No decontamination		With decontamination		No decontamination		With decontamination	
	Fast	Slow	Fast	Slow	Fast	Slow	Fast	Slow
>3,000	>1.43	>4.32	>1.10	>2.19	>5.67	>38.4	>4.25	>9.83
1,000–3,000	0.90	2.52	0.70	1.36	5.06	32.8	3.81	8.62
600–1,000	–	–	–	–	3.72	20.3	2.83	6.08
300–600	–	–	–	–	2.91	13.0	2.23	4.64
100–300	–	–	–	–	1.81	5.90	1.40	2.80
60–100	–	–	–	–	0.61	1.66	0.48	0.92

fast natural dispersion rate = 0.534 year^{-1}; *slow* 0.05 year^{-1}; – air dose rates always below 20 mSv/year

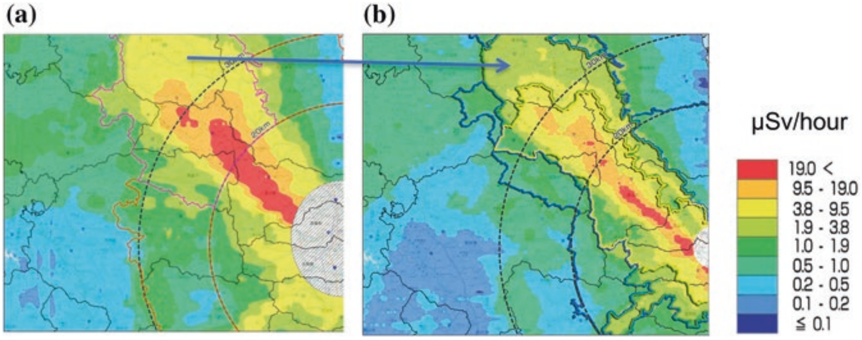

Fig. 4.8 Air dose rates (μSv/h) [8] a September 18, 2011 and b September 28, 2013

If the natural dispersion is actually fast, as observed in Fig. 4.7, effects of artificial decontamination on shortening the time to lower the dose rate below 20 mSv/year are limited; only a fraction of a year shortening is observed with the fast dispersion assumption. Because the natural dispersion processes occur heterogeneously in the environment, this observation indicates that artificial decontamination should be applied only in such areas where natural dispersion occurs slowly for the purpose of minimizing waste generation by decontamination.

How long will it take for annual doses to become 1 mSv/year or lower at any location? For the area with the initial contamination <100 kBq/m^2, in any conditions of natural dispersion, within at most 1.66 years the dose rate becomes below 1 mSv/year. This time would not be significantly reduced by artificial decontamination. Thus, it makes no sense to apply artificial decontamination to areas with this low level of contamination. Not engaging in artificial decontamination also helps avoid waste generation. Between 100 and 1,000 kBq/m^2, if the natural dispersion is observed to be fast, then artificial decontamination should not be applied because the time for the dose rate to become below 1 mSv/year would not shorten significantly. However, if the natural dispersion is observed to be slow, artificial decontamination should be applied. Thus, similar to the observation for Question (1), it is crucial to identify regions where natural dispersion occurs slowly.

4.4 Waste Generation by Decontamination

4.4.1 Model and Data

As Fig. 4.5 shows, artificial decontamination generates waste materials containing radioactive cesium. From the observation in the previous section, we consider that artificial decontamination should be applied only in the region with the initial contamination of 300 kBq/m^2 or greater. The area roughly corresponds to that shown in the expanded map in Fig. 4.3. In Table 4.2, the area for each contamination level is shown in the second column from the left. The total area subject to artificial decontamination is approximately 1,500 km^2.

According to in-situ measurements for soil contamination [9], cesium has migrated into the soil to a depth of about 5 cm. Assuming that the contaminated materials are removed from the area to a depth of 5 cm, we can estimate the volume and mass of the radioactive waste to be generated by artificial decontamination activities (see Appendix for mathematical formulation).

4.4.2 Results

The third and fourth columns of Table 4.2 show results of the waste volume estimate for the cases of fast and slow natural dispersion by the model shown in the Appendix. Depending on the speed of natural dispersion, 16 or 24 million m^3 of waste will be generated from decontamination for regions with 1,000 kBq/m^2 or greater (the yellow and red regions in Fig. 4.3), respectively. But if artificial decontamination is applied to regions with lower contamination levels, the total volume of radioactive waste generated could be as large as 37 or 58 million cubic meters, respectively. The total volume of waste and, as discussed below, the cost are dependent on how decontamination is applied in the two low-contamination regions.

Radioactive waste from artificial decontamination will be characterized by huge volumes of low and heterogeneous radioactivity concentrations. Average concentrations of radioactivity that would be included in the waste from artificial decontamination are shown in Fig. 4.9. Those wastes have similar levels of radioactivity concentrations to those generated from hospitals, research laboratories, and nuclear-facility decommissioning, which are categorized as “very low-level waste (VLLW)” in Japanese regulations (Chap. 15). The results of previous studies [10] on cost estimates for disposal of Very Low Level Waste indicate that the least expensive option, called trench disposal, was estimated to be 650,000 yen/m^3, or \$25 per gallon of waste.

Table 4.2 Evaluation of volume and cost of disposal for radioactive waste arising from decontamination

Initial soil contamination, β (kBq/m^2)	Area, A, included in Fig. 4.3 (km^2)	Waste volume (million m^3)		Estimated cost (trillion yen)	
		Fast dispersion	Slow dispersion	Fast dispersion	Slow dispersion
>3,000	183	5.60	8.13	3.64	5.28
1,000–3,000	368	10.5	15.7	6.83	10.2
Subtotal	*551*	*16.1*	*23.8*	*10.5*	*15.5*
600–1,000	282	6.60	10.5	4.29	6.83
300–600	721	14.1	23.2	9.17	15.1
Subtotal	*1,003*	*20.7*	*33.7*	*13.5*	*21.9*
Total	*1,554*	*36.8*	*57.5*	*23.9*	*37.4*

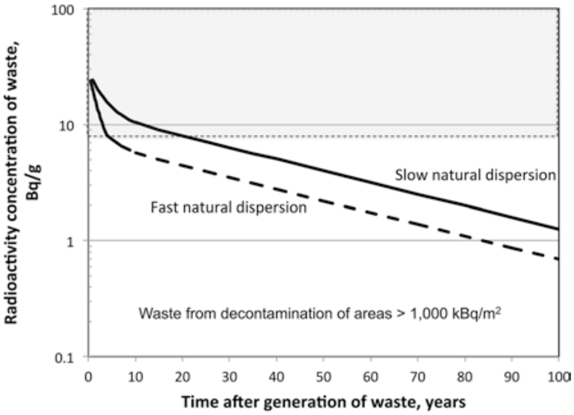

Fig. 4.9 Average radioactivity concentration in Bq/g of waste generated from decontamination of areas with initial contamination of >1,000 kBq/m^2 for fast or slow natural dispersion. Average density of 1,600 kg/m^3 is assumed. For waste with concentrations in the hatched region, disposal in controlled landfill sites is required by Japanese law (see Chap. 15)

The two rightmost columns in Table 4.2 show the estimated cost. Depending on the area targeted for decontamination, the cost of decontamination varies greatly. Even if decontamination is limited to highly contaminated areas where the dose rate is above 20 mSv/year, the cost is likely to be on the order of ten trillion yen.

4.5 Concluding Remarks: Conflicting Values and Motives

This result from the waste generation analysis indicates the importance of waste volume reduction, for which basically two approaches can be considered. The first is strategic selection of areas for decontamination. Decontamination has been found to effectively contribute to reduction of the air dose rate if it is applied in areas where natural dispersion is slow. The second is development of volume reduction technologies, which include incineration, physical and chemical partitioning, and compaction. Both approaches should be applied in a concerted manner.

Thanks to fast natural dispersion processes as observed in Fig. 4.6, the air dose rate due to surface soil contamination in the environment has been decreasing more rapidly than expected. To take advantage of this natural process, it is crucially important to strategically select areas for artificial decontamination, i.e., where natural dispersion occurs more slowly than in other areas, so that generation of unnecessary waste can be effectively avoided. This will accelerate decontamination, and consequently help return evacuees to their homes.

Unfortunately, sufficient information and knowledge that enable strategic prioritization of areas for decontamination are *not* currently available. From the analysis shown in this chapter, these are primarily related to in-depth understanding about natural dispersion phenomena represented by λ_S, including (1) the interaction of radionuclides with materials in the natural environment, (2) the transport and dispersion of radionuclides in the natural environment, and (3) the measurement of radiation and radionuclides in the environment. Furthermore, the value of the rate λ_R of artificial decontamination for the model used in this chapter should have been obtained through actual decontamination work. In the past 3 years, although decontamination has been carried out in more than 100 local municipalities, data, experience, and knowledge have not been made available in the public domain in forms that can be utilized for further analyses and feedback.

However, even with perfect knowledge and information about natural dispersion phenomena and decontamination effects, strategic prioritization cannot be actually implemented unless a broad range of stakeholders agrees on prioritization. On the contrary, what has actually occurred in the past 3 years indicates that the issue of decontamination has sensitized differences among people about what needs to be achieved by decontamination, resulting in belated decision making on various important matters, which has led to greater and prolonged hardship for the evacuees.

We observe a vicious cycle consisting of a lack of integrated scientific knowledge base about environmental contamination and deterioration in trust among stakeholders in society. For trust building, a goal that can be shared by various stakeholders needs to be set, and exactly for that purpose, a solid scientific basis is crucially important. At the same time, without understanding the goal, the right set of scientific bases cannot be defined.

To halt this vicious cycle, we need to establish a fundamental scientific basis, both natural and social, for enabling in-depth analysis about what has been the most crucial damage resulting from the accident and why that occurred, and how radiological risk can or should be compared with other risks in society. Coupled with such scientific efforts, advanced concepts and technologies should be developed and implemented to facilitate decision making by a broad range of stakeholders, which would significantly enhance the resilience of society (see more discussion in Chap. 24).

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Appendix: Mathematical Formulations

For Decontamination

During Decontamination $(0 \leq t < t_1)$

For the radioactivity M_i [kBq] of nuclide i in contaminated area of A [m^2]:

$$\begin{aligned} &\frac{dM_i}{dt} = -(\lambda_i + \lambda_R + \lambda_S)M_i, \quad 0 < t \le t_1, \\ &\text{subject to } M_i(0) = M_i^o \quad i = 134,\ 137 \end{aligned} \tag{4.1}$$

where $M_i^0 = \beta A r_i \left[\text{kBq}\right]$, where $r_{137} + r_{134} = 1$. The quantity r_i is the mass fraction of nuclide i included in the contamination. The quantity β is the initial soil contamination [kBq/m^2] for the area of interest. The constants λ_i, λ_R, and λ_S are the radioactive decay constant, the rate of artificial decontamination, and the rate of natural dispersion, respectively. The time t_1 is the time when the air dose of the area becomes 1 mSv/year and the decontamination actions are stopped.

The solution for this is written as:

$$M_i(t) = M_i^o \exp(-\lambda_i' t), \quad 0 \le t \le t_1, \quad \text{where} \quad \lambda_i' = \lambda_i + \lambda_R + \lambda_S \tag{4.2}$$

With the dose conversion factor C_i [(μSv/h)/(kBq/m^2)], the air dose rate is written as C_iM_i/A [μSv/h]. Assume the person stays outside for 8 h a day and inside 16 h a day, and 40 % dose while inside, the annual dose is calculated to be $FC_iM_i(t)/A$ [mSv/year], where $F = (8\text{ h} + 16 \times 0.4\text{ h}) \times 365/1{,}000 = 5.26$ [(mSv/μSv) · (hour/year)]. The annual dose $S_i(t)$ [mSv/year] due to nuclide i in this area is formulated as:

$$\begin{aligned} S_i(t) &= {}^{FC_iM_i(t)}\!/_{A} = \left({}^{FC_iM_i^o}\!/_{A}\right)\exp(-\lambda_i' t) \\ &= (FC_i\beta r_i)\exp(-\lambda_i' t)\ [\text{mSv/year}], \quad 0 \le t \le t_1. \end{aligned} \tag{4.3}$$

The cumulative dose due to nuclide i is obtained by integrating this with respect to time as:

$$\Sigma_i(t) = \left({}^{FC_i\beta r_i}\!/_{\lambda_i'}\right)\left[1 - \exp(-\lambda_i' t)\right]\ [\text{mSv}], \quad 0 \le t \le t_1. \tag{4.4}$$

Termination of Decontamination ($t = t_1$)

The time t_1 for terminating decontamination is when the total air dose rate becomes less than 1 mSv/year. The time t_1 can be obtained by solving numerically

$$S_{137}(t_1) + S_{134}(t_1) = 1\left[\text{mSv/year}\right]. \tag{4.5}$$

If the dose rate is already less than 1 mSv/year at $t = 0$, then no decontamination is necessary. For that, the initial soil contamination level is obtained as

$$S_{137}(0) + S_{134}(0) \le 1\left[\text{mSv/year}\right]. \tag{4.6}$$

Or

$$\beta \le \beta_{threshold} = \frac{1}{F(C_{137}r_{137} + C_{134}r_{134})}\left[\text{kBq/m}^2\right]. \tag{4.7}$$

With the values of $F = 5.26$, $C_{137} = 2.1\text{E}{-3}$, $C_{134} = 5.6\text{E}{-3}$, $r_{137} = r_{134} = 0.5$, $\beta_{\text{threshold}} = 49.4$ kBq/m^2.

After Termination of Decontamination ($t > t_1$)

For the radioactivity M_i [kBq] of nuclide i in contaminated area of A [m^2]:

$$\begin{aligned}&\frac{dM_i}{dt} = -(\lambda_i + \lambda_S)M_i, \quad t > t_1,\\ &\text{subject to } M_i(t_1) = M_i^o \exp\left(-\lambda_i' t_1\right), \quad i = 134,\ 137\end{aligned} \tag{4.8}$$

The solution for this is written as:

$$M_i(t) = M_i(t_1)\exp(-(\lambda_i + \lambda_S)(t - t_1)), \quad t \geq t_1. \tag{4.9}$$

The annual dose $S_i(t)$ [mSv/year] due to nuclide i in this area is formulated as:

$$S_i(t) = S_i(t_1)\exp(-(\lambda_i + \lambda_S)(t - t_1))\left[\text{mSv/year}\right], \quad t \geq t_1. \tag{4.10}$$

The cumulative dose due to nuclide i is obtained by integrating this with respect to time as:

$$\Sigma_i(t) = \Sigma_i(t_1) + \frac{S_i(t_1)}{\lambda_i + \lambda_S}\left[1 - \exp(-(\lambda_i + \lambda_S)(t - t_1))\right] \text{ [mSv]}, \quad t \geq t_1. \tag{4.11}$$

For Waste Characterization

During Decontamination ($\mathbf{0 \leq t < t_1}$)

For the radioactivity W_i [kBq] of nuclide i in waste:

$$\begin{aligned}&\frac{dW_i}{dt} = \lambda_R M_i - \lambda_i W_i, \quad 0 < t \leq t_1,\\ &\text{subject to } W_i(0) = 0, \quad i = 134,\ 137\end{aligned} \tag{4.12}$$

where

$$\begin{aligned}M_i(t) &= M_i^o \exp\left(-\lambda_i' t\right), \quad 0 \leq t \leq t_i,\\ \lambda_i' &= \lambda_i + \lambda_R + \lambda_S,\\ M_i^o &= \beta A r_i[\text{kBq}], \quad \text{where } r_{137} + r_{134} = 1\end{aligned} \tag{4.13}$$

The solution is

$$W_i(t) = M_i^o \frac{\lambda_R}{\lambda_R + \lambda_S} \exp\left(-\lambda_i t\right)\{1 - \exp\left(-(\lambda_R + \lambda_S)t\right)\}\left[\text{kBq}\right], \quad 0 \leq t \leq t_1. \tag{4.14}$$

Assume that radionuclides are included in the waste materials removed from the area. The cumulative volume, $W_V(t)$ [m^3], of the waste materials is formulated as:

$$W_V(t) = Ad\{1 - \exp(-\lambda_R t)\}\left[\text{m}^3\right], \quad 0 \leq t \leq t_1. \tag{4.15}$$

The cumulative mass, $W_M(t)$ [kg], of the waste materials is formulated as:

$$W_M(t) = Ad\rho\{1 - \exp(-\lambda_R t)\}\,[\mathrm{kg}], \quad 0 \le t \le t_1. \tag{4.16}$$

The average radioactivity concentration of the waste is

$$\frac{W_{137}(t) + W_{134}(t)}{W_M(t)}\,[\mathrm{Bq/g}], \quad 0 \le t \le t_1. \tag{4.17}$$

After Termination of Decontamination ($t > t_1$)

For the radioactivity W_i [kBq] of nuclide i in waste:

$$\begin{aligned} &\frac{dW_i}{dt} = -\lambda_i W_i, \quad t > t_1 \\ &\text{subject to } W_i(t_1) = M_i^o \frac{\lambda_R}{\lambda_R + \lambda_S} \exp(-\lambda_i t_1)\{1 - \exp(-(\lambda_R + \lambda_S)t_1)\}, \\ &i = 134,\ 137 \end{aligned} \tag{4.18}$$

The solution is

$$W_i(t) = W_i(t_1)\exp(-\lambda_1(t - t_1)), \quad t \ge t_1 \tag{4.19}$$

After t_1, no more waste is generated. Thus, the cumulative volume, $W_V(t)$ [m^3], and the cumulative mass, $W_M(t)$ [kg], of the waste materials are constant at the value of t_1:

$$W_V(t) = Ad\{1 - \exp(-\lambda_R t_1)\}[\mathrm{m}^3], \quad t \ge t_1, \tag{4.20}$$

$$W_M(t) = Ad\rho\{1 - \exp(-\lambda_R t_1)\}\,[\mathrm{kg}], \quad t \ge t_1. \tag{4.21}$$

The average radioactivity concentration of the waste is:

$$\frac{W_{137}(t) + W_{134}(t)}{W_M(t_1)}\,[\mathrm{Bq}/g], \quad t \ge t_1. \tag{4.22}$$

References

1. An, K (1996) Kokoro no kizu wo iyasuto iu koto: Kobe—365 nichi (To heal mental trauma: Kobe 365 days) (in Japanese). ISBN-10: 487893249X. Sakuhinsha, Tokyo
2. Ministry of Education, Culture, Sorts, Science and Technology (MEXT), Japanese Government (2011) Results of airborne monitoring by MEXT. Available at: http://radioactivity.nsr.go.jp/ja/contents/5000/4896/24/1910_092917_1.pdf (in Japanese). Accessed 10 July 2014

3. International Atomic Energy Agency (2001) Generic models for use in assessing the impact of discharges of radioactive substances to the environment. Safety Reports Series 19, STI/PUB/10103 (ISBN 92-0-100501-6). IAEA, Vienna
4. Komori M, Shozugawa K, Nogawa N, Matsuo M (2013) Evaluation of radioactive contamination caused by each plant of Fukushima Daiichi Nuclear Power Station using ^{134}Cs/^{137}Cs activity ratio as an index. Bunseki Kagaku 62(6): 475-483 (in Japanese)
5. Act on Special Measures concerning the Handling of Environment Pollution by Radioactive Materials Discharged by the Nuclear Power Station Accident Associated with the Tohoku District – Off the Pacific Ocean Earthquake that Occurred on March 11, 2011 enacted on August 30, 2011 by the National Diet of Japan. Available at: http://law.e-gov.go.jp/htmldata/H23/H23HO110.html (in Japanese).
6. Ministry of Education Culture, Sports, Science and Technology (MEXT), Japanese Government (2012) Results of continuous measurement of air dose rates by moving automobiles conducted by MEXT as of December 2012. Available at: http://radioactivity.nsr.go.jp/ja/contents/6000/5052/24/338_0321_18.pdf (in Japanese)
7. International Atomic Energy Agency (2006) Environmental consequences of the Chernobyl accident and their remediation: Twenty years of experience. Report of the UN Chernobyl Forum Expert Group "Environment", Radiological Assessment Reports Series 8, STI/PUB/1239 (ISBN 92-0-114705-8)
8. Japan Map Center (2011) Extension site of distribution map of radiation dose, etc. Available at: http://ramap.jmc.or.jp/map/eng/
9. Shiozawa S (2013) Vertical migration of radiocesium fallout in soil in Fukushima. In: Nakanishi TM, Tanoi K (eds) Agricultural implications of the Fukushima nuclear accident. Springer Japan. ISBN: 978-4-431-54327-5 (Print) 978-4-431-54328-2 (Online)
10. Ministry of Education, Culture, Sports, Science and Technology (MEXT), Japanese Government (21 July 2006) Efforts toward realization of disposal of RI and laboratory wastes (Shallow Land Burial) Available at: http://www.mext.go.jp/b_menu/shingi/gijyutu/gijyutu2/toushin/06110922/001.htm (in Japanese)

Chapter 5
Long-Term Energy and Environmental Strategies

Yasumasa Fujii and Ryōichi Komiyama

Abstract This chapter investigates long-term energy and environmental strategies, employing a regionally disaggregated Dynamic New Earth 21 model (called DNE21) which allows us to derive a normative future image of energy systems through the comprehensive incorporation of forecasted future technologies. This integrated energy system model, explicitly considering the availability of advanced nuclear technologies such as nuclear fuel cycle and fast breeder reactors which can improve the usage efficiency of natural uranium resources, employs computational tools to evaluate the optimal global energy mix compatible with low atmospheric CO_2 concentrations. Simulation results in the model indicate that massive CO_2 mitigation targets can be achieved with the large-scale deployment of innovative technology, highlighting roles for nuclear, renewables, efficient use of fossil fuel, and carbon capture and storage (CCS). The results support the simultaneous pursuit of multiple technologies, rather than focusing merely on realistic technological options based on current perceptions. However, the validity about the expected role of nuclear energy for the future should be critically evaluated in the new technical and political contexts that exist after the Fukushima nuclear accident.

Keywords Energy model · Global energy mix · Nuclear fuel cycle

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5.1 Introduction

Innovative technologies are expected to play a key role in long-term transitions of the global energy system. This is particularly the case for the realization of climate change mitigation targets that stabilize atmospheric CO_2 concentrations at levels that avoid a greater than 2 °C increase in average global temperatures above pre-industrial levels. We have been investigating long-term energy and environmental strategies compatible with low atmospheric CO_2 concentrations, employing a regionally disaggregated Dynamic New Earth 21 model (called DNE21). The energy model used here employs computational tools to conduct quantitative analyses on future global energy systems, but the outputs of the energy models should not be like the illusions in a fortune-teller's mystical crystal ball. Its major concern is, therefore, not to forecast a likely future image of the global energy system by extending secular trends in the systems, but rather to derive a normative future image of the systems through the comprehensive incorporation of forecasted future parameters and scenarios published in related academic literature and governmental reports.

5.2 Regionally Disaggregated DNE21

DNE21 is an integrated assessment model that provides a framework for evaluating the optimal energy mix to stabilize low atmospheric CO_2 concentrations. The recent version of the DNE21 model [1] has featured a more detailed representation of regional treatments, including nuclear and renewable energy. The model seeks the optimal solution that minimizes the total system cost, in multiple time stages for the years from 2000 to 2100 at 10-year intervals in multiple regions, under various kinds of constraints, such as amount of resource, energy supply and demand balance, and CO_2 emissions. The model is formulated as a linear optimization model, in which the number of the variables is more than one million.

Figure 5.1 shows the division framework of world regions and assumed transportation routes. In the DNE21 model, the world is divided into 54 regions. In the model, large countries such as the United States, Russia, China, and India are further divided into several sub-regions. Furthermore, in order to reflect the geographical distribution of the site of regional energy demand and energy resource production, each region consists of "city nodes" shown as round markers in Fig. 5.1 and "production nodes" shown as square markers, the total number of which amounts to 82 points. The city node mainly shows representative points of intensive energy demand, and the production node exhibits additional representative points for fossil fuel production to consider the contribution of resource development in remote districts. The model takes detailed account of intra-regional and inter-regional transportation of fuel, electricity, and CO_2 between these points.

Fig. 5.1 Regional disaggregation by node and transportation routes

DNE21 involves various components that model energy production, conversion and transport, primary energy resources, secondary energy carriers, final energy demand sector, power generation technology, energy conversion process, and CO_2 capture (3 types) and storage. End-use electricity demand is assumed with a specific daily electricity load curve divided into six time intervals. Major modules considered in the model are as follows:

1. *Primary energy resources*: conventional fossil fuels (coal, oil, natural gas), unconventional fossil fuels (heavy crude oil and oil sand, oil shale, shale gas, other unconventional gas), biomass (energy crops, forestry biomass, residue logs, black liquor, waste paper, sawmill residue, crop residue at harvest, sugar cane residue, bagasse, household waste, human feces, animal dung), nuclear power, hydro power, geothermal power, solar power, and wind power;
2. *Secondary energy carriers*: hydrogen, methane, methanol, dimethyl ether (DME), oil products, carbon monoxide, electricity;
3. *Final energy demand sector*: solid fuel demand, liquid fuel demand, gaseous fuel demand, electricity (daily load curves with seasonal variations) demand;
4. *Power generation technology*: coal-fired, oil-fired, natural gas (Methane)-fired, integrated gasification combined cycle (IGCC) with CO_2 capture, nuclear, hydro, geothermal, solar, wind, biomass direct-fired, biomass integrated gasifier/gas turbine (BIG/GT), steam injected gas turbine (STIG), municipal waste-fired generation, hydrogen-fueled, methanol-fired;

5. *Energy conversion process*: partial oxidation (coal, oil), natural gas reformation, biomass thermal liquefaction, biomass gasification, shift reaction, methanol synthesis, methane synthesis, dimethyl ether (DME) synthesis, diesel fuel synthesis, water electrolysis, biomass methane fermentation, biomass ethanol fermentation, hydrogen liquefaction, liquid hydrogen re-gasification, natural gas liquefaction, liquefied natural gas re-gasification, carbon dioxide liquefaction, liquefied carbon dioxide re-gasification;
6. CO_2 *capture* (*3 types*) *and storage*: chemical absorption, physical adsorption, membrane separation, enhanced oil recovery operation, depleted natural gas well injection, aquifer injection, ocean storage, enhanced coal bed methane operation.

5.3 Nuclear and Photovoltaic (PV) Modeling

Additionally, the recent version of DNE21 incorporates a nuclear module, which describes in detail the nuclear fuel cycle and advanced nuclear technology. The new model takes account of the availability of advanced nuclear technologies, such as nuclear fuel cycle and fast breeder reactors, which can drastically improve the usage efficiency of natural uranium resources. Light-water reactors (LWR), light-water mixed oxide fuel reactors (LWR-MOX), and fast breeder reactors (FBR) are considered specific kinds of nuclear power generation technologies. This model considers four types of nuclear fuel and spent fuel (SF): fuel for initial commitment, fuel for equilibrium charge, SF from equilibrium discharge, and SF from decommissioning discharge. Fuel for initial commitment is demanded when new nuclear power plants are constructed. Equilibrium charged fuel and equilibrium discharged SF are proportional to the amount of electricity generation. Decommissioning discharged SF is removed from the cores of decommissioned plants. This model also considers time lags of various processes in the system for initial commitment, equilibrium charge, equilibrium discharge, and decommissioning discharge. Supply and demand balances of each type of fuel and SF during the term interval (10 years) were formulated to consider the effects of the time lags mentioned above. In the nuclear waste management process, SF, which is stored away from power plants, is reprocessed or disposed of directly. Uranium 235 and Plutonium (Pu) can be recovered through reprocessing of SF. Recovered Uranium 235 is recycled through a re-enrichment process. Some of the recovered Pu is stored if necessary and the remaining Pu is used as FBR fuel and LWR-MOX fuel. In this model, it is assumed that SF of FBR is also reprocessed after cooling to provide Pu.

A new photovoltaic power (PV) module was incorporated in the most recent version of the model. The intermittent characteristics of PV power generation due to changes in weather conditions are taken into account by stochastic programming. The model considers two states of weather conditions (sunny and cloudy) and the amounts of PV power generation are calculated by node, year, season, time, and weather. Each city node has its own occurrence probability of sunny days by season. When it is cloudy, the level of PV power generation output may drop substantially as compared to a sunny day. It is necessary to ready other types of power generation to compensate for the PV output drops. As a result, this model can calculate a more realistic power generation mix. It is assumed that the effective amounts of solar radiation for each node on sunny days and cloudy days are 80 and 30 % of the theoretical maximum value, respectively. The value of the occurrence probability of sunny days for each node and each season was estimated by comparing the theoretical maximum solar radiation with the actual measurement value.

5.4 Model Simulation

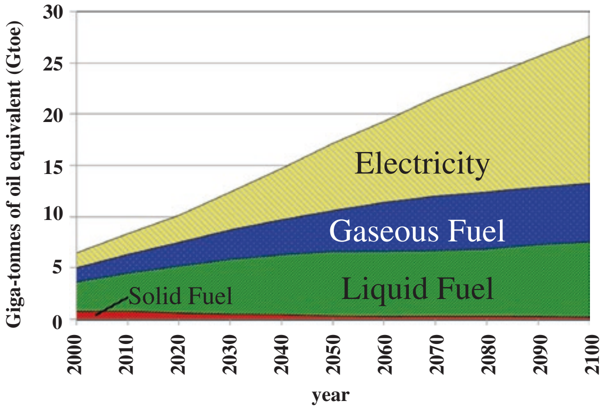
5.4.1 Simulation Assumptions and Settings

Table 5.1 shows data on nuclear fuel cycle [2] and photovoltaic costs. FBR is assumed to be available after the year 2030, and PV capital cost is reduced by 2 % per annum up to the year 2050 through technological progress. The maximum electricity supply by PV is limited to less than 15 % of the electric load for each time period when it is available, and that by wind power is less than 15 % of the electricity demand of all the periods. However, if water electrolysis or electricity storage is used, the upper limits on their supply share no longer apply. Natural uranium and depleted uranium contain 0.711 and 0.2 % U-235, respectively. In this simulation,

Table 5.1 Assumed cost data

	Unit	Cost
LWR capital cost	$/kW	2,000
FBR capital cost	$/kW	3,000
LWR/FBR load factor	%	80
Annual leveling factor	%	19
^{235}U enrichment	$/kg-SWU	110
UO_2 fabrication	$/kg-U	275
MOX fabrication	$/kg-HM	1,100
SF reprocessing	$/kg-HM	750
VHLW final disposal	$/kg-HM	90
SF storage	$/kg-HM/year	8
SF direct disposal	$/kg-HM	350
FBR cycle cost	$/MWh	10
Pu storage	$/kg-Pu/year	500
PV capital cost	$/kW	6,000
Discount rate	%	5
Life time of plant	year	30

Fig. 5.2 World energy demand scenario



the energy demand scenario is given exogenously with reference to SRES-B2 (Special Report on Emissions Scenarios-B2) by IPCC (Intergovernmental Panel on Climate Change) [3]. Figure 5.2 shows the world energy demand scenario.

Here we assume two cases for model simulation. One case is the no CO_2 regulation case (Base case) and the other is the CO_2 regulation case (REG case). The REG Case is the scenario to halve CO_2 emissions by the year 2050 for the world as a whole, and thereafter the emissions are regulated so that atmospheric CO_2 concentration is maintained at a level avoiding some 2 °C increase in the average global temperature from pre-industrial levels. Furthermore, in the REG case the developed countries (high-income OECD countries) are assumed to reduce CO_2 emissions by 80 % compared with 2,000 levels.

5.4.2 Calculated Results

Figure 5.3 shows electric power generation for the world and selected countries. In the Base case, a majority of the world's primary energy is almost exclusively derived from coal, gas, and oil until the middle of this century. In particular, coal, whose reserves and resources are abundant and economically affordable, shows remarkable growth in supply among fossil fuels. After the middle of this century, when the extraction of conventional sources peaks, unconventional oil and gas, which is more expensive than conventional oil and gas, will start to be produced. This decline in the economic efficiency of fossil fuel encourages in part the introduction of nuclear energy and, to a lesser extent, renewable energy such as solar, biomass, and wind power. This fossil fuel-intensive scenario leads to substantial CO_2 emissions, which in turn causes a rise in atmospheric concentrations.

By contrast, in the REG case, the imposition of a carbon regulation target encourages the large-scale adoption of carbon-free energy in addition to reduced demand from a combination of improvements in efficiency. On one hand, at the beginning of the century, coal, concentrated in thermal plants, becomes

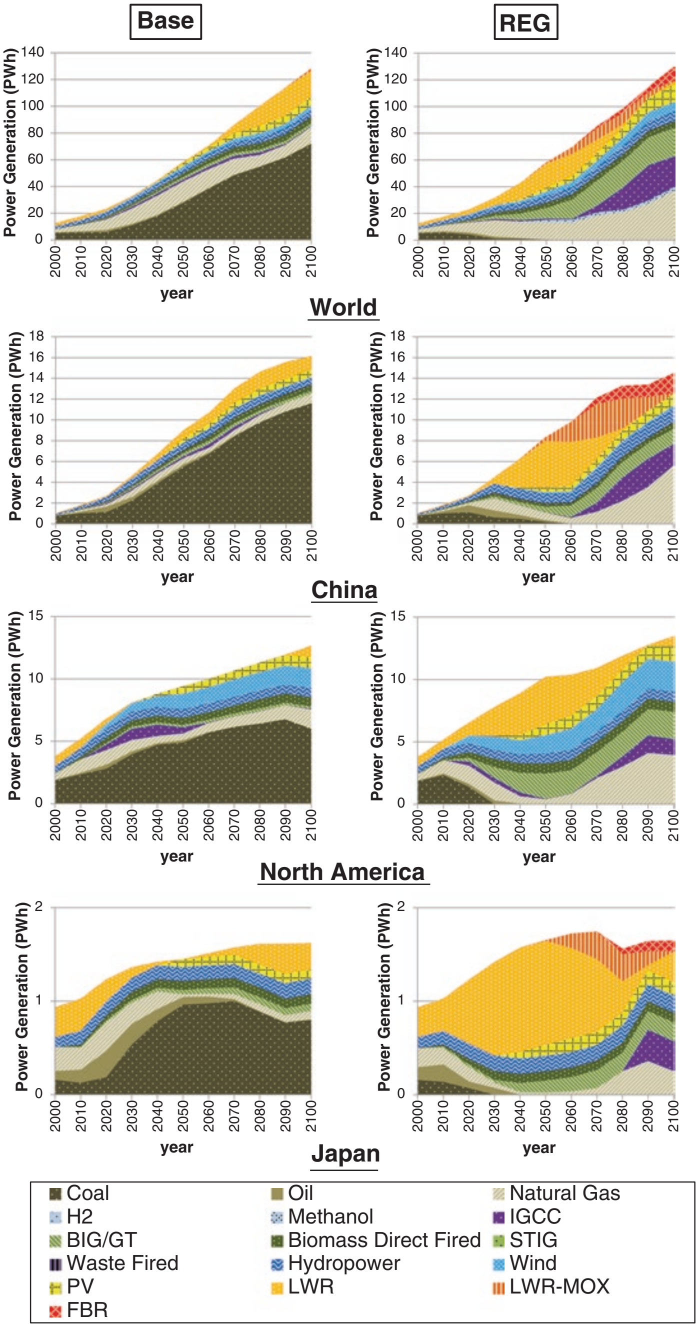


Fig. 5.3 Electric power generation (*Left* Base case/*Right* REG case)

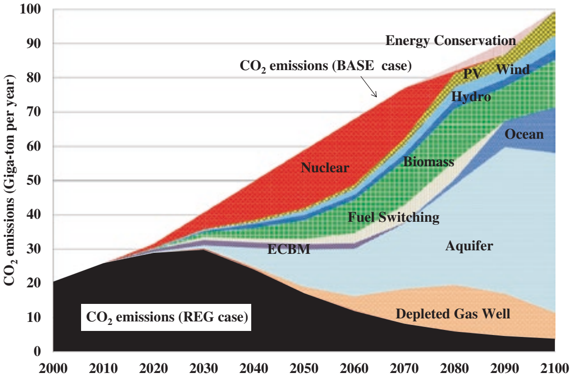
significantly less competitive due to the carbon penalty, although IGCC with carbon capture and storage (CCS) play an important role later in the century. On the other hand, natural gas, introduced early in the century based on its economic attractiveness, maintains this position later with the adoption of CCS, with gas-fired power plants supplying around a quarter of total electric power capacity in the second half of the century.

Concerning the perspective on nuclear energy, nuclear LWR is limited in the second half of the century by the exhaustion of uranium resources. Introduction of FBR reactors enables these technologies to supply power requirements well beyond 2050. In addition, achieving low stabilization does not appear to be possible without large-scale deployment of renewables over the long term. Later in the century, biomass, solar, and wind power are expected to play an essential role in decarbonizing the electric power supply. It is worth noting that renewable technologies are deemed essential for achieving low stabilization targets.

Concerning nuclear power generation, however, it is difficult to explicitly consider the impact of disruptive events such as the Fukushima nuclear disaster with the energy model developed here; the Fukushima accident has caused increased concerns about nuclear safety focusing on the resilience of nuclear facilities for a huge natural disaster and has amplified the uncertainty of nuclear energy in the global long-term energy mix due to the issue of public acceptance. In order to expect a certain role for nuclear energy in the long-term energy scenario as already described, it should be noted that an enormous technical and political effort will be necessary to resolve these concerns and recover public confidence in the safety of nuclear reactors.

Figure 5.4 represents CO_2 mitigation by technological measures by shifting from the Base case to the REG case to realize CO_2 emission levels. Toward the middle of the century, nuclear, biomass, and CCS in aquifers have considerable impact on reducing emissions. And thereafter to 2100, CCS in aquifers, depleted gas wells and oceans, combined with biomass, PV, and wind, greatly contribute to massive emissions abatement.

Fig. 5.4 CO_2 mitigation by technological measures in order to realize CO_2 emissions in REG case



5.5 Energy Modeling Challenge After Fukushima

Basically, the long-term energy model as explained in this chapter serves to yield a normative future scenario for the energy systems under specific given conditions, and it is currently difficult to develop a future scenario explicitly considering the unexpected impact of short-term disruptive events such as the Fukushima incident in a consistent way. The challenge in energy modeling is to consistently incorporate both long-term structural risks, such as climate change and energy resource depletion, and short-term contingent risks, such as disruptive shortages of energy supply as observed in Fukushima and fuel embargo, in order to allow us to effectively evaluate the concept of resilient energy systems. After Fukushima, resilience is regarded as an indispensable element in energy systems under various unanticipated risks for short-and long-term perspectives.

The Fukushima nuclear disaster triggered the shutdown of all of the country's nuclear power plants, which produced 30 % of the country's electricity supply at that time. Since the utilization of nuclear power generation significantly declined due to the accident and to political reasons, fossil fuel consumption for power generation shows the highest level in the last three decades. This meant Japan's fuel imports bill jumped immediately as power companies ramped up gas-fired (LNG-fired) and petroleum-fired power generators, as illustrated in Fig. 5.5. In particular, a radical shift to LNG occurred to compensate for the loss of nuclear energy, and its imports dramatically increased.

In addition, the nuclear suspension and the rise in Japan's LNG import added pressures to push up its already high prices even higher. Japan's LNG is traded at the highest price over the world at around $15/MMBtu, while U.S. natural gas is priced at around $5/MMBtu, as shown in Fig. 5.6. The total import costs of LNG for power generation increased by 64 % after Fukushima, causing the balance of payments to turn negative in fiscal year 2011 for the first time since 1980. Before

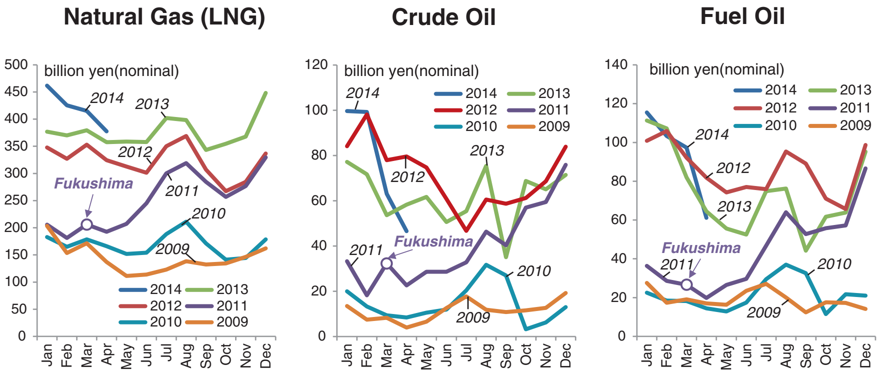


Fig. 5.5 Fuel import cost for power generation in Japan before and after the Fukushima nuclear plant accident [4–6]

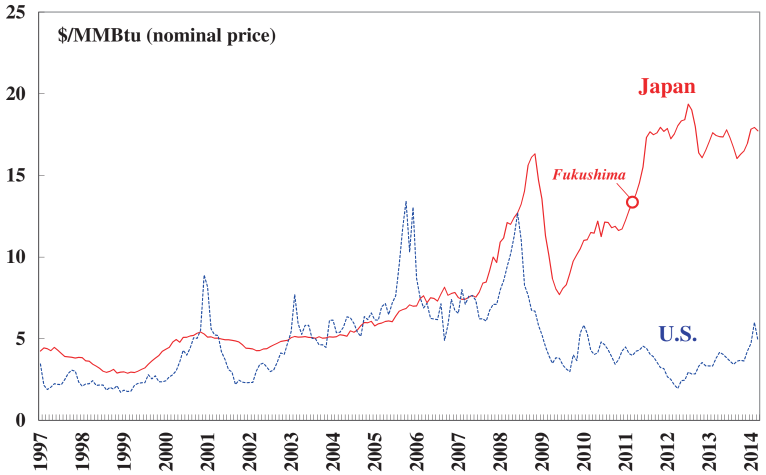


Fig. 5.6 Gas price movement between U.S. and Japan [5, 7]

the Fukushima disaster, nuclear power was considered to serve as a bargaining chip for Japan to purchase LNG at affordable prices.

Resilience is expected to play a role in building a robust energy system to contend with such aforementioned emergent events. The future energy model should enable us to evaluate the amount of adaptive capacity needed to withstand extreme shocks with minimal disruption, to facilitate a recovery from the shocks, and to provide favorable persistent features such as stability, sufficiency, affordability, and sustainability. This model also needs to serve as a platform for discussing appropriate wider responses to the growing risks faced by societies and economies and for suggesting the short- and long-term countermeasures to intensify diversification, redundancy, and emergency responsiveness of energy system.

5.6 Conclusion

The calculated result indicates that nuclear power plants with fuel recycling, renewable energies, and CCS technologies are estimated to play significant roles to reduce CO_2 emissions. Under a great deal of uncertainty it is difficult to draw firm conclusions as to which options have the greatest potential in achieving significant CO_2 reduction. However, the simulation results in the model indicate that massive CO_2 mitigation targets can be achieved with the large-scale deployment of innovative technology, highlighting roles for nuclear, renewables, efficient use of fossil fuel, and CCS. The results support the simultaneous pursuit of multiple technologies, rather than focusing merely on realistic technological options based on current perceptions.

Although we assumed the availability of fuel recycling of nuclear spent fuels and the upper limits of intermittent renewables in the total power generation capacity, the validity of those assumptions should be critically evaluated in the new technical and political contexts that exist after the Fukushima accident. The Fukushima nuclear disaster has caused increased concerns about nuclear safety and has heightened the uncertainty of nuclear energy in the long-term energy scenario, although considerable growth of nuclear energy utilization in emerging Asian countries is actually projected even after Fukushima. Consequently, in order to effectively position nuclear power in the long-term energy mix, nuclear policy needs to highlight nuclear safety even more by developing advanced nuclear technologies and by upgrading nuclear safety standards continuously after Fukushima.

The quantitative value of uranium as an underground natural resource is estimated to be equivalent to that of conventional oil if we consider light-water reactor use only, and it is far less than that of coal. If we abandon the technological option of nuclear fuel recycling, it is self-evident that we will deplete uranium resources within a few decades, rather than conserving it for future generations.

The extensive introduction of intermittent renewable power generation in power systems is definitely considered to have significant influences on power system operations and their optimal configurations. However, nobody knows the clear answer to the question of to what extent power systems should rely on intermittent renewables.

References

1. Hosoya Y, Fujii Y (2010) Analysis of energy strategies to halve CO_2 emissions by the year 2050 with a regionally disaggregated world energy model. Paper presented at the Tenth International Conference on Greenhouse Gas Control Technologies (GHGT-10), Amsterdam, Netherlands, 19-23 September 2010
2. Nagano K, Yamaji K (1988) Optimal reactor strategy for commercializing fast breeder reactors. Power Economic Research 26:71-83
3. Intergovernmental Panel on Climate Change (IPCC) (2000) IPCC Special Report: Emissions Scenarios (SRES) B2. ISBN: 92-9169-113-5. Available at https://www.ipcc.ch/pdf/special-reports/spm/sres-en.pdf. Accessed 23 July 2014
4. Ministry of Economy, Trade and Industry (2014) Monthly report on electric power statistics, 64(3)
5. Ministry of Finance Japan (2014) Trade of Japan, No.16 (824)
6. Ministry of Economy, Trade and Industry (2014) Monthly report of mineral resources and petroleum products statistics 68(4)
7. Energy Information Administration, Department of Energy (2014) Natural gas. http://www.eia.gov/dnav/ng/hist/rngwhhdm.htm. Accessed 8 Jun 2014

Chapter 6
Impact of Fukushima Daiichi Accident on Japan's Nuclear Fuel Cycle and Spent Fuel Management

Joonhong Ahn

Abstract This chapter briefly summarizes the current status of spent nuclear fuel and historical development of nuclear fuel cycles in Japan, and problems that Japan faces after the Fukushima Daiichi nuclear accident for spent fuel management. (1) Aomori Prefecture's refusal to store HLW and spent fuel in Rokkasho without a plan for them to be taken out to a permanent geological repository, (2) drainage of national wealth for purchasing additional oil and gas, (3) international pressure on Japan not to have an unnecessary Pu stockpile, and (4) perpetual safeguards inspection and higher potential radiological risk to be imposed on a final repository for spent fuel and separated Pu and U, are coupled to each other, creating a deadlocked situation after the accident.

Keywords Spent fuel management · Nuclear fuel cycle · Pu stockpile · Phase-out · Post fukushima

6.1 Status Quo

Nuclear fuel before usage in a contemporary light-water reactor (LWR) is made of uranium oxide (UOX) consisting of the fissile U-235 isotope comprising 4.5 % of total uranium (U) atoms. After producing 45,000 mega-watt-days of heat per metric ton (MWd/MT), the fuel is discharged from the reactor. This spent fuel still contains around 0.8 % of U-235 and 0.9 % of plutonium (Pu) (approximately 9 kg), of which about 0.5 % (5 kg) is fissile. If one metric ton (MT) of spent fuel is reprocessed, 9 kg of Pu and approximately 960 kg of U are recovered separately,

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Table 6.1 Japan's spent fuel balance (02/2013)

Stored at JNFL in Rokkasho	3,350 MT
Stored at nuclear power plants	14,170 MT
Reprocessed in U.K. and France	7,100 MT
Reprocessed at Tokai-mura	1,020 MT
Total	25,640 MT

Table 6.2 Japanese plutonium stockpile (kg) (as of the end of 2011) [1]

in Japan (Pu fissile)	*9,295* (*6,316*)
Reprocessing plants	4,364
MOX fuel plant	3,363
Stored at reactors	1,568
in Europe (Pu fissile)	*34,959* (*23,308*)
U.K.	17,028
France	17,931
Total (Pu fissile)	*44,254* (*31,837*)

and the rest becomes vitrified high-level waste (HLW), including fission-product isotopes and minor actinide isotopes, such as neptunium, americium, and curium. The HLW is solidified with borosilicate glass in a stainless steel canister.

In the past 50 years of nuclear power utilization in Japan, 25,640 MT of spent nuclear fuel has been generated. Of this amount, 7,100 MT was reprocessed in France and U.K., and the plant in Tokai-mura currently owned by Japan Atomic Energy Agency (JAEA) reprocessed 1,020 MT (Table 6.1). As a result, Japan possesses approximately 44 MT of plutonium (Pu) (Table 6.2) and about 8,000 canisters of HLW. The un-reprocessed spent fuel ($25,640 - 1,020 - 7,100 = 17,520$ MT) is stored either at each nuclear power plant in Japan (total 14,170 MT) or in the storage facility attached to the Rokkasho reprocessing plant (3,350 MT). 14,170 MT occupies approximately 70 % of total storage capacity (20,000 MT) in all existing nuclear power plant sites. 3,350 MT is already 97 % of the spent fuel storage capacity at the Rokkasho reprocessing plant.

6.2 How Has This Status Quo Been Generated?

In 1955, 10 years after the end of World War II, Japan established the Atomic Energy Basic Law, and launched its nuclear development program. The Japanese national policy for nuclear fuel cycle was established during the 1970s and 1980s to achieve "energy independence" by decreasing dependence on oil, motivated by the experience of the oil crises in 1973 and 1979. The establishment of the nuclear fuel cycle, consisting of U enrichment, reprocessing of spent nuclear fuel to recover Pu and U, and a fast breeder reactor (FBR), became the national policy with the highest priority. In 1988, Japan successfully reached a comprehensive Nuclear

Cooperation Agreement (NCA) with the United States that allowed Japan to develop and own the nuclear fuel cycle. It was a remarkable diplomatic achievement in the international environment after the nuclear test by India in 1974, upon which the U.S. strengthened its anti-nuclear fuel cycle policy. Indeed, Japan is the only non nuclear weapons country[1] that has industrial-scale capability of U enrichment, PUREX reprocessing, and FBRs, acknowledged by the international community, particularly by the U.S.

After reaching the U.S.—Japan NCA in 1988, Japan made steady progress toward construction of nuclear fuel cycle facilities. In 1992 the Japan Nuclear Fuel Industry (JNFI), a private company established by the utilities companies, started commercial operation of the first commercial U enrichment plant in Rokkasho, with the capacity of 150 MT Separative Work Unit/year. In 1989, the Japan Nuclear Fuel Services (JNFS), yet another company established by the utilities, submitted a license application for the first commercial reprocessing plant in Rokkasho, and in 1993, its construction began.[2] JNFI and JNFS were later merged into Japan Nuclear Fuel Limited (JNFL). In 1995, an experimental FBR, Monju, started electricity supply to the grid.[3]

After the 1997 Kyoto Protocol ratified at the United Nations Framework Convention on Climate Change (UNFCCC), reduction of greenhouse-gas emissions was added as the main objective of nuclear power utilization. In other words, the 1997 Kyoto Protocol solidified the raison d'etre of Japan's nuclear energy industry, and this was the mindset in place until the Fukushima Daiichi accident on March 11, 2011. Prior to it, the nuclear community firmly believed that the fleet of nuclear reactors supported by the nuclear fuel cycle would grow and expand, that capacities for U enrichment and spent fuel reprocessing should be established, that Pu should be bred by FBRs, and so forth. The Japanese nuclear community had never conceived of "sudden braking" scenario as the situation currently observed in Japan that all reactors halted operation after the Fukushima Daiichi accident. The sudden braking clearly revealed that there was a serious oversight, or lack of plan B, in the national policy for development of the nuclear fuel cycle and for spent fuel management.

6.3 What Are the Problems with the Current Situation?

After March 11, 2011, all forty-eight operable nuclear reactors in Japan had been put out of service one after another due to previously scheduled regular maintenance and inspection, and none could resume operations except for the Number 3 and 4 reactors at Kansai Electric's Oi Nuclear Power Station for the term between

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[1] EURATOM consisting of EU countries has similar NCA with the U.S.

[2] But as of 2014 the plant has not started its operation due to a series of technical troubles.

[3] But soon after that it had the sodium leak accident, and stopped its operation since then until now.

July 2012 and September 2013. Prime Minister Noda expressed his support for the restarting of Oi's two reactors on June 8, 2012, driven by the projection that the Kansai area, including Osaka, Kyoto, and Kobe, would otherwise suffer from a severe electricity shortage in the coming summer.

While the two units at Oi could restart for a year as an emergency measure, others could not, because more stringent regulations implemented after the accident require all existing 48 reactors to be back-fitted before they obtain permission to restart. Aged reactors in general need more work to comply with new regulations, which creates higher costs, but investing in aged reactors may not pay off if the remaining license term is not long enough. This would lead utilities companies to consider decommissioning their reactors before the license term ends, and thus almost certainly the total number of Japanese nuclear reactors will be reduced in the future. What is not so clear at this moment is how fast the reduction process will occur, and at what capacity the Japanese nuclear fleet size will level off.

The Japanese monthly trade statistics [2, 3] indicate that Japan's import of natural gas jumped from about 3 trillion yen in 2009 and 2010 to 5.4 trillion yen in 2011. Similarly, oil imports in 2011 increased to 12 trillion yen from 9 to 10 trillion yen in the previous years. Such hikes occurred because the gap created by loss of the nuclear reactor fleet had to be filled by the existing fleet of fossil-fired plants. If this situation continues, Japan has to spend an extra 4–5 trillion yen every year. In addition, burning oil and gas emits carbon dioxide into the atmosphere. In 2011, Japan emitted an extra 175 million ton of carbon dioxide compared to the average annual emission before the accident. This pattern will continue as long as Japan relies fully on fossil fuels.

When Aomori Prefecture agreed in 1989 to build in Rokkasho the reprocessing plant and attached interim storage facilities for spent fuel and HLW canisters, the central government promised that Rokkasho would never be the final disposal site for HLW. After the accident, in the course of public discussions about whether nuclear power utilization should be continued or phased out and whether reprocessing should be carried out or abandoned, Aomori Prefecture warned that all spent fuel and HLW canisters currently stored in the Rokkasho site must be returned back to their original plants *if* reprocessing is not carried out in Rokkasho. In this case, 3,350 MT of spent fuel stored currently in Rokkasho and 8,000 canisters of HLW to be returned from U.K. and France would need to be relocated from Rokkasho.

In October 2013, in Mutsu city, Aomori, the interim storage facility for spent fuel became available first with a 3,000 MT capacity with a planned expansion to 5,000 MT in the future. Considering that the fleet size is likely to be significantly reduced, and that there is a total of approximately 10,000 MT (6,000 in individual power plant sites and 3,000–5,000 in Mutsu) of available space for spent fuel storage, Japan can restart reactors for a decade or longer while postponing decision on reprocessing. This offers Japan an invaluable grace period to review policy, during which time a plan must be developed for the medium- and long-term range.

The United States has been demanding that Japan make clear its plans for commercial Pu utilization to avoid creating a large Pu stockpile. However, with the onset of delays in the development of FBR technologies, the Atomic Energy Commission and utilities companies decided to introduce utilization of Pu in the form of mixed oxide (MOX) fuel with existing LWRs. 44 MT of separated Pu (Table 6.2) can be made into approximately 640 MT of MOX fuel at the MOX fuel fabrication plant to be commissioned in 2017 at JNFL's Rokkasho site with production capacity of 130 MT/year. Thus, if LWRs can be restarted, the Pu stockpile can be burnt in LWRs in the form of MOX. Assurance of timely Pu consumption by MOX utilization will be helpful for the Rokkasho reprocessing plant to commence its operation. However, if an immediate nuclear phase-out is chosen, this MOX option for dealing with the Pu stockpile would no longer be viable.

Without establishing a complete fuel cycle with FBR, geological disposal becomes more complicated. Before the accident, the policy was to reprocess all spent nuclear fuel and to utilize separated Pu as MOX first for LWRs, but eventually for FBRs. If FBRs are deployed, the resultant wastes that require deep geological disposal are HLW and intermediate-level waste (so-called TRU waste) from reprocessing. Because only trace amounts of weapons-usable materials, such as Pu, are included in HLW or TRU, the International Atomic Energy Agency (IAEA) would terminate its safeguards inspection for a disposal facility for these two types of waste. But, if a repository is for disposal of spent fuel (either MOX or UOX), separated Pu and U, IAEA will not terminate its safeguards inspection in perpetuity. In addition to safeguardability issues, a geological repository for spent fuels can potentially be a greater radiological risk than that for HLW and TRU.

These issues, i.e., (1) Aomori Prefecture's refusal to store HLW and spent fuel in Rokkasho without a plan for them to be taken out to a permanent geological repository, (2) drainage of national wealth for purchasing additional oil and gas, (3) international pressure on Japan not to have an unnecessary Pu stockpile, and (4) perpetual safeguards inspection and higher potential radiological risk to be imposed on a final repository for spent fuel and separated Pu and U, are coupled to each other, creating a deadlocked situation after the accident. If reactors are back in operation and reprocessing is conducted at Rokkasho, aforementioned issues (1), (2), and (3) could be solved, but the resultant repository would require high maintenance for a long-term period. Public agreement on this scenario seems to be very difficult to reach under the current situation. If reactors restart but reprocessing is abandoned, (2) and (3) could be solved, while (1) and (4) remain unsolved. If reactors and reprocessing are decommissioned, all four issues remain unsolved, while public support for this option may be the greatest.

References

1. Cabinet Secretariat, Japanese Government (11 Sep 2012) Status of plutonium management. Handout No. 2 distributed at the 39th meeting of Atomic Energy Commission. Available at: http://www.aec.go.jp/jicst/NC/iinkai/teirei/siryo2012/siryo39/siryo2.pdf. Accessed 20 July 2014 (in Japanese)
2. Ministry of Finance, Japanese Government (n.d.) Trade statistics of Japan. Available at: http://www.customs.go.jp/toukei/info/index_e.htm. Accessed 20 July 2014
3. Ministry of Economy, Trade and Industry, Japanese Government (2014) Statistics on resources and energy. Available at: http://www.meti.go.jp/statistics/tyo/sekiyuka/index.html#menu1. Accessed 20 July 2014 (in Japanese)

Chapter 7

Political Impact of the Fukushima Daiichi Accident in Europe

Mikael Jensen

Abstract The description in this chapter mentions reactions in Europe on the Fukushima Daiichi accident, seen from the author's Swedish perspective, from the observation post offered by the Swedish Radiation Protection Institute, SSI (now the Swedish Radiation Safety Authority).

Keywords Fukushima impact in Europe · Past nuclear accidents · European nuclear policy

7.1 Earlier Accidents

When interpreting the reactions on the Fukushima Daiichi accident in Europe—and elsewhere—it is valuable to know about some earlier accidents that affected people, notably the Three Mile Island and Chernobyl accidents. These accidents both had important impacts on popular views on nuclear power.

7.1.1 The Three Mile Island Accident

This accident was the first major accident in a civilian nuclear power plant. It occurred on Wednesday, March 28, 1979, in Three Mile Island, Dauphin County, Pennsylvania, near Harrisburg, United States. The containment was intact after

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the accident but a large amount of noble gases and some iodine was released. The official description of the consequences implied that the dose to individuals of the public most affected by the accident was marginally higher than the natural yearly dose. In the U.S., with its highly polarized nuclear debate, this has been disputed, but it was generally accepted by authorities in Europe. The general features of the official description of the release scenario would have been assumed in any case, based alone on the fact that the containment was intact and the absence of long-lived nuclides outside the containment, leaving room only for some uncertainty about the amount of iodine released.

It was understood by the public that the releases would not threaten the safety of Europeans, but the fact that an accident had occurred in the motherland of nuclear power did trigger a general debate on the safety and wisdom of nuclear power production.

In Austria, a referendum half a year earlier had already led to a halt for nuclear power. This meant abandoning a newly built and licensed facility, the Zwentendorf Nuclear Power Plant, planned to produce 10 % of Austria's power. The accident, therefore, did not directly affect the nuclear policy, other than preventing Austria from looking back on the nuclear power alternative.

In a somewhat similar way as Austria, Sweden had a debate before the TMI accident, but it was related to final disposal of the waste. In Sweden, a referendum on nuclear power was held in March 1980, with 3 different alternatives: (1) No, accompanied by a phase—out period of 10 years; (2) Yes, but with phase out as alternatives become available; and (3) with partly similar text as (2). The second option was different from the third in that it also had a provision that required public ownership of nuclear reactors and taxation of part of the generated profit, the "surplus profit." Alternatives 2 and 3 received a majority.

Also, a safety evaluation in Sweden lead the regulators, then SSI and SKI (The Swedish Nuclear Power Inspectorate), to require filtered containment venting systems for the Swedish reactors, to mitigate releases in an accident situation where the containment remained intact but with pressure build-up. The filters were required to stop 99.9 % of any release, noble gases and iodine excluded.

In the rest of Europe the Three Mile Island accident triggered an intensive debate, in particular in Germany.

7.1.2 The Chernobyl Accident

The accident occurred April 26, 1986 and had an important impact on several European states. Doses were significant in around Chernobyl, and elsewhere in Ukraine, Belarus, Russia, and iodine tablets were distributed in Poland. In Western Europe, individual doses attributable to Chernobyl were low, at most in the region of a few mSv and national averages were very low, in Sweden 0.01 mSv. However, counter-measures were significant and included prohibition of selling and advice against consumption of several types of foodstuffs, including game, reindeer, and fish from certain lakes.

In Ukraine and Belarus, the incidence of thyroid cancer increased as a result of the accident. Until 2005, approximately 6,000 cases of thyroid cancer in children (of whom 15 have died) were considered attributable to the accident [1]. The collective dose was estimated to be around 0.5 million man * sievert.

After the accident at Chernobyl, the nuclear power debate flared up again. In Sweden the parliament, Riksdagen, made a declaration of intent that reaffirmed an earlier reference for the nuclear phase-out to be completed by 2010 and gave a timetable for early decommissioning of two reactors. The timetable decisions were later reversed, but the two units in Barsebäck were eventually halted (in 1999 and 2005, respectively) mainly because their proximity to—and the resultant pressure from—the Danish capital Copenhagen.

In Italy the power reactors were stopped in a decision in 1988 after a referendum 1987.

7.2 The Fukushima Accident and Radiological Impact

7.2.1 The Accident

The accident, which took place at the Fukushima Daiichi site on March 11, 2011, was the second accident ever to be reported in the highest category (7) on the INES scale (International Nuclear and Radiological Event Scale) for a civilian nuclear power reactor. The cause was a combination of an earthquake and a subsequent tsunami. The details of the accident are reported elsewhere in this publication. As in Chernobyl, a large-scale local evacuation (tens of kilometers) has taken place, combined with large scale, national control of foodstuffs and drinking water.

7.2.2 The Size of the Radiological Impact Outside Japan

Geographical and meteorological factors and the features of the accident determine its long-range radiological impact. By comparison, the extreme height of the Chernobyl accident's plume accounted for much of its higher long-range effects. In Korea, the maximum air concentration of Cs-137 after the Fukushima accident was around 3 mBq/m^3, about 100 times lower than the highest corresponding concentration measured in Sweden [2, 3] after Chernobyl. The EPA's monitoring in the U.S. after Fukushima presented similar values as Korea (around 3 mBq/m^3 or 0.1 pCi/m^3).

7.3 Technical Assessments and Stress Tests in Europe

7.3.1 IAEA Reports

The IAEA issues regular Status Reports to the public on the current status of the Fukushima Daiichi Nuclear Power Plant, which includes information on environmental radiation monitoring, the status of workers, and current conditions on-site at the plant. While information such as IAEA's has been given on a regular basis after the accident, more complete reports have been in preparation for several years, leaving a few years' vacuum or gap in the more detailed public technical discussion for those not directly involved with the assessments.

A comprehensive report from the IAEA will be finalized by year-end 2014. The report contains details from five subgroups covering the areas:

1. A description of the accident as it unfolded, "what happened";
2. Safety assessment;
3. Emergency preparedness and response and "lessons learned";
4. Assessment of the radiological consequences to humans and biota; and
5. Post-accident assessment.

7.3.2 The European Union

The European Union (EU) nuclear regulators group (ENSREG) and the European Commission (EC) have carried out stress tests for all reactors in the EU and a number of others (Switzerland and Ukraine, both of which fully participated in the EU stress tests according to the Commission, and Armenia, Turkey, Russia, Taiwan, Japan, South Korea, South Africa, and Brazil). The initiating events studied were earthquakes and flooding.

The initial request was made by the European Council on March 25, 2011 and reports were finalized in 2012 with the lengthy title "Technical summary on the implementation of comprehensive risk and safety assessments of nuclear power plants in the EU, accompanying the document communication from the commission to the council and the European Parliament on the comprehensive risk and safety assessments ("stress tests") of nuclear power plants in the EU and related activities."

While both the published EC report and the expected IAEA 2014 report will probably be valuable in boosting discussion on all aspects of nuclear safety, the political impact may not be dependent solely on the technical reports, partly because no drastic conclusions are made or expected and partly because many politicians' opinions have been more or less fixed during the last decades.

7.4 Political Impact in Europe from Fukushima

For reasons given above, the Fukushima Daiichi accident may be expected to produce a more general debate outside Japan, somewhat similar to the political impact from Three Mile Island. The U.S. has never had any major radiological consequences from nuclear accidents, but in Europe, the memory from Chernobyl is still close enough to be remembered by many. One could therefore speculate that the reaction would be stronger in Europe. In any case, the most articulate reactions came in Germany and Italy.

German energy production plans have replaced one political sensitive production method (nuclear energy) by another (dependency of Russian gas) and have lived with criticism since the first steps of this transition were taken. According to the magazine *The Economist*, "Germany … under its new chancellor, Angela Merkel, has been far too keen on bilateral deals, such as the building of a new under-sea pipeline, heedless of the concerns of its nearest eastern neighbors" (May 11, 2006). In Germany, the latest version of a nuclear phase-out was decided, clearly attributable to the Fukushima accident, to be complete and to occur within 11 years. The corresponding earlier Swedish decision was made after the startup of the units Ringhals and Forsmark 3, assumed at the time of the parliamentarian announcement to have (or be given) a 25-year lifetime. The Swedish position was modified but the much shorter time to the deadline in Germany makes it much more difficult to reverse the decision.

In Italy a court ruling decided in January 2011 that a referendum might validate a change in legal requirements and start planning for nuclear power. It may seem a strange time for the Italian government to ask for such support, but it was the result of a process that had started much earlier. (The question was also awkwardly formulated requiring a yes vote to vote against the nuclear plans, i.e., yes to change existing legal anti-nuclear requirements.)

In contrast to Germany and Italy, Finland and to some extent Sweden represent a trend towards nuclear energy. In Finland the building of a new reactor is well underway, despite a considerable delay. The decision-in-principle was taken in 2002. In Sweden an amendment of the Nuclear Activities Act and the Environmental Code came into force on January 1, 2011. The new legislative amendment makes it possible to gradually replace existing nuclear power reactors with new nuclear power reactors.

Partly because decisions were already made, there was no discussion about the wisdom of nuclear power related to an imminent decision, which could be spurred by the Fukushima accident and that probably influenced the debate climate. In Sweden, the Vattenfall Company submitted on July 31, 2012 a pro forma application to build a new reactor, and the environmental impact consultation process started formally in January 2014.

7.5 Influence of Green Politics in Europe

In the final analysis, whatever psychological explanation one might seek out, perhaps the influence of environmental issues in European politics is the most important factor in understanding the European response to Fukushima. Green, in Europe denoting anti-nuclear, parties are influential in most European countries and environmentalism also strongly pervades many other parties such as the German social democrats. Heated nuclear debates have been long-standing features in Austria, Sweden, and Germany with important influence on the political scene, both before and after the TMI, Chernobyl, and Fukushima accidents.

The European responses such as the German and Italian dramatic decisions should not be seen solely as a political reflex attributable to the Fukushima accident alone. It does reflect a reinforced concern for safety, but this is superimposed on a delicate balance, with long histories and trends, for nuclear policies between European popular views and parliamentary positions.

References

1. The United Nations Scientific Committee on the Effect of Atomic Radiation, UNSCEAR (2008) Ionizing radiation, sources and effect of ionizing radiation. Report to the General Assembly, with Scientific Annexes, Volume II, Scientific Annexes C, D and E
2. OECD/NEA (2011) Report of the Korean Government, Response to the Fukushima Daiichi Nuclear Accident to OECD/NEA
3. SSI (2007) The radiation environment in Sweden, SSI Report 2007:02 (in Swedish)

Part II
Etiology

Chapter 8
Where Was the Weakness in Application of Defense-in-Depth Concept and Why?

Akira Omoto

Abstract The accident at Fukushima Daiichi Nuclear Power Station was caused by an unprecedented Magnitude 9.0 earthquake and tsunami. However, the plant was not well prepared to withstand such an unexpected natural hazard. Although defense-in-depth was supposed to be compensating for uncertainties and incompleteness in our knowledge, there were weaknesses in the application of the concept. This paper analyzes where the weakness was and why. Besides technical lessons, the analysis goes to the background of the weakness and concludes with the importance of questioning and critical review of the current practices and provisions, and learning from best practices in order to continuously improve safety. However, it should be considered that this insufficiency in preparedness was not necessarily unique to Japan (its environment and other national factors). Hence, nuclear power countries and those new entrants launching nuclear power programs are expected to learn lessons from this accident, such as the need for continuous re-assessment of design basis natural hazards, understanding of where the cliff edge to core melt exists, how to increase distances to the cliff edge, and, above all, that technical fixes do not solve everything and attitude matters.

Keywords Nuclear safety · Tsunami · Defense in depth

8.1 Introduction

The accident at the Tokyo Electric Power Company (TEPCO)'s Fukushima Daiichi Nuclear Power Station was not a black swan, but was probably a gray swan [1]. The technical problem that led to the multi-unit accident involving

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core melt and fission product release to the environment was insufficient preparedness for complete Station Blackout (SBO: loss of all AC/DC power) coupled with Isolation from Heat Sink (IHS) caused by the tsunami (see Chap. 2—eds.). The tsunami resulted in flooding of the Electric Equipment Room (containing switchgears, power center, batteries, power source for Reactor Protection System) located on the underground floor of Turbine Buildings of Units 1–4, which almost completely (with exception of DC power in Unit 3) deprived AC/DC power supply capability to safety systems as well as to other components required to function for Accident Management in Beyond Design Basis Events (BDBE).

Historically, tsunami had frequently hit coastlines in Japan. With the advent of knowledge of plate tectonics and other factors, Japanese nuclear reactor operators had discussed re-evaluation of Design Basis Tsunami (DBT) for more than 10 years before March 11, 2011. Nevertheless, decision-making on counter-measures to possible high tsunami after 2002 (when revision of design basis tsunami was made) was not done in time for 3.11 (hereafter the accident is also referred to as 3.11). Furthermore, progress in preparedness in the form of Accident Management to BDBE after the Chernobyl accident and the 9.11 attack was not fully developed, especially on two points: incapability to withstand extended SBO and IHS, and insufficient capability to implement Accident Management under disabled conditions [given damage to Structure, System and Component (SSC), team, communication, etc. by external hazard]. Similar provisions as those represented by B.5.b[1] in the U.S. nuclear industry to protect plant safety under damaged conditions did not exist.

This chapter discusses why there was incompleteness in preparation to the unexpected disaster in Japan, utilizing information from reports including accident investigation committees' reports and other studies and insights [2–14].

The etiology naturally goes to the question "what was behind the insufficient preparedness and decisions by those involved in the accident, namely TEPCO, the regulatory body, the nuclear community, as well as those involved in Emergency Preparedness and Response (EPR)?" This discussion leads to national factors including cultures prevailing in an organization, the nuclear community, and society as a whole. However, as researchers in safety culture argue, *cultures are not good or bad by themselves but are good or bad at achieving certain outcomes*.

8.2 Weakness in the Application of Defense-in-Depth Concept

Since defense-in-depth is the key concept for better assurance of nuclear safety by compensating for uncertainties and incompleteness in our knowledge, the review will start where there were weaknesses in the application of the defense-in-depth

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[1] Considering the event of September 11, 2001, U.S. Nuclear Regulatory Commission (NRC) imposed licensees, by Section B.5.b of the order, to take compensatory measures. This section was kept confidential due to security reasons.

concept and why. For levels 1, 4, and 5 of the defense-in-depth concept, lessons learned, possible cultural attitudes, and others issues are discussed. However, the reader should note that this chapter does not touch upon technical lessons related to safety designs such as accident instrumentation, location of spent fuel pool, multi-unit installation, conflict between containment isolation, and use of heat removal system.

8.2.1 Level 1

Level 1 in the defense-in-depth concept is about Prevention of abnormal operation and failures.

8.2.1.1 Setting Design/Evaluation Basis

Guide for Licensing Review of Safety Design of LWR (de facto General Design Criteria in Japan, originally issued in 1970 and last updated in 1990 by Nuclear Safety Commission (NSC) [15]) required that, for SSC to perform safety functions, it must be designed to withstand postulated natural hazards and to maintain its safety functions under these and other loadings, such as due to an accident. Though tsunami was raised as one of the natural hazards to be considered in the note [15], unlike for earthquakes, no specific guide for how to define its design basis nor how to evaluate its impact on nuclear facilities, etc. was provided on tsunami neither by NSC nor industry until 2002.

The height of a tsunami depends on specific local characteristics such as subduction plates, faults, depth of the sea near the coast, and the shape of coastline. For instance, indented areas in Sanriku historically frequently experienced high tsunami following earthquakes [16]. Therefore, each NPS site has its own unique definition of DBT. A construction permit and a license to operate the Fukushima Daiichi NPS was given based on TEPCO's licensing basis document (Establishment Permit) that set DBT at 3.0 m by using the highest level ever historically recorded at this site by 1960 Chile Tsunami. With the rising concern over tsunami hazard (especially after the tsunami that hit Okujiri Island, Hokkaido, in 1983 and 1993) and the advent of knowledge about plate tectonics, the nuclear industry with the help from academia started studies to re-assess DBT. This resulted in the guide [17] by the Nuclear Power Division of Japan Society of Civil Engineers (JSCE) in 2002.[2] Based on this deterministic guide, TEPCO redefined

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[2] Still existent in Annex II (Assessment of Tsunami Hazard: Current practice in some states) to the IAEA Special Safety Guide No. SSG-18 [18], the guide describes "The first step is to conduct literature surveys for dominant historical tsunamis affecting the target site, and then the validity of recorded tsunami heights needs to be examined. On the basis of the results, fault models for numerical simulations for historical tsunamis can be set up."

DBT as 5.7 m and modified the design of components in the seawater intake structure and control logics to secure net positive suction head of pumps required to function during and after a tsunami attack.

In hindsight, the JSCE guide had some problems: (a) Modeling of tsunami source started with historical (literature) tsunami records, rather than study of tsunami deposit sediments, which can cover records of time periods before written records existed; (b) The guide did not appropriately (other than those historically experienced) deal with fracture of multiple segments occurring within a narrow time window as they had occurred on March 11, 2011 (the EPRI report [11] also points this out); and (c) JSCE had not asked for public comment to invite alternative views.

In July 2002, the Research Committee of the Headquarters for Earthquake Research Promotion (HERP) released "Long-Term Projection" [19] of possible earthquakes along the coastline off of Sanriku to Bōsō Peninsula facing the Pacific Ocean, in which it said a large scale (M8.2) earthquake can occur anywhere along the Japan trench. This coastal stretch includes Fukushima. TEPCO had expressed concern over this projection and had communicated [3] with this Committee. Also, TEPCO started further study on possible tsunami hitting the Fukushima coast, not necessarily to change the design basis but for evaluation, including (Fig. 8.1):

- Refinement of tsunami model;
- Probabilistic study (in 2006) of tsunami hazard (probability of exceeding 6 m would be less that 10^{-2}/year in the coming 50 years and exceeding 10 m less than 10^{-5}/year) [20];
- Calculation (in 2008) of maximum tsunami height by hypothetically placing the epicenter of the earthquake off the Fukushima coast (15.7 m inundation height);
- Tsunami deposit study;
- Possible new installation of tall break water wall off the Fukushima site; and
- Creation of an expert panel and internal Working Group.

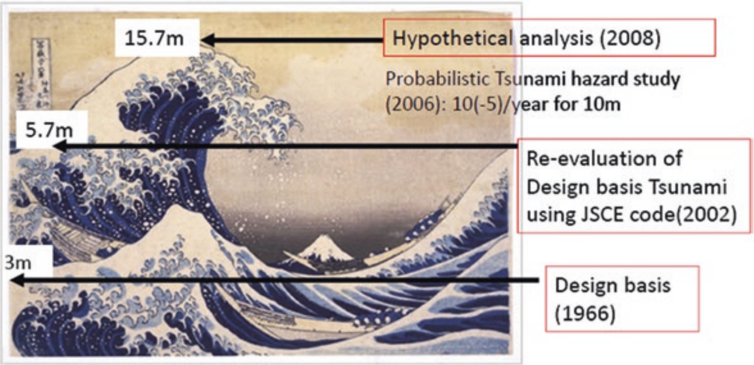

Fig. 8.1 Re-evaluation of design basis and possible maximum tsunami height

It must be noted that:

- The tsunami deposit studies, including that of Jogan Tsunami (AD 869) [21], did not necessarily help model construction for TEPCO, and JSCE's guide did not encourage a deposit study nor base its model on a deposit study;
- TEPCO regarded JSCE's "Methodology for Probabilistic Tsunami Hazard Analyses" [22] as being in the development stage, although it provided an opportunity for considering multi-segment failure given by logic-tree analysis;
- TEPCO also started to hypothetically place an earthquake source off the Fukushima coast where no record existed, got estimation that inundation height could be 15.7 m, and consulted with external experts;
- The idea of installation of a tall breakwater wall was abandoned due to concern over possible increase of tsunami height hitting the neighboring municipality adjacent to the Fukushima Daiichi site. No action was successfully taken before March 11, 2011 when the site was hit by the earthquake with magnitude 9.0 and tsunami with around 14–15 m inundation height; and
- TEPCO had regarded the results from external-event probabilistic risk analysis (PRA) as not much useful due to significant uncertainty, rather than thinking it represents the state-of-art of their knowledge, and that the Operator needs to address possible consequences of beyond design basis by considering where the "cliff edge" exists when hit by a high tsunami as described before.

Meanwhile, stimulated by the Sumatra Earthquake and Tsunami (2004) and others, the Nuclear and Industrial Safety Agency (NISA), then the regulatory body, and Japan Nuclear Energy Safety Organization (JNES), which provided NISA with technical support, jointly established in 2006 a study group on flooding. Experts in JNES recognized the risk of SBO if Fukushima Daiichi were hit by a significantly high tsunami, and their concern seems to have been shared with TEPCO, according to the Diet's Accident Investigation Report [3].

Furthermore, the revised licensing review guide on seismic design (2006) [23] called for minimizing residual risk and mentioned tsunami as follows:

> safety functions of the Facilities shall not be significantly impaired by tsunami which could be reasonably postulated to hit in a low probability in the service period of the Facilities.

NISA, in a meeting with operators, also called for attention to potentially small margins against high tsunami in the current fleet of nuclear power plants [3].

Defining design/evaluation basis of external events for its NPS sites is the responsibility of the Owner/Operator, although it may outsource necessary investigations to consulting companies. To fulfill this task, the Owner/Operator usually consults with experts and researchers, such as seismologists.

It appears that opinions of seismologists split, though not evenly, when it comes to a possible earthquake off the Fukushima coast: one camp considered that continuous slip of the Pacific plate could explain the absence of giant earthquakes in this area [24] with due attention to GPS data somewhat contradictory to the "continuous slip" theory, whereas another camp considered such earthquakes can occur anywhere along the Japan trench, such as the 2002 long-term prediction made by the Headquarters for Earthquake Research Promotion (HERP) [19], but this view was not adopted by the Central Disaster Management Council (CDMC) as a basis for Disaster Management. It also must be understood that the theory based on tsunami deposit study failed to predict the tsunami height as the one TEPCO saw on March 11. Fracture of multiple fault segments within a short time period that occurred on March 11 did not seem to be the basis for the JSCE guide in 2002 [17] or for HERP's long-term prediction in 2002 [19]. Tsunami height off the Fukushima coast was amplified due to superposition of waves from multiple segments.

On the matter of failure of the earthquake hazard map, which resulted in around 20,000 casualties on March 11, a retrospective paper [24] describes "the presumed absence of giant a earthquake was implicitly interpreted as indicating that much of the subduction occurred aseismically," and "the revised idea about the maximum earthquake and tsunami size were not yet fully appreciated and incorporated into the Japanese hazard map." IAEA Safety Standards SSG-9 [25] describes: "comparison with similar structures for historical data which are available should be used in this determination" (design basis earthquake). Given the ring of subduction zone surrounding the Pacific Ocean, should Japan have assumed M9.5 (Chile, 1960), or M9.2 (Alaska, 1964), or M9.1 (Aleutian, 1957) anywhere along the Japanese trench?

Comparative subductology by Japanese and American seismologists [26, 27] suggested the magnitude of the biggest earthquake in a certain subduction zone depends on local characteristics of the subducting plate (convergence rate and the age of the plate). Given this theory, it was considered that subduction zones like Mariana or Northeast Japan were different from that of Chile, or Alaska, or Aleutian. This notion seems to have prevailed, and apparently, influenced guides by JSCE and CDMC. However, the Sumatra earthquake in 2004 (M9.2) was a big challenge to this theory, since the expected magnitude there was much smaller (M7.9) [28, 29]. Given the Sumatra earthquake, Japanese seismologists re-evaluated model, reviewed GPS data for status of asperity, and so on, until 3.11 occurred.

8.2.1.2 Technical Lessons

There are many lessons as to how to define design basis earthquakes in subduction zone and postulated tsunami in the design of NPS: use of data from similar structures (SSG-9), study of deposit sediments, rupture of multi-segment in an almost simultaneous manner and consequential superposition of waves. Had CDMC changed its position after the Sumatra earthquake, things might have been different and the casualty number of 20,000 might have been much less. Had TEPCO, under advice from some scientists, taken a conservative view and consideration of earthquakes in similar subduction zones, as indicated by the IAEA Safety Standard SSG-9, things might have been different. Now, based on this lesson, the Japanese regulatory body, Nuclear Regulatory Authority (NRA), has published a new tsunami guide which requires for Northeast Japan to assume M9.6 as a plate boundary earthquake with a note about giant slip and possibly released accumulated strain by the 3.11 earthquake [30].

Since there remains a certain possibility that earthquakes or tsunami greater than the design basis can occur, consideration must be given to preparedness for the unexpected by:

- Where is the cliff edge leading to degraded core conditions?
- What means are possible to increase the distance to cliff edge?

Had TEPCO's study, rather than focusing on what is the new design basis tsunami or waiting for uncertainty to be reduced, addressed the location of the cliff edge that may render the NPS to be in a serious situation and how to increase the distance to the cliff edge, then the accident might not have occurred. The cliff edge to go to core melt was flooding of the Electric Equipment Room. Even an assessment of internal flooding by a rupture in low grade piping in the turbine building could have found this vulnerability, especially given the experience of flooding of a part of the turbine building in December 1991 at Fukushima Daiichi Unit 1.

The Operator is responsible for defining design basis external hazards and for preparing for the unexpected that may go beyond the design basis, and needs to discharge this responsibility by continuous re-assessment of such hazards based on updated information and listening to experts' views including minority views. Since decision-making on external hazards is based on multi-disciplinary knowledge, implicit assumptions even in a professional society's guide need scrutiny by experts in other disciplines and the guide must be, before making it official, subject to public review and comment.

8.2.1.3 Possible Cultural Attitude Issue in the Background

Basically, a possible underlying issue could be that there was not enough consideration to preparedness for unforeseen events by increasing the distance to the cliff edge, thinking "Beyond Design Basis" can really occur. When TEPCO decided to raise DBT height to 5.7 m, TEPCO had also studied what might happen if a tsunami was 10 m high. The study was relatively optimistic due to the availability of the Air-Cooled Emergency Diesel-Generator (EDG) located at a high place and to consideration of possible use of the ultimate heat sink (atmosphere) instead of seawater by containment feed and bleed operation.

Critical and reflective thinking was missing in the JSCE guide, evidenced by its insufficient study of deposit sediments and assumption of multi-segment failure. Sound decision-making on multi-disciplinary issues is not possible when experts in each disciplinary area do not critically review the work done in other disciplinary areas (called "vertical silo situation" [31, 32]) in the organization or among the professional societies. Compared with the JSCE study on tsunami, the Atomic Energy Society of Japan (AESJ) did not act to formulate a safety assessment guide by considering the possibility of higher tsunami beyond DBT.

Plant engineers could have asked civil engineers questions on these points. Civil engineers also could have listened more carefully to a wide variety of views including alternative views by soliciting public comments.

Difficulty in decision-making under uncertainty and incomplete knowledge is a common issue in the area of natural hazards. Delaying decision by expecting that uncertainty would be reduced and more information would be available unfortunately often results in fatal accidents. A huge uncertainty should not be used to justify not using insights from probabilistic hazard analysis. Construction of a logic tree could have given new insights, especially on multi-segment rupture. Since supposedly around 10 % of tsunami occur by land-sliding of the seabed such as Storegga slides [33] that presumably occurred 8,000 years ago near Norway, tsunami deposit study should have been considered for all the NPS located along the coastline at an early stage.

8.2.1.4 Possible Institutional Issue in the Background

Since Government officials (such as in NISA) are frequently rotated to different positions, it is difficult for them to develop expertise in specific technical areas such as tsunami. Also, regulators have no real plant experience in the absence of a nuclear Navy, unlike some other countries, and the limited number of staffers recruited from Operators due to concern over conflict of interest.

JSCE did not invite comments publicly before releasing its tsunami guide in 2002, which is not the ordinary practice in establishing consensus standards by professional societies.

8.2.2 Level 4

Level 4 in the defense-in-depth concept concerns control of accident beyond Design Basis.

8.2.2.1 Assumptions in Accident Management

In light of the Chernobyl accident, provisions and procedures for Severe Accident Management (SAM) were prepared by all the Operators in Japan, which include hardened venting for BWR containment, connection of versatile low pressure makeup systems to the reactor for reactor water makeup such as by Fire Protection System pumps driven by dedicated EDG, and flooding capability to reactor cavity in BWR. A report [34] from the "Common Issues Committee" submitted to NSC reviewed the results of PRA by Japanese Operators, global trends in SAM, and strategies that could help prevent and mitigate the consequence of severe accidents. It encouraged Operators to prepare SAM on a voluntary basis. It also called for action by NSC to establish a direction and framework for Regulator and Operators to act on SAM. In response, NSC immediately decided [35] to receive reports from Nuclear and Industrial Safety Agency (NISA, Regulator) on an individual operating plant basis on preparation of SAM as well as PRA that forms its basis. For new plants, NSC also demanded Operators to prepare SAM before fuel loading. Probably partly to avoid impact to the lawsuit to “Establishment Permit” of NPS, i.e., to argue there is no fault in licensing practices under current regulations having no rule on SAM, no change in regulatory requirements was made until 2013 when the newly established NRA, in the light of the Fukushima accident, set regulations on severe accidents (Fig. 8.2).

There seems to be a prevailing misunderstanding that Operators did not implement hardened venting for BWR as was requested by U.S. Nuclear Regulatory Commission (NRC) in the Generic Letter 89–16 [36], but as the above description clarifies, this is not true. The report from the “Common Issues Committee” elaborated on specific SAM strategies. There was no mention about the capability of SAM under damaged conditions by external hazards. The report discussed differences between filtered venting and hardened venting in BWR, and found no significant differences since over-temperature failure in the drywell would dominate, by referring to Peach Bottom PRA. Since filtered venting does not address the risks from over-temperature failure in the drywell, the report emphasized the importance of cooling inside containment as well as suppression of Molten Core Concrete Interaction (MCCI).

In the Fukushima Daiichi NPS accident, Operator’s action for prevention of core damage, as shown on Fig. 8.3, was supposed to enable long-term cooling, after the short-term automatic response by AC-independent makeup capability by the use of steam produced by decay heat. The Reactor Core Isolation Cooling System (RCIC) and the High Pressure Core Injection System (HPCI) functioned for 2 or 3 days to sustain core cooling. In order to enable the above transition, Operator tried [4]

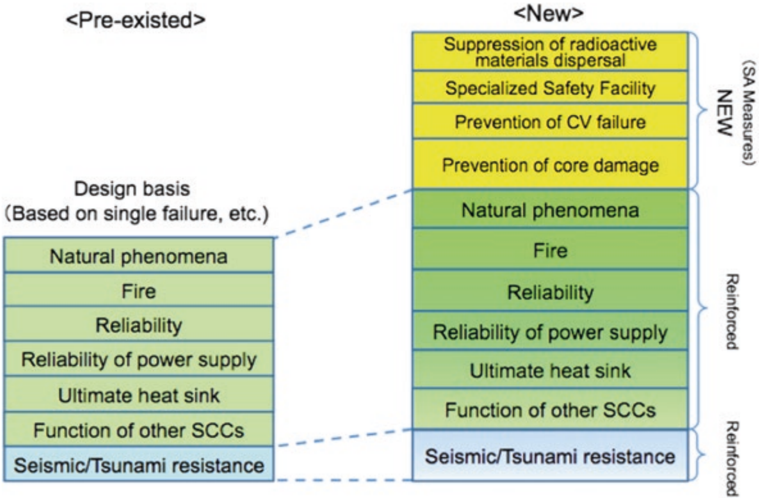

Fig. 8.2 Regulatory changes after Fukushima [37]

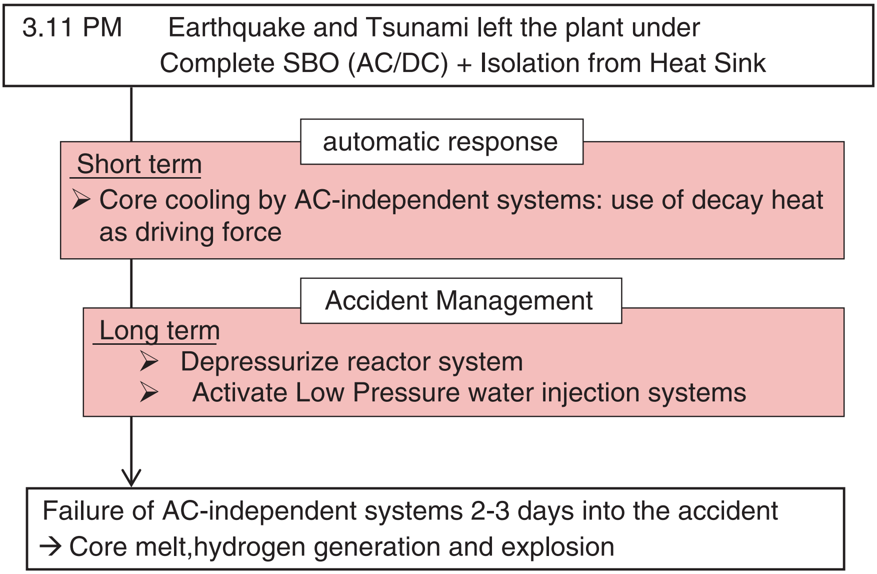

Fig. 8.3 Accident progression in Fukushima-Daiichi Units 2 and 3 [39]

to depressurize the Reactor Coolant Pressure Boundary (RCPB) to send water from the low-pressure makeup system to the reactor core. Operator tried to resume power necessary for instrumentation, venting, RCPB depressurization, and water makeup by collecting mobile power units or batteries from automobiles. Due to lack of drills emulation of real accident conditions, it was found only at the time of the accident that the connection from mobile power units to the plant electric system did not match. DC power from automobile batteries enabled occasional reading of plant parameters. However, there was not enough power (air and electricity) to operate safety relief valves to depressurize RCPB or containment vent valves.

Emergency Operating Procedure (EOP) nor SAM did not assume:

- Complete loss of both AC and DC power (SBO) for an extended time period and simultaneous IHS (although this assumption was not unique to Japan), nor
- Damages given by external hazards to Structure/System/Component (SSC), off-site power, communications system, workforce at NPS, nor
- Hydrogen explosion outside of the containment vessel, although redundant recombiners were installed in the containment to cope with design basis accident (unlike statement in a report [13]). Possibility of hydrogen accumulation and explosion outside of the containment was studied in a Finnish paper [38], but it is not clear what action was taken to counter.

Especially, flooding by tsunami of Electric Equipment Room located on the underground floor of Turbine Building and IHS (by damage to sea-water intake structure) by tsunami occurring simultaneously were beyond consideration in preparing for the unexpected. SBO and Isolation from Heat Sink by tsunami meant common cause failure at levels 3 and 4 of defense-in-depth.

The experience of the 2007 Chuetsu-Oki earthquake [40] at Kashiwazaki-Kariwa NPS prompted TEPCO to install fire engines, underground water tanks, and an onsite Emergency Response Facility (ERF) with seismic isolation design. Although seismic-resistant ERF helped greatly for management of accidents, modifications to the plant in order to increase SAM capability against external hazards were not sufficient against tsunami.

One reason why such damages by external hazards were not a part of the consideration when establishing SAM, was that Operator's priority in the 1990s in preparation for SAM was on enabling plant capability without losing time, while leaving issues of external events, such as realistic capability of those provisions at the time of earthquake [2], to a later stage. Operator waited for reduction of uncertainties associated with seismic risk assessment. However, later, attention to upgrading accident management capability to withstand external events faded in the aftermath of the following:

- Falsification of inspection records of components such as shroud and piping in the 1990s at TEPCO [41] had surfaced in August 2002,[3], [4] and
- Move to amend the seismic design regulatory guide, such as upgrading the magnitude of near-field earthquake. TEPCO focused on the need for seismic upgrading of underground safety-class piping and the concrete structure containing them in Fukushima-Daiichi NPS, which could be necessitated by regulatory change [23].

It may be worth to note that the fact that SAM provisions did not meet the high level of requirements globally was discussed in the IAEA international expert meeting held in March 2012 on Reactor and Spent Fuel as one of the issues surrounding present day EOP and SAM.

The Fukushima accident raised concerns over the nexus between safety and security [42], since terrorists could have learned from the accident how to cause nuclear accidents, i.e., attacking offsite power, Ultimate Heat Sink (intake structure), and so on. After the 9.11 attack, U.S. NRC placed a requirement

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[3] Many BWR plants were forced to shut down for inspection and repair. Since this was an issue with significant implication to nuclear power generation, considerable management attention and resources were given to tackle this issue, rather than the hypothetical severe accident issue.

[4] Part of the falsification was driven by production culture but not necessarily all; part was relevant to regulatory interface. Japanese nuclear regulation has been based on the implicit assumption that plant is maintained in the same condition as when newly built. In fact, degradation develops upon use and components are not immune to cracking by fatigue or SCC (Stress Corrosion Cracking). FEPC (Federation of Electric Power Companies, including TEPCO) has long been (since early 1980s) asking adoption of similar evaluation and acceptance rule as fitness-for-service evaluation and acceptance rule prescribed in ASME Boiler and Pressure Vessel Code Section XI (ASME Section XI) for Nuclear Power Plants, applicable also to SCC cracking. However, this has been continuously denied from the regulatory body. Facing SCC cracks, TEPCO modified its inspection rule as if no cracks exist, while TEPCO had evaluated growth of cracks and confirmed fitness-for-service.

to Licensees in the U.S. to install provisions and procedures to maintain safety functions under a postulated attack, commonly called B.5.b [43, 44]. Although Japanese regulatory body (then NISA belonging to Ministry of Economy, Trade and Industry) had received information verbally in a meeting with U.S. NRC on this topic [45], no warning or information were given to Japanese Operators. After 9.11, the nuclear industry and Operators' efforts were focused on hardware; proving that missiles would not penetrate inside of the containment cause by terrorist attack or by the use of airplanes or missiles, rather than trying to find strategies for maintaining safety function under damaged conditions.

The report [3] by the Diet's Investigation Committee raised the opinion that damage caused by the earthquake played an important role in the progress of the accident, which is more or less in conflict with the estimated scenario in Fig. 8.3. Though it is not easy to raise evidence to show that this hypothesis is wrong, TEPCO has this view that:

- Transient recorder shows functioning of safety systems as intended without trace of damage given to those systems or to RCPB,
- Given the magnitude of the earthquake almost equivalent to Design Basis (though time of continuation of shake is considerably longer in the 3.11 case) and seismic resistance capability as shown in Chuetsu-Oki Earthquake in 2007 to Kashiwazaki-Kariwa NPS where acceleration exceeded design basis considerably, it is estimated there was no significant damage by the Great East Japan Earthquake,
- Walk-down to Fukushima Daiichi Unit 5 on the same site and with BWR/4 generation design (similar to Units 2, 3, and 4) revealed no damage attributable to the earthquake.

The report [46] by the Atomic Energy Society of Japan (AESJ) on the Fukushima accident is also of the opinion that no damage was caused by the earthquake itself, and even if it existed, it had not led to core melt.

During the course of the accident, there had been cases of misunderstanding of the plant status, such as availability of the Isolation Condenser (IC) of Unit 1. This affected prioritization of actions and use of resources in the early stage of the accident [10]. This represents an issue of knowledge about design information by Operator.

This is also linked with the issue of not trying to benefit from independent check or oversight of strategies and actions.[5] Unlike the U.S. or France, Japanese Operators had not institutionalized a system to deploy a shift safety engineer or shift technical advisor, who provides independent assessment on plant safety. This seems to represent a significant problem associated with group thinking among Japanese. A few days into the accident, TEPCO had organized a group of experts consisting of retirees to provide advice [6], but how the reports from this group were utilized is not clear.

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[5] INPO report [10] quotes; "The decision-making approach did not provide for independent challenges or second check by other groups in the organization."

8.2.2.2 Technical Lessons

Simply said, there was lack of preparedness for the unexpected in the context of:

- Robustness of accident management, especially against SBO and HIS occurring simultaneously was lacking,
- Independence of each layer of defense-in-depth was jeopardized by external hazards, since provisions for both level 3 and level 4 failed due to a common cause (tsunami),
- EOP and SAM provisions and procedures did not assume damages given by external hazards, and
- B.5.b-like function was not considered after 9.11 in Japan and information on B.5.b. did not reach Japanese Operators.

8.2.2.3 Possible Cultural Attitude Issue in the Background

Given that NPSs in Japan are located in areas prone to natural hazards, careful attention had to be given to damage by external hazards to SAM provisions. Waiting for uncertainties of seismic risk analysis to be reduced was not the right attitude to take. One could have questioned why Operators were not assuming damages caused by external events in SAM provisions at the beginning of SAM deployment. Operators wanted to make use of all available onsite resources of SAM without losing time, irrespective of their seismic and quality grades. Operators had set aside this grade issue for later consideration.

Group thinking and the trait of not raising concerns could have been in the background.

There is a possibility that complacency also played a certain role. Lack of “reality drills” by emulating realistic accident scenarios and lack of concern over what was prepared in the U.S. after 9.11 may suggest assumptions in the mind of Operators that *accidents cannot happen here*. Issues of similar assumptions and not enough sensitivity to information (in this case B.5.b) could apply to Regulator as well.

To enable knowledge-based actions by Operator in beyond design basis conditions, the Operator is expected to possess design basis knowledge. To what detail will be a matter of discussion. However, generally speaking, Operators are, as an intelligent user, expected to be knowledgeable of design—including why the system is designed in such a way. With the life extension of Generation II nuclear power plants of more than 40 years in many countries, in other words, as plant life is exceeding the life span of engineers’ employment, component products, and even the company, chances are rising for Design Basis information to be scattered among operators, plant designers, and component manufacturers that may include those other than original suppliers. In this situation, Operator is expected to function as the Design Authority [47] for plant life after the plant has started operation. The culture of becoming the Design Authority and an intelligent user/customer did not seem to be strong among Operators. Given the situation that, when a nuclear accident occurs, liability is channeled solely to the Operator whatever the design, the Operator needs to be thoroughly knowledgeable about the design of the plant it uses.

There was a possibility that concern over lawsuits (against the Government for licensing of NPS as well as against the Operator for incurring undue risk to the plaintiff by potential nuclear accident) and opposition to nuclear power intimidated Government officials and Operator to engage in continuous improvement to address risks including that of severe accidents. This also hindered open communication to discuss issues such as severe accidents and containment venting, even though the action of venting is justified to take a small risk to avoid a bigger risk. The situation is just like the “prisoner’s dilemma” where both prisoners failed to achieve a common goal due to distrust of each other. Likewise, the society and Operator failed to achieve the common goal of nuclear safety by distrusting each other.

However, we should not forget to look at the positive side. The professional attitude, dedication, and spirit of self-sacrifice shown by staffers working at the Fukushima Daiichi NPS [4, 9] to alleviate core damage and health risks to the public are really impressive.

8.2.2.4 Possible Institutional and Societal Issues in the Background

Since Government officials (such as in NISA) are rotated to different positions frequently, it is difficult for them to develop expertise in specific technical areas such as SAM, Severe Accident, or B.5.b. Recruitment of professionals knowledgeable about plant design and operation to the Regulator needs careful consideration, to avoid conflict of interest.

A mechanism of independent check or oversight of strategies and actions was not institutionalized in Japan’s operating organization. There was no system of shift safety engineer or shift technical advisor. The problem of group thinking was not well-recognized.

8.2.3 Level 5

Level 5 in the defense-in-depth concept concerns Offsite Emergency Response.

8.2.3.1 Identified Problems During the Course of Accident

Although overall offsite actions (Emergency Response) helped reduce health risks associated with radiation, many problems have been identified and mentioned in detail, especially in Diet’s Investigation Committee’s report [3]. The problems include:

- Loss of offsite center's function (coordination of offsite action) due to damage by earthquake to communication line and habitability under radiation environment,
- Confusion and lack of necessary actions due primarily to lack of knowledge and drills,
- Confusion in the line of command including Prime Minister, Government, and TEPCO.

A different perspective [48] has been presented that, since evacuation significantly degrades quality of life of evacuees and even may lead to physical and mental health problems, the necessity of extended evacuation could be better evaluated (not necessarily at the time of accident but before anything happens) objectively by not singling out risk of radiation but by using multi-criteria decision analysis such as J-value technique developed from a life-quality index.

There is also an argument by some experts that reduction of acute and chronic effects of radiation are not well balanced, and that evacuation was unnecessary beyond 3 km from the NPS to reduce health risk [49]. On the contrary, it increased health risk by forcing evacuees into a stressful life and reportedly even brought about death to more than 60 patients in hospitals. According to the UNSCEAR report on the Fukushima Accident [50] "No discernible increased incidence of radiation-related health effects are expected among exposed members of the public or their descendants. The most important health effect is on mental and social well-being."

Recognizing but setting these discussions aside, this Sect. 8.2.3 of the chapter focuses on practical problems that surfaced during the course of the accident in the area of the fifth layer of defense-in-depth.

A report on implementation of the Emergency Plan from the association of municipalities having NPPs [51] provides valuable details of how the Emergency Plan was implemented (or not implemented), what information source local residents depended on in deciding to evacuate, etc.

A Japanese Health Physics Society's (JHPS) report [52] covers comprehensively, based on information including accident investigation reports [2, 3], the issues in Emergency Plan and post-accident health physics issues, including monitoring and ingestion control, computerized projection system, evacuation, radiation protection standards, exposure to the public and its assessment, exposure to the workers and its assessment, and risk communication. It is appropriate to list some of the identified problems raised by JHPS to help consider what causes were behind the issues.

Monitoring and Ingestion Control

- 23 of 24 radiation monitoring posts were rendered unusable due to tsunami (physically lost) and loss of transmission line;
- Mobile survey systems faced difficulties (road, fuel, transmittal of data, etc.);
- Aerial survey was not available (not planned and needed modification of helicopter), while U.S. Department of Energy (DOE)'s "drone" survey started 6 days after the accident;

- Problems of contaminated beef were caused by feeding contaminated rice straw (Government alerted only cattle farmers and not suppliers of rice straw); and
- Management system for monitoring and ingestion control was not fully preplanned (procedures and devices).

Computerized Projection System

- Computerized tool was not available or not used, while Emergency Preparedness and Response (EPR) depended on computerized tool (ERSS/SPEEDI) developed by the Government;
- Emergency Response Support System (ERSS) was based on Safety Parameter Display System (SPDS) data coming from the plant but they were not available due to loss of DC power in the plants;
- SPEEDI (Dose Prediction System) was usable by assuming unit release due to loss of ERSS, but calculated results were not released from the Government (Cabinet Office staffers) to the public to help their evacuation;
- Calculation using SPEEDI was sent to the prefectural government of Fukushima after March 12. However, the staffers in the local government did not consider the use of this calculation in EPR. Consequently, out of 86 emails including SPEEDI calculation results they had received, 65 were deleted without sharing even within the organization;
- Simulation of radioactivity diffusion in the ocean was not planned, consequently not available; and
- Even though measurement was done for seawater by taking samples, nothing was done to check the level of radioactivity deposit on the seabed, whereas this deposit led to contaminated fish (flounder, sole, and other fishes according to food chain).

Evacuation

- Offsite center did not function for coordination of offsite activities including evacuation due to loss of communication and insufficient design for radiation protection;
- Local municipality and residents decided on evacuation based on different sources [3, 51] (Prime Minister's Office, municipality, commercial media);
- Area of evacuation was changed many times as the accident evolved, which forced some evacuees to change place of settlement more than six times (for residents in townships of Namie and Futaba located north, more than 70 % of residents had relocated more than four times) [3];

- Due to lack of information from SPEEDI to local authorities or residents, evacuees headed northwest where the plume was spreading (leeward) on the morning of March 15, when release of radioactivity was largest;
- Questions had already been raised before the accident from experts on the use of atmospheric diffusion of released radioactivity and subsequent dose prediction system in emergency response. The argument is that basically the basis of precautionary offsite action should be on plant condition rather than measured or predicted dose. The fact is that codes are not technically mature enough (ERSS cannot predict well timing and magnitude of containment failure. SPDS does not necessarily cover all the parameters that describe the plant condition leading to core damage. SPEEDI cannot predict well diffusion under condition of precipitation.)[6];
- There was no drill before the accident assuming that information from ERSS or SPEEDI is unavailable;
- There was no clear pre-plan for the evacuation path and where to settle;
- Residents experienced difficulty living in sheltering zone due to stoppage of incoming food;
- Evacuees considered this to be temporary evacuation, and did not imagine it would end up becoming de facto relocation;
- Evacuation of hospitalized patients was difficult and ended up in more than 60 deaths. Hospitals were supposed to establish evacuation plan on their own (according to the plan by the local government), but it was revealed they had not; and
- JHPS report raised the role of local government as one of the key points to be scrutinized in light of the Fukushima case where lack of its capability faced with combined disaster of earthquake, tsunami, and nuclear accident became evident.

Radiation Protection Standards

- There was confusion about taking iodine tablets. Recommendation from NSC was handled by the recipient local governments inappropriately, and local governments did not release orders, while certain municipalities instructed, on their own decision, the taking of iodine tablets.
- There were some cases of denial by hospital staffers to see contaminated evacuees; and
- Standards have been changed by facing reality such as
  - Screening level (for decontamination of residents),
  - Exposure to school for pupils to play (from 20 to 1 mSv/year), and
  - Allowable level of radioactivity in foods.

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[6] IAEA Safety Standard [53] requires offsite precautionary actions be taken on the basis of conditions at the facilities, before release of radioactive material occurs.

Risk Communication

- Government frequently used the phrase “no immediate threat,” which was ambiguous. Recipients of this message may think “there is no risk” or may think “not immediate effect but, in the long run, there will be a health effect”;
- There had been cases of delay of disclosure (intended or not) of information or release of unclear messages from the Government and TEPCO, which fueled distrust from the public;
- According to opinion polls, 70 % of the public distrust information from the Government;
- Disparity in the level of knowledge between experts and lay people was occasionally completely neglected in communication;
- Delay of notice to neighboring countries on release of slightly contaminated water (3,000 m^3) to the ocean, though intended to avoid larger risk of spill-over of heavily contaminated water, invited distrust from them;
- Need for mental health care and for education on risk of low level radiation were raised after the accident; and
- The role played by the Social Media System (SMS) was highlighted in the Fukushima accident. There were cases of disguised authoritative information sources, which led the public authority to use authentication. TEPCO delayed starting the use of Twitter and heavily used PDF files in release of information, which frustrated the public. Generally speaking, neither the Government nor TEPCO had enough SMS-savvy staffers.

8.2.3.2 Technical Lessons

The following issues need revisiting and changes:

- Delineation of responsibility,
- Command line, coordination,
- Design and function of “offsite center,”
- Offsite emergency plan (zoning, drills, and others), and
- Mental health care of evacuees.

In particular, training of staff members to understand what obtained information or data mean, especially, preparedness for accidents by frequent drills, using realistic scenario and education/training, would improve capability. Amendment of relevant laws by addressing the issue of delineation of responsibility and to increase national capability in emergency response is needed.

Evacuation forces evacuees significant degradation of their quality of life and may lead to physical and mental health problems. Prior careful thinking of the value of evacuation such as by the use of J-value as a tool could have assisted minimization of overall risk associated with the nuclear accident.

8.2.3.3 Possible Cultural Attitude Issue in the Background

The fact that serious "reality drills" and education/training were not in place indicates that those involved were not seriously thinking "an accident can happen here."

8.2.3.4 Possible Institutional and Societal Issues in the Background

Operators' tendency to assure to local residents that no such accident could happen here to avoid uneasiness with NPS deprived residents of an opportunity for realistic drills involving them.

There is no such organization like U.S. Federal Emergency Management Agency (FEMA) or Nuclear Emergency Planning Delivery Committee (NEPDC), which coordinates activities across different agencies in the Government for concerted actions. The Cabinet's Crisis Management team in the Japanese Government did not function in confronting the nuclear accident. In an environment where ministries and agencies did not communicate with each other very well, coordinated action was difficult.

Education and training of staffers in local and central governments involved in Emergency Response could have enabled them to understand what actions to take and what is the significance of information they had received from experts or Operator.

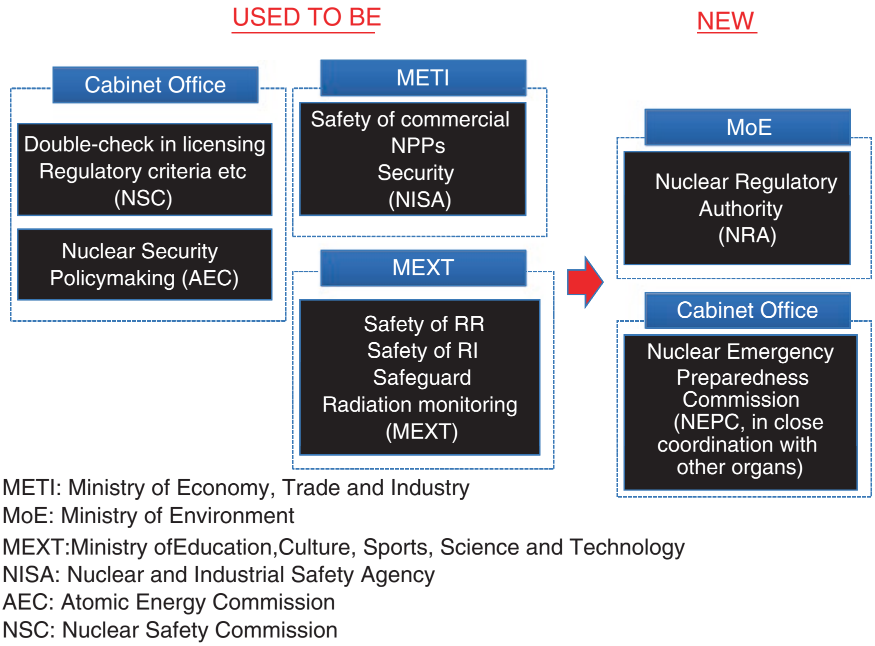
Although a group of experts was functioning to provide advice to the Cabinet Office and meetings had been held on a daily basis with participation of politicians [6], it is not clear to what extent the recommendations from this group (such as on the use of SPEEDI information) was used in decision-making. There is a similarity with the case of TEPCO in the handling of information from senior advisory groups mentioned relevant to the 4th layer of defense-in-depth.

8.3 Nuclear Safety Regulation

Characteristics of Japanese nuclear safety regulation were found in three points: two-agency system (not necessarily very unique), hardware focus, and frequent shuffling of staff members. Although there may be a criticism that the regulatory body NISA belonged to the Ministry of Economy, Trade and Industry (METI) and consequently lacked independence, NISA claimed it has "functional independence." What is important is not the formality of independence but if safety-first decisions can be made without outside intervention. There seems to be no clear evidence to support failure of functional independence.

8.3.1 Two-Agency System

Japan's nuclear safety regulation historically developed in two sectors of the Government, namely Science and Technology Agency (STA, currently part of Ministry of Education, Culture, Sports, Science and Technology, MEXT) and Ministry of International Trade and Industry (MITI, predecessor of METI). STA used to be primarily for radiation safety and licensing of nuclear facilities, whereas MITI was for inspection of operating power reactors. As the number of operating units increased, licensing and regulation for power reactors were taken over by METI. Nevertheless, there were multiple regulatory reviews under the name of "double check" performed by the Nuclear Safety Commission (NSC, part of the Cabinet Office separated from STA when STA was merged with MEXT) and by METI. Regulatory requirements were primarily formulated by STA, and later by NSC, whereas practical regulation using such requirements was carried out by NISA belonging to METI. This complexity had been criticized in IAEA's Integrated Regulatory Review Service (IRRS) mission report [54], but this scheme had continued until June 2012 when the regulatory structure was changed in light of the Fukushima accident (Fig. 8.4). An NPO report on the Fukushima accident criticized this state of "lack of governance of nuclear regulation" by the two-agency system as irresponsible [6].



METI: Ministry of Economy, Trade and Industry
MoE: Ministry of Environment
MEXT:Ministry ofEducation,Culture, Sports, Science and Technology
NISA: Nuclear and Industrial Safety Agency
AEC: Atomic Energy Commission
NSC: Nuclear Safety Commission

Fig. 8.4 Change of regulatory structure before and after the Fukushima Daiichi accident

8.3.2 Hardware Focus

A culture is observed in Japan in engineering and manufacturing to place heavy emphasis on hardware—component quality and reliability, which itself is presumably a source of strength for Japanese industry, while being weak in system thinking. By benefitting from Professor E. Hollnagel's insight [55], key lessons from a major nuclear accident can be summarized as follows:

- Pre-Three-Mile Island (TMI) accident era: Accidents are primarily attributed to failure of components, hence component reliability was deemed important;
- TMI: Highlighted human factor;
- Chernobyl: Highlighted organizational safety culture and SAM; and
- Fukushima: Highlighted Resilience and social license to operate [56].

It seems that the Japanese paradigm for nuclear safety had still primarily rested in the pre-TMI era. Three examples can be raised:

- Tendency to focus on component reliability and inspections (and inspection records) to assure this reliability, while not paying much attention to soft aspects (risk governance, culture, human factor), and systems thinking was traditional. The Japanese code for design and inspection of mechanical components are mostly equivalent to the ASME Boiler and Pressure Vessel code in the U.S. However, unlike the ASME code (professional society's code), this Japanese code became part of a regulation (Ministerial ordinance #501), requiring Government examination of compliance to code requirements by review of stress analysis calculations. This focus on component reliability had also been subject of discussion as a part of inappropriate regulatory emphasis and practices in Japan together with other issues of Establishment Permit (PSAR/FSAR) and Operational Technical Specification.
- After the 9.11 attack in the U.S., the Japanese nuclear community's effort was focused on proving containment would remain intact after an airplane attack, setting aside the issue of maintaining safety functions assuming the plant may potentially receive significant damages. Consequently B.5.b-like strategy was remote from their thought.
- In developing coping strategy against high tsunami, TEPCO was considering construction of a tall break water wall, while not trying to find where the cliff edge is and how to increase the distance to the cliff edge when hit by beyond design basis tsunami.

8.3.3 Frequent Shuffling

Although this is not unique to the regulatory body, the Japanese government as a whole had a practice of frequent (once in 2–3 years or even shorter intervals) staff shuffling, partly to cultivate wider views and partly to avoid collusion with the regulated bodies. However, this is not necessarily an appropriate practice for nuclear regulation, which requires highly professional competence (knowledge and experience).

8.4 Differences in Plant Responses Among 17 Nuclear Power Plants

There are 17 nuclear power plants (Fig. 8.5) affected by the 3.11 Earthquake and tsunami. Why did only three units in Fukushima Daiichi NPS cause core melt? The gap (Table 8.1) between tsunami (Design Basis, inundation height on March 11) and Ground Level (GL) is one of the key parameters, but that does not explain everything.

Three factors need to be considered to explain the different responses: Gap in elevation (tsunami and GL), Availability of power, and SAM. Figure 8.6 shows that the location of the Electric Equipment Room (EER) was a critical factor that led Units 1–3 of Fukushima Daiichi to core melts. Within Fukushima Daiichi NPS, three air-cooled Emergency Diesel Generators functioned as designed, one of which served electricity to Unit 5 (then to Unit 6 by EOP) saving Units 5 and 6,

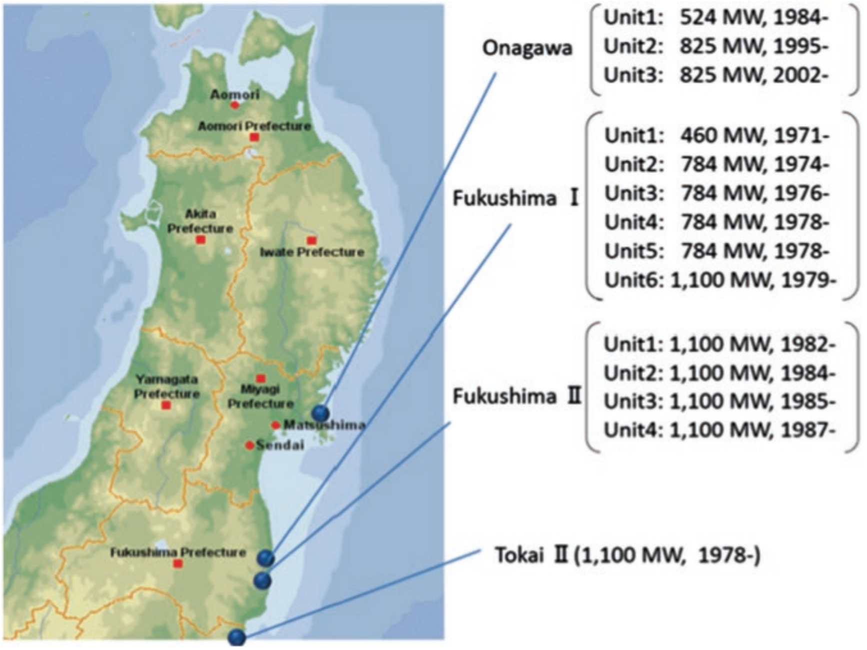


Fig. 8.5 Nuclear power plants affected by 3.11 earthquake and tsunami

Table 8.1 Tsunami height and Ground Level [57]

	Tsunami		GL of R/B, Tb/B (m)
	Design basis (m)	Observed (m)	
Fukushima-Daiichi 1–4	5.7	14–15 (inundation)	10.2
Fukushima Daiichi 5–6			13.2
Fukushima Daini 1–4	5.2	14–15 (inundation)	12
Onagawa 1–3	9.1	13	13.8
Tokai 2	4.9	5.1–5.4 (inundation)	8

Note GL Ground level, *R/B* Reactor building, *Tb/B* Turbine building

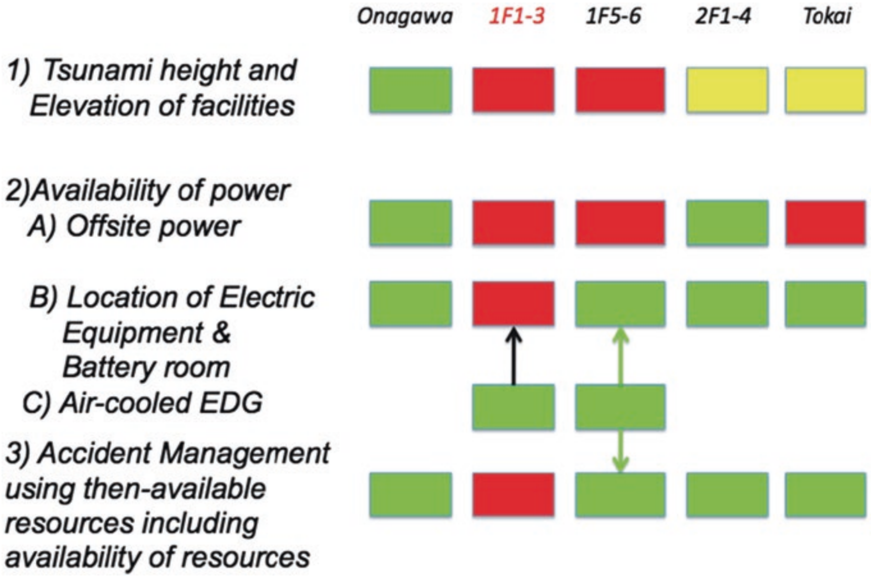


Fig. 8.6 Factors affecting plant response. *Red* failure was fatal, *yellow* failure was not critical, *green* success

whereas two air-cooled Emergency Diesel Generators serving electricity to Units 1–4 functioned but power was not distributed to equipment due to flooding of EER.

8.5 Cultural Attitude Issues

8.5.1 General Observation

For those who may have been watching Japanese nuclear energy from the outside and saw a series of incidents and accidents, such as sodium leakage in Monju (1995), JCO criticality accident (1999), falsification issues (surfaced in 2002, but bad practices were found to be existent since 1990s), they may have wondered if something might go wrong recently, felt governance by the Japanese nuclear community was weak, and thought some belt-tightening efforts may be necessary. To answer if there are underlying commonalities with the Fukushima accident, we must await extensive research based on fact-finding study; hence it is not discussed here.

Weakness of defense (in the context of defense-in-depth) may arise from inappropriate decisions and insufficient information available to decision-makers as well as uncertainties. Naturally, organizational culture, group culture (of the nuclear community), priority of management, and even national culture influence such decisions and decision-making processes. This section discusses such cultural and cultural attitude aspects that could have been relevant to the Fukushima accident. Four points are important to note before discussing this topic:

- National culture is a part of national factors influencing culture for safety.
- Cultures are not good or bad in themselves, but are good or bad at achieving certain outcomes [58]; in this particular case outcome is "achieving safety."
- It is not an appropriate learning attitude to regard the Fukushima accident as a very unique accident that occurred only under a unique natural environment (earthquake and tsunami) and a unique culture.
- A warning was given in the "overview" section of the Kemeny report [59]: "We have stated that fundamental changes must occur in organizations, procedures, and, above all, in the attitudes of people. No amount of technical 'fixes' will cure this underlying problem." This message should not be forgotten. Even though technical fixes are well established, the bottom line lies in human factors in successful prevention and mitigation of an accident. The holistic safety approach takes the position that human/cultural, organizational, and technological aspects contribute to safety.

8.5.2 Related Studies

In autumn 2011, GoNERI (Initiative for Nuclear Education and Research by Global Center of Excellence) at the University of Tokyo commenced the study "Why the nuclear community in Japan failed to prevent this accident." A series of interviews was conducted by GoNERI members of 24 well-recognized nuclear experts from Universities, Regulatory body, Atomic Energy Commission, Operators, Industry, Research institutes, Institute under the umbrella of Operators, and NPO critics. The results were reported [42] at an international conference, according to which discussion focused on three points:

(1) **Why was the nuclear community not well prepared for the unexpected natural hazard?**

Answers were:

- The nuclear community in Japan focused on internal events in PRA and tsunami was outside its radar scope
- Generally, no question was raised to U.S. original designs (GE/EBASCO design placing electric equipment room in the underground floor of Turbine Building for Fukushima Daiichi Units 1 and 2)
- There was lack of communication and mutual understanding between natural science and engineering on uncertainty and margin in designs to cope with these hazards

(2) **Why prevention/mitigation against beyond Design Basis was not enough?**

Answers were:

- Operators' culture for safety had degraded over time; they had shown signs of complacency, lack of sensitivity to safety-related information from outside of Japan, delayed action to alert, and over-confidence in nuclear safety
- Lack of tension between Regulatory body and Operators
- Operators' staffers are generally too busy in caring for day-by-day problems
- Society takes risk-related actions and modifications as evidence of unsafe plants ("prisoner's dilemma"), which delayed or prevented safety-related modifications for improvements
- Failure of safety regulation
- "Problems of culture were more or less recognized even before 3.11"

(3) **(Since a number of interviewees mentioned cultural issues which were already recognized, a further question was asked) If you recognized serious problems beforehand, what did you do?**

Some answered that actions such as below were taken in this context but were not enough to prevent the disaster:

- Creation of Japan Nuclear Technology Institute (JANTI) emulating U.S. INPO.
- In light of the 2007 Kashiwazaki-Kariwa earthquake, TEPCO constructed seismic isolation ERC, underground water storage tanks, deployed fire engines.
- "Change culture" project (called "Renaissance Project" in TEPCO) in light of the falsification problem, Corrective Action Program (CAP) [9, 60] by learning from INPO, and by "Safety alert" reports, etc.
- Local Information Committee was created at TEPCO's Kashiwazaki-Kariwa site by learning from the French good practice of sharing information with local residents.

Others answered generally no significant actions (by themselves or by members in the nuclear community) were taken because:

- Operator is King, allowing no criticism from outside
- No question was asked about the nuclear energy program implemented by Operators under the National Policy

- "Loose lips sink ships"
- Members in nuclear community are too busy to care

It must be recognized, however, these views were necessarily offered without their own detailed analysis of causal relationship with the Fukushima accident.

Another example is a paper [61] in INSS (Institute of Nuclear Safety System) Journal, which overviewed the organizational issues that may have been factors leading to the Fukushima accident or were observed during the course of the Fukushima accident, based on accident investigation reports. It claims it found problems in the context of the framework proposed for organizational excellence as follows:

- Consideration of residual risks
- Production culture
- Lack of preparedness to low probability unexpected scenarios such as earthquakes and tsunami
- Safety culture
- Higher priority on cost and impact litigation against operating fleet, less on nuclear safety
- Not enough disclosure and sharing of information
- Insufficient training of individual competence for emergency actions including severe accident situations
- Insufficient planning for emergency actions
- Insufficient use of lessons learned from past incidents

The study also noted that three areas have an outstanding number of identified problems: deficiency of safety infrastructure, lack of open discussion and information sharing, and limited communication with stakeholders.

8.5.3 Link with National Culture

National culture is only one of the factors influencing the culture for nuclear safety. Others include but are not limited to: historically cultivated organizational culture, professional culture (component focus, weak systems thinking, Operators' heavy outsourcing), institutional aspect of national nuclear system (Operator as a local giant stockholder-owned monopoly, Nuclear Energy program endorsed and strongly backed by Government and implemented by Operators), interface with regulatory body, interface with society as a whole ("prisoner's dilemma") and local municipality (Government subsidies to local infrastructure building), relationship with academia (especially seismology when it comes to the Fukushima accident), etc. All of these are worth further study. However, influence of national culture in particular is picked up here, since understanding of this aspect may benefit newcomers when launching a nuclear power program.

8.5.3.1 Collectivism, Group Thinking, Insufficient Critical/Reflective Thinking and Questioning Attitude, not Raising Concerns

There has been a general tendency in which the Japanese are not trained in critical thinking. No such training and debates have been a part of Japanese traditional education, which placed emphasis on transfer of knowledge and learning by heart, rather than teaching how to think. INPO report also points out TEPCO could have benefitted from additional questioning and challenging of assumptions [9].

"Harmonization is our core value," says the Article 1 of Japan's oldest Constitution promulgated in year 604. People's attitude tends to be one of not speaking out. In the area of nuclear safety culture, Japanese definition of traits of safety culture often drops "raising concerns." Also, according to Prof. Hofstede's international comparison [62], collectivism seems to be one of the salient features of Japanese culture.[7]

8.5.3.2 Lack of Big-Picture Thinking, Losing Sight of Substance by Being Distracted by Formality and Details

Unlike the argument by Nisbett [63], it seems that very often Japanese tend to be distracted by formality and details and forget the big picture. Rather than viewing something as an integral part of the whole issue, single-criteria (as against multi-criteria) analysis and decision-making are observed. The following is a case involving nuclear regulation in 2000s.

In the aftermath of the falsification scandal involving many Operator companies, Operators' staffers consumed a significant amount of time in assuring consistency and accuracy of the documents, partly by regulatory requirement. This blurred the focus on the significance of safety. Even after the Fukushima accident, insufficient dialogue between Regulator and Operator was often argued. This may be a case of distraction by the formality of independence and losing the basics of "what independence is for." Independence is for assuring safety-first decision-making and collection of information not only from the Operator but also others through dialogue, which serves well for informed decision-making.

8.5.3.3 Hardware Culture and Technology-Focus

This trait in the nuclear community is not necessarily unique but present in many fields of Japanese industry. Excessive hardware-focus, technology-focus, and overconfidence in component reliability may result in lack of preparedness in case

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[7] INPO Fukushima LL report: "decision-making approach did not provide for independent challenge or second checks by other groups within the organization. … the site ERC did not independently review and provide feedback prior to decisions by the control room staff."

technology fails. No analysis of causal relationship is available, but the observation is that these traits (hardware-focus, technology-focus and lack of preparedness for technology failure) co-existed.

8.5.3.4 Positive Aspects

However, positive aspects were observed during the Fukushima accident, namely the dedication and professionalism of TEPCO's site staffers. INPO special report [64] on the nuclear accident, November 2011 cites: "… Some workers lost their homes and families to the earthquake and tsunami, yet continued to work. Many workers slept at the station… usually on the floor." TEPCO's investigation report [4] Appendix touches on heroic acts by operators sacrificing themselves. Generally speaking, a utilities employee has the mentality of dedication to work for the betterment of society. Other virtues of Japanese culture include compassion, politeness, and diligence.[8]

8.5.4 Future Directions

Possible cultural attitude issues have been discussed [65, 66], which may have existed behind the weakness of each layer of defense-in-depth. Discussions below are on the areas where transformation of cultural attitudes would be required for Japan to achieve nuclear safety:

- Change in priority of risk management by management of utility companies.
- Avoid complacency prevailing among those working in nuclear energy.
- Avoidance of "prisoner's dilemma" situation prevented continuous safety improvement.
- Avoid parochialism in decision-making; encourage multi-disciplinary and critical review.

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[8] Relevant statements:

(1) Prof. D. Klein, former Chairman of U.S. NRC, wrote for The Ripon Forum [67], "In a culture where it is impolite to say 'no' and where ritual must be observed before all else, I think that Western style 'safety culture' will be very hard for the Japanese to accept. But there were also extraordinary—even heroic efforts made by the brilliant dedicated engineers, operators…." He also mentioned, "I do not doubt that the Japanese nuclear industry has the capability to transform to a nuclear operations safety culture."

(2) Prof. K. Kurokawa in his Chairman's message for the Diet's Investigation Committee's Report [3] (July 2012) said "This was a disaster 'Made in Japan.' Its fundamental causes are to be found in the ingrained conventions of Japanese culture (our reflexive obedience; our reluctance to question authority; our devotion to 'sticking with the program'; our groupism; and our insularity)."

- Enhance professionalism.
- Encourage questioning attitude, critical/reflective thinking.
- Recognize the value of independent checks to avoid falling into the pit of group thinking.
- Recognize the importance of being an intelligent user including being Design Authority.
- Need to learn global good practices. Need to learn from precursors, incidents, and accidents (The JCO accident in 1999 [68, 69], for instance, illustrates an example of production culture, lack of knowledge of design on the part of workers, complacency.).

Further, improvements can be made in the application of defense in depth by;

- Assuring independence of each layer of defense in depth to avoid common cause failure.
- Setting Design Extension Condition to cover severe conditions not covered by design basis so that significant release is practically eliminated by strengthening containment function.
- Scrutiny of the quality of defense in depth by use of objective tree (IAEA Safety Report Series 46 Annex).
- Critical review and regulatory requirement.

8.6 Conclusions

The Fukushima accident was a gray swan in the context that such an accident was very low in probability but can happen, rather than can never happen (black swan). Can this gray swan be found only in Japan?

Probably not, if the nuclear utility industry is not well prepared and if problems exist in safety culture because: (a) insufficient preparedness of nuclear power plants, particularly to extended SBO coupled with Isolation from Heat Sink and to possible damages to SAM provisions, is more or less common, and (b) even though an attack by a giant earthquake and tsunami might be rare in other countries, other natural disasters beyond design basis may trigger similar accidents.

This disaster of some 20,000 casualties by the tsunami and subsequent nuclear accident in Japan, one of the most industrialized countries, may have been a surprise to many in the world. Germany, in its Ethics Commission's report [70] that led to the phase = out of nuclear power in Germany immediately after the Fukushima accident, noted a change in the perception of the risk of nuclear accidents because it had "occurred in a high-tech country like Japan" and "this has caused people to lose faith that such an event could not happen in Germany."

Why was such an industrialized country not well prepared? Most probably, whether a country is industrialized or not does not matter, since human and organizational factors, as discussed above, played a critical role. Presented here are five simplified plausible reasons:

- Complacency and consequential poor training for emergency situations, especially evident when we see confusion in implementing EPR (level 5 defense-in-depth), but, in general, there seems to have been the prevailing notion of "accident will not happen here," and "nothing much to learn from outside of Japan".
- Delayed decision-making to prepare for unexpected.
- Over-confidence in technology: focus on component reliability and technology is probably linked to the optimistic attitude of not assuming failure of components or technological measures, such as the case of SBO or SPEEDI.
- Lack of critical/reflective thinking, insufficient listening to alternative or even opposing views, and group thinking.
- Insufficient continuous improvements, partly due to "prisoner's dilemma" situation with society.

The root cause could be said to lie in history, since this cultural attitude was developed during the course of development and utilization of nuclear power for more than half a century. Investigation of organizational causes (not only TEPCO, but including Industry, Government, and local government as well) would need historical insight as was done in the CAIB report [71]. Also needing to be taken into account are national factors influencing the culture for safety.

References

1. Taleb NN (2008) The black swan: The impact of the highly improbable. Penguin, London
2. Investigation Committee on the Accident at the Fukushima Nuclear Power Stations (ICANPS) (July 2012) Investigation report. Cabinet Secretariat, Japanese Government, Tokyo. Available at: http://www.cas.go.jp/jp/seisaku/icanps/eng/. Accessed 19 July 2014
3. Fukushima Nuclear Accident Independent Investigation Commission (NAIIC) (July 2012) Report. National Diet of Japan, Tokyo Available at: http://warp.da.ndl.go.jp/info:ndljp/pid/3856371/naiic.go.jp/en/. Accessed 19 July 2014
4. Tokyo Electric Power Company (20 June 2012) Fukushima nuclear accidents investigation report. TEPCO, Tokyo. Available at: http://www.tepco.co.jp/en/nu/fukushima-np/interim/index-e.html. Accessed 19 July 2014
5. The Nuclear Reform Special Task Force (29 Mar 2013) Reassessment of the Fukushima nuclear accident and outline of nuclear safety reform plan. Tokyo Electric Power Company, Tokyo
6. Independent Investigation Commission on the Fukushima Nuclear Accident (Feb 2012) Chōsa kenshō hōkokusho. Rebuild Japan Initiative Foundation, Tokyo. ISBN-10: 4799311581. English edition: (February 22, 2014) The Fukushima Daiichi nuclear power

station disaster: Investigating the myth and reality [Paperback]. Routledge, London. ISBN-10: 041571396X

7. International Atomic Energy Agency (May-June, 2011) IAEA mission report, IAEA international fact finding expert mission of the Fukushima Dai-ichi NPP accident following the Great East Japan Earthquake and Tsunami. IAEA, Vienna
8. Nuclear Energy Agency, The Organization for Economic Co-operation and Development (OECD/NEA) (Sep 2013) The Fukushima Daiichi nuclear power plant accident: Response and lessons learnt. OECD/NEA, Paris
9. Institute of Nuclear Power Operations (INPO) (Aug 2012) Lessons learned from the nuclear accident at the Fukushima Daiichi nuclear power station. INPO 11-005 Addendum. INPO, Atlanta
10. American Nuclear Society (Mar 2012) Fukushima Daiichi: ANS Committee report. Available at: http://fukushima.ans.org/report/Fukushima_report.pdf. Accessed 19 July 2014
11. Electric Power Research Institute (EPRI) (Mar 2012) Fukushima Daiichi accident – Technical causal factor analysis. EPRI, Palo Alto
12. Gauntt R, Kalinich D, Cardoni J, Phillips J, Goldmann A, Pickering S, Francis M, Robb K, Ott L, Wang D, Smith C, St.Germain S, Schwieder D, Phelan C (Aug 2012) Fukushima Daiichi accident study: Status as of April 2012. Sandia National Laboratories, SAND 2012–6173. Available at: http://energy.sandia.gov/wp/wp-content/gallery/uploads/Fukushima_SAND2012-6173.pdf. Accessed 19 July 2014
13. Mohrbach L (2011) The defense-in-depth safety concept: Comparison between Fukushima Daiichi units and German nuclear power units. ATW– International Journal for Nuclear Power 56(4/5): 3-10
14. Swiss Federal Nuclear Safety Inspectorate ENSI (July 2012) ENSI Report on Fukushima I: Chronology ENSI-AN-7999, II: Analysis (People and Organisation) ENSI-AN-8000, III: Lessons Learned ENSI-AN-8001. ENSI, Brugg
15. Nuclear Safety Commission of Japan (1970) Guide for licensing review of safety design of LWR, last amended in Aug 1990. Nuclear Safety Commission, Japanese Government, Tokyo (Japanese). Available at: http://www.nsr.go.jp/archive/nsc/shinsashishin/anzen.htm. Accessed 19 July 2014
16. Headquarters for Earthquake Research Promotion (HERP) (Mar 2009) The Meiji Sanriku Earthquake (June 15, 1896, M 8 1/2) and Sanriku Earthquake (March 3, 1933, M 8.1). Available at: http://www.hp1039.jishin.go.jp/eqchreng/eqchrfrm.htm. Accessed 19 July 2014
17. Tsunami Evaluation Subcommittee and the Nuclear Civil Engineering Committee, Japan Society of Civil Engineers (JSCE) (Feb 2002) Tsunami assessment method for nuclear power plants in Japan. JSCE, Tokyo. Available at: http://www.jsce.or.jp/committee/ceofnp/Tsunami/eng/JSCE_Tsunami_060519.pdf. Accessed 19 July 2014
18. International Atomic Energy Agency (2011) Meteorological and hydrological hazards in site evaluation for nuclear installations. IAEA, Vienna. Special Safety Guide No. SSG-18
19. Headquarters for Earthquake Research Promotion (HERP) (July 2002) Long-term projection of earthquake from off-Sanriku to the Bousou peninsula. HERP, Tokyo
20. Sakai T, Takeda T, Soraoka H, Yanagisawa K (2006) Development of a probabilistic tsunami hazard analysis. In: Proceedings of ICONE14 international conference on nuclear engineering, Miami, Florida, 17-20 July 2006
21. Minoura K, Imamura F, Sugawara D, Kono Y, Iwashita T (2001) The 869 Jōgan tsunami deposit and recurrence interval of large-scale tsunami on the Pacific coast of northeast Japan. Journal of Natural Disaster Science 23(2): 83-88
22. Annaka T, Satake K, Sakakiyama T, Yanagisawa K, Shuto N (2007) Logic-tree approach for probabilistic tsunami hazard analysis and its applications to the Japanese coasts. Pure Appl. Geophys 164: 577–592
23. Nuclear Safety Commission of Japan (May 1978) Regulatory guide for reviewing seismic design of nuclear power reactor facilities, revision in Sep 2006. NSCRG: L-DS-I.02. Available at: http://www.nsr.go.jp/archive/nsc/NSCenglish/guides/lwr/L-DS-I_02.pdf. Accessed 19 July 2014

24. Matsuzawa T (2012) The reasons why we failed to anticipate M9 earthquakes in northern Japan. In: Proceedings of the international symposium on engineering lessons learned from the 2011 Great East Japan Earthquake, Tokyo, Japan, March 1-4, 2012
25. International Atomic Energy Agency (2010) Seismic hazard in site evaluation for nuclear power plants. IAEA, Vienna. Special Safety Guide No. SSG-9
26. Uyeda S, Kanamori H (1979) Back-arc opening and the mode of subduction. Journal of Geophysical Research 84(B3): 1049-1061
27. Ruff L, Kanamori H (1980) Seismicity and the subduction process. Physics of the Earth and Planetary Interiors 23: 240-252
28. McCaffery R (2008) Global frequency of magnitude 9 earthquake. Geological Society of America 36: 263-266
29. Stein S, Geller RJ, Liu M (2012) Why earthquake hazard maps often fail and what to do about it. Tectonophysics 562–563: 1–25
30. Nuclear Regulatory Authority of Japan (June 2013) Guide for design against tsunami (in Japanese)
31. Select Strategy (2002) Improving performance by breaking down organizational silos – Understanding organizational barriers. Available at: http://selectstrategy.com/download/Breaking%20down%20organizational%20barriers.pdf. Accessed 19 July 2014
32. Ward J (2011) Influencing leadership and culture for safety. In: Australian Radiation Protection and Nuclear Safety Agency (ARPANSA) License Holder Forum 2011
33. Hanssens O (ed) (2012) SAFETY Status & signals 2011-2012. Petroleum Safety Authority, Norway. Available at: http://www.psa.no/getfile.php/PDF/SSS%202012/Safety%20-%20Status%20and%20sSignals2012__Eng.pdf. Accessed 19 July 2014
34. Common Issues Committee, Nuclear Safety Commission of Japan (28 May 1992) Accident management measures to cope with severe accidents in LWRs
35. Nuclear Safety Commission of Japan (28 May 1992) Decision on the matter of severe accident management for LWR
36. US Nuclear Regulatory Commission (1 Sep 1989) Installation of a hardened wetwell vent. Generic Letter 89-16
37. Nuclear Regulatory Authority of Japan (8 July 2013) Enforcement of the new regulatory requirements for commercial nuclear power reactors
38. Silde A, Redlinger R (Jan 2001) Three-dimensional simulation of hydrogen detonations in the Olkiluoto BWR reactor building. Nordisk kernesikkerhedsforskning (Nordic nuclear safety research) NKS-27. ISBN 87-7893-078-2
39. Omoto A (2013) What happened in Japan and why? Presented at IVA seminar: Nuclear safety culture in perspective of Fukushima, Stockholm, 29 Nov 2013
40. International Atomic Energy Agency (Aug 2007) Preliminary findings and lessons learned from the 16 July 2007 earthquake at Kashiwazaki-Kariwa NPP. Vols 1 and 2. IAEA, Vienna
41. Tokyo Electric Power Company (17 Sep 2002) Press release. Available at: http://www.tepco.co.jp/en/press/corp-com/release/betu02_e/images/0917e2.pdf. Accessed 19 July 2014
42. Omoto A (2011) Safety and security issues in light of the accident at TEPCO's Fukushima Daiichi NPP. Paper presented at International Conference GLOBAL 2011, Toward and over the Fukushima Daiichi accident, Makuhari, Japan, December 11-16, 2011
43. Bowman EE (28 Apr 2011) Extensive damage mitigating guide (B.5.b). US Nuclear Regulatory Commission, Washington DC
44. U. S. Nuclear Regulatory Commission (25 Feb 2002) Order for interim safeguard and security compensatory measures. EA-02-026. U. S. NRC, Washington DC. Available at: http://www.nrc.gov/reading-rm/doc-collections/enforcement/security/2002/security-order-2-25-02.pdf. Accessed 19 July 2014
45. Asahi Shimbun (Aug 2013) Purometeusu no wana (Prometheus Trap). vol. 5. Asahi Shimbun, Tokyo (Japanese)
46. Atomic Energy Society of Japan (Sep 2013) Fukushima accident investigation report. AESJ, Tokyo (Japanese)

47. International Nuclear Safety Advisory Group (Dec 2003) Maintaining the design integrity of nuclear installations throughout their operating life. International Atomic Energy Agency, Vienna. INSAG-19
48. French S (2013) The early phase of a radiation accident: Revisiting thinking on evacuation and exclusion zones. In: Proceedings of the 10th international ISCRAM conference, Germany, May 2013
49. Wilson R (Aug 2011) Lessons from history of radiation use and nuclear accidents particularly Fukushima. http://users.physics.harvard.edu/~wilson/2011_Fukushima_pictures_inserted.html
50. United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) (2014) Sources, effects and risks of ionizing radiation, UNSCEAR 2013 report to the general assembly. United Nations, New York
51. Association of Municipalities Having NPPs (Mar 2011) Report on implementation of emergency plan. Reported in the 19th meeting of Atomic Energy Commission of Japan. Available at: http://www.aec.go.jp/jicst/NC/iinkai/teirei/siryo2012/siryo19/siryo1-1.pdf. Accessed 19 July 2014
52. Japan Health Physics Society (2014) Issues identified at Fukushima Daiichi accident and recommendations on protection against radiation, draft 4.2. Available at: http://www.jhps.or.jp/jhp/wp-content/uploads/2014/02/f2_draft4.2s.pdf. Accessed 19 July 2014
53. International Atomic Energy Agency (2002) Preparedness and response for a nuclear and radiological emergency. IAEA, Vienna. GS-R-2
54. International Atomic Energy Agency (Dec 2007) Integrated regulatory review service to Japan. IAEA, Vienna. NSNI-IRRS-2007/01
55. Hollnagel E (2012) Resilience engineering. Presented at IAEA FORATOM 11th Management System Workshop on promoting a sustainable management system – key factors for success, Vienna, 12 – 14 June 2012
56. International Energy Agency, The Organization for Economic Co-operation and Development (OECD/IEA) (May 2013) Golden rules in the golden age of gas: World energy outlook special report on unconventional gas. OECD/IEA, Paris
57. Japanese Government (Jun 2011) Report to the IAEA ministerial conference on nuclear safety
58. Packer C (2013) Culture, leadership and management. Presented at IVA seminar: Nuclear safety culture in perspective of Fukushima, Stockholm, 29 Nov 2013
59. President's Commission on The Accident At Three Mile Island (Nov 1979) The need for change: the legacy of TMI. Government Printing Office, Washington DC
60. Institute of Nuclear Power Operations (INPO) (Aug 2005) Guidelines for performance improvement at nuclear power stations. INPO 05-005. INPO, Atlanta
61. Sakuda H, Takeuchi M (2013) Safety-critical human factors issues driven from analysis of the TEPCO Fukushima Daiichi accident investigation report. INSS Journal 20(R-1): 267-276
62. Hofstede GH, Hofstede GJ, Minkov M (2005) Cultures and organizations: Software of the mind, Revised and Expanded 2nd edn. McGraw-Hill
63. Nisbett R (2004) The geography of thoughts: How Asians and Westerns think differently… and why? Free Press, New York
64. Institute of Nuclear Power Operations (INPO) (Nov 2011) Special report on the nuclear accident at the Fukushima Daiichi nuclear power station. INPO 11-005. INPO, Atlanta
65. Omoto A (2013) Post-Fukushima transformations in Japan's nuclear regulatory, management and cultural attitudes. Presented at 8th nuclear plants current issues symposium: Challenges & opportunities, Orlando, Florida, 23-25 Jan 2013
66. Omoto A (2014) Cultural attitude issues in relations to the Fukushima accident. Presented at IAEA workshop on global safety culture – National factors relevant to safety culture, Vienna, 8-11 Mar 2014
67. Klein D (2011) In the wake of Fukushima. The Ripon Forum 45(3). Available at http://www.riponsociety.org/forum113dk.htm. Accessed 19 July 2014

68. U. S. Nuclear Regulatory Commission (Apr 2000) Review of the Tokai-mura criticality accident. U. S. NRC, Washington DC
69. International Atomic Energy Agency (Apr 2009) Lessons learned from the JCO nuclear criticality accident in Japan in 1999. IAEA, Vienna
70. Ethics Commission for a Safe Energy Supply (May 2011) Germany's energy transition: A collective endeavor for the future. Available at http://www.ecojesuit.com/wp-content/uploads/2011/06/The_Phase_Out_of_Nuclear_Energy_is_Ethically_Demanded.pdf. Accessed 19 July 2014
71. Colombia Accident Investigation Board (CAIB) (Aug 2003) Report, Chapter 7. National Aeronautics and Space Administration and the Government Printing Office, Washington, D.C

Chapter 9
Ethics, Risk and Safety Culture

Reflections on Fukushima and Beyond

William E. Kastenberg

Abstract This chapter discuses the relationship between safety culture and societal culture within the context of ethics and risk, and how this relationship may have influenced the accident at Fukushima. Following a brief historical perspective on culture and technology, the context espoused by the International Atomic Energy Agency and the United States Nuclear Regulatory Commission regarding safety culture is summarized, as they pertain to the accident at Fukushima. Based on some reflections regarding the accident at Fukushima, the chapter then argues that when safety culture, which is explicit and is "designed" to fulfill a task in present time, and societal culture, which is implicit and evolves "organically" over millennia are incongruent with each other, the latter can undermine the former, thus highlighting the difficulty in bringing the nuclear safety culture of Japan up to international standards. This chapter concludes that a cultural risk assessment be carried out to help overcome this difficulty in the future.

Keywords Culture · Safety · Ethics · Risk · Fukushima

9.1 Preamble

On March 11, 2011 I was in Mexico sitting on a veranda overlooking the beautiful blue Pacific Ocean when I received an e-mail from my son asking me whether or not there would be a core-melt accident following the earthquake in Japan.

The views expressed in this paper are entirely my own and do not reflect the views of any organization that I am associated with.

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My gut reaction was that the Japanese "probably had it handled" given their history of large earthquakes and experience with seismic design. Several hours later I received another e-mail from a former graduate student who came from Japan to study nuclear engineering at Berkeley. The e-mail read in part, "Everything you taught us about core melt accidents in your class is happening in Japan," and even more alarming, "Why aren't they telling us the truth; my friends and I know what is happening and it is worse they say?"

I scrambled to get CNN and was at once shocked and appalled. Shocked because it felt like everything I had been researching and lecturing on regarding reactor safety was no longer an abstract concept and appalled about what I was hearing from "the experts", mostly colleagues from universities around the country. I began to ask myself, "What happened to the lessons of NUREG 1150[1] where this same station blackout (SBO) scenario was quantified and determined to be the dominant contributor to risk, as well as detail what steps were needed to prevent or mitigate such an accident in the future?" And from my colleagues, I could feel a state of hubris… a patriarchal know-it-all attitude of defensiveness: "It can't happen here…." even before they actually knew what happened there! This was painful for me.

In the aftermath of the accident, the focus has been mostly on the machine and how to support the machine with other machines…. better protection from severe external events, strengthening back-up power supplies (from diesel generators to longer battery life), strengthening the regulations and controlling hydrogen, among others. But what about the people involved? When Professor Ahn asked me to give a lecture at this summer school, and I began to look more closely at what happened, I decided to focus more on the people than on the machine. I began my lecture by saying, "Most of the other lecturers will be talking about the machine, so I am going to do something very different, I am going to talk about the people… and this means you! And some of you may get angry and argue with me, and say that I don't know what I am talking about, and some of you may be astounded and say, wow, why didn't I think of that, or yes, this feels right and want to know more. In either case, I will consider the talk a success!" And so to you, the reader of this chapter… whether you agree or disagree, my goal is to make you think beyond the machine… to think about the people involved… and what all this means for the future of nuclear energy. I hope this paper is a first step at making the implicit assumptions, values and beliefs we hold regarding the nuclear endeavor explicit… and we begin to recognize this was as much a people accident as a machine accident.

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[1] I was Chairman of the Peer Review Committee for the Draft of NUREG-1150 and a member of the Peer Review Committee for the final draft and so I am familiar with this accident for BWR-4, Mark-1 containments such as those at Fukushima Units 1–4.

9.2 Introduction

The disastrous events that took place at the Fukushima-Daiichi Nuclear Power Station beginning on March 11, 2011 have raised questions about Japan's ability to both assess and manage the risks of core-damage accidents and radiological releases at nuclear power plants, especially when initiated by severe natural phenomena. Moreover, the accident has raised serious doubts about whether those in authority had adequate emergency plans and were prepared to manage such an accident while it was in progress. An article in the New York Times [1] raised serious ethical issues regarding the massive public relations campaign in Japan that resulted in, "the widespread adoption of the belief—called the 'safety myth'—that Japan's nuclear power plants were absolutely safe." The nuclear establishment's embrace of this "safety myth" apparently led to a state of hubris both in its regard for safety and risk, as well as it's duties and obligations to the public in the days following the accident. Taken together, these questions and doubts, and this state of hubris have undermined public confidence in nuclear power as witnessed by the unprecedented and growing anti-nuclear sentiment in Japan, and perhaps worldwide.

In this chapter, I will explore the role of cultural conditioning with respect to ethics, risk and safety culture (see for example [2]),[2] an aspect of risk analysis that has received little or no attention in the past. I believe that cultural conditioning has implications for understanding what happened at the Fukushima Daiichi Nuclear Power Station and that such an understanding might help prevent the next Fukushima Daiichi from happening. Moreover, I will argue that when cultural conditioning, which underlies[3] a society's values, assumptions and beliefs, is inapposite to safety culture, the former will undermine the latter.[4]

This chapter revolves around the following three inter-related questions:

1. What would it take to improve the quality of risk analysis and emergency planning so that this terrible accident and the subsequent loss of public confidence can be avoided in the future?
2. Can a risk analysis paradigm be developed that incorporates the cultural conditioning of people and organizations responsible for nuclear energy?
3. Can a global safety culture be developed while still preserving the societal culture of host nations?

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[2] I will also elaborate on the concept of safety culture later in this chapter.

[3] By underlie, I mean they are implicit and so lie at the unconscious or subconscious.

[4] Other aspects of human behavior, such as those related to family of origin psychological dynamics are inextricably linked to cultural conditioning, and as important as they are, are unfortunately beyond the scope of this paper.

9.3 Preliminaries

Risk can be defined as: (a) the possibility of loss or injury, (b) a dangerous element or factor or (c) the chance or likelihood of loss. These definitions connote both a negative event or state as in loss, injury or danger (hazard or consequence), and a possibility or likelihood (probability or frequency) of that negative event or state occurring. In contrast, safe or safety can be defined as: free from harm or risk, secure from threat of danger, harm or loss, affording safety from danger. Being safe has an absolute quality to it, one is either safe or not. On the other hand, there is a spectrum of risk depending on the severity of the consequences, as well as its degree of probability.

Paul Slovic and his colleagues argue that [3]:

> Risk in the modern world is confronted and dealt with in three fundamental ways. *Risk as feelings* refers to our fast, instinctive and intuitive reactions to danger. *Risk as analysis* brings logic, reason, and scientific deliberation to bear on hazard management. When our ancient instincts and our modern scientific analysis clash, we become painfully aware of a third reality—*risk as politics*.

Risk as feelings is an aspect of risk that gives rise to the subject of risk perception, while *Risk as analysis* gives rise to the subject of risk assessment and management. To those who study risk perception, emotion and affect (good or bad feelings towards an external stimulus) are essential ingredients in risk management. To those who are expert in risk assessment and management, risk as feelings is "irrational," violating the "rational" or normative rules of decision theory (for example, cost/benefit analysis). The same arguments take place regarding ethics and technological risk [4]. The rationalist believes that ethics is objective, and hence emotions have to be eliminated from moral reasoning. The subjectivist believes that ethics is based on emotions (subjective), and so believes there cannot be objective moral truths. When the emotional and the cognitive aspects of consciousness are held separately, psychologists call these two views "dual process" theory [5]. *Moral Emotions* is a term that is being used in an attempt to give equal weight to these two human processes [6].

Risk as analysis is a means of addressing the following questions:

1. What are the risks imposed by technology and natural phenomena on society and the environment?
2. Are these risks acceptable?
3. What are the options for reducing these risks?
4. On what basis should we choose among these options?

Risk assessment is concerned with Question #1 and risk management is concerned with Questions #2–4. Risk assessment focuses on the *factual*—a quantification of the "undesirable consequences" of technology and severe natural phenomena. In doing so, it treats technology like a machine. For the purposes of this chapter, it is important to recognize that risk assessment does not model the individuals or organizations that are responsible for designing, constructing, operating or regulating these machines.[5] Nor does risk assessment consider the individual or individuals that perform the analysis in the first place.[6] When risk assessment does consider individuals (mainly control room personnel) it quantifies "human error" and as such, human error rates become failure rates, in essence, treating people (the operators) just like the machines or parts of a machine.

Risk Management originates at the intersection of the *factual* and the *axiological*—the study of the nature, types, and criteria of values (good or bad; right or wrong), of ethical codes (principles or standards that express the values) and of moral acts (behaviors of people that play out in real time). The question of acceptable risk straddles the domains of risk as analysis and risk as feelings, and is at the crux of risk as politics. Moreover, risk management, similar to risk assessment, only deals with the machines; it does not deal with the individuals and organizations that are responsible for the machines. Organizational factors are usually considered separately, if at all. And last, but not least, risk as analysis does not consider that humans are emotional, mental, physical and spiritual beings, and not machines.

The current culture of risk analysis in the West derives from *Utilitarianism*; the ethical theory based on the philosophy of Jeremy Bentham and John Stuart Mill. Utilitarianism's underlying principle is to achieve *the greatest good for the greatest number.* Indeed, risk, which is traditionally defined as the "expected value of an undesirable consequence," and economic determinism as manifest in risk/cost/benefit analysis, are direct descendants of *Utilitarianism*. The greatest good is usually measured in monetary terms and is interpreted as "…and at the least cost." This leads to what the Philosopher, Charles Taylor calls the primacy of "instrumental reason", the "kind of rationality we draw on when we calculate the most economical application of a means to a given end [7]." Taylor goes on to say that instrumental reason in terms of cost-benefit analysis uses efficiency as the measure of success, narrowing our choices, and excluding decisions we might make on other (moral) grounds.

Risk analysis can best be understood by a decomposition in terms of initiating events; systems, structures and component fault trees; event trees: containment release categories, environmental and compartmental fate and transport models; dose-response models, and incremental costs and benefits, all indicative of this linear reductionist approach. All accident sequences are assumed to be independent of one another, and the results are deterministic in that there is a "causal" relationship between each input and output.[7] Risk assessment, therefore, is reduced to a search for "causal links" or "causal chains" verified by "objective" experimental

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[5] The field of "human factors" attempts to design systems with humans in mind, however, this is treated independent of risk analysis.

[6] The individual or individuals performing the analysis have a choice regarding the data, models and phenomena that are included and/or used in the analysis.

[7] An exception is the so-called "common mode" failure due to, for example, an earthquake (and tsunami) or manufacturer's defect. But even here, the basic fault and event tree structure is maintained, and the failure probabilities are modified accordingly.

processes, i.e. by quantifying the behavior of various elements of the system (e.g. pumps, valves, etc.) in terms of failure rate data, dose-response parameters, etc. The behavior of the system elements is then integrated so as to quantify the behavior of the system as a whole. Hence this linear paradigm gives rise to the current culture of risk-analysis itself.[8]

The discussion above about ethics and risk has to do with "safety culture" in particular, and individual and societal culture in general, subjects that risk as analysis does not speak to. In the next section of this chapter, I will explore the effects of twenty-five hundred years of cultural conditioning in the East (e.g. China, India, Japan and Korea) and in the West (Europe and the United States), and its relationship with the concept of safety culture. I believe such an understanding is required for relating the two cultures.[9] The arguments presented in this chapter are based on the following basic premises:

- First, culture can be defined as the integrated pattern of human behavior that includes thought, speech, action and artifacts on human capacity for learning and transmitting knowledge to succeeding generations.
- Second, culture gives rise to a society's values, assumptions and beliefs. Hence culture is concerned with the act of developing the intellectual and moral facilities, especially by education.
- Third, culture itself, arises out of a context[10] or paradigm[11] that defines an individual's or a society's cultural conditioning. Hence an individual's or a society's values, ethics and morality are contextually or paradigmatically dependent.[12]
- Fourth, for the most part, societal conditioning and the context or paradigm from which it arises is implicit, i.e. cultural conditioning resides in the unconscious (emotive) and sub-conscious (mental).[13] The conscious aspects of cultural conditioning that are cognitive, resides in the mental.
- Fifth, safety culture is "designed" within the larger societal cultural context that is "developed organically". Hence safety culture is affected by the larger culture, usually in an implicit way, as an overlay to achieve a specific goal.
- Sixth, when the societal culture runs counter to the demands of safety culture, and is left implicit, it can shift from underlying to undermining.

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[8] A more detailed description of risk analysis can be found in Appendix A.

[9] Borrowing the phrase from C.P. Snow, the two cultures I am referring to here are safety culture and societal culture.

[10] By context, I mean the interrelated set of conditions by which something exists or occurs.

[11] The historian of science Thomas Kuhn gave *paradigm* its contemporary meaning when he adopted the word to refer to the set of practices (or premises) that define a scientific discipline at any particular period of time. Here we mean the, "lens through which we see the world."

[12] Contextualism in not Relativism!

[13] I am indebted to Daniel Barron who describes this in his book *No Such Thing as a Negative Emotion.* According to Barron, all human activities are comprised of four elements: motivation (unconscious emotive), intention (sub-conscious and conscious mental), action and outcome.

- Seventh, approaches to quantifying and managing the risk of core-melt accidents before they occur, as well as approaches for emergency preparedness and response should an accident occur, are based on the "safety culture" of the individuals and the organizations/institutions that comprise the nuclear establishment.
- Eighth and last, in order to explore the safety culture of a host nation with respect to nuclear power, it is essential to understand the context or paradigm out of which cultural conditioning, and hence its ethics and technology arise.

9.4 Historical Perspective on Culture and Technology

As I look back over the development of human consciousness in general, and ethics and morality in particular, two great ages or eras stand out. And we, as a society, are embarking on a third.

The first is the period between 800 and 200 BCE dubbed the Axial Age by the philosopher Karl Jaspers [8]. Jaspers argued that during the axial age "the spiritual foundations of humanity were laid simultaneously and independently… And these are the foundations upon which humanity still subsists today". These foundations were laid by individuals within a framework of a changing social environment, and having a profound influence on future philosophy (based in logic and reason) and religion (based in revelation). These Axial Age individuals include Socrates, Plato and Aristotle in the West, the prophets in the Middle East, and Confucius, Lao-Tzu and the Buddha in the East.

As noted by Huston Smith [9], compassion and wisdom are the hallmarks of the Axial Age. Paradigmatically, this Age is pre-egoic, i.e., operating before the rise of individualism and liberal values, and is marked by "collectivism" wherein nomadic peoples came together to form tribes, villages and towns, and the "physical," where technology supported physical labor, from weapons to support hand-to-hand combat to hand tools for agriculture and beasts of burden. When taken in its entirety, the wisdom traditions (i.e. including Judaism, Christianity and Islam) give us the three Virtues in the West: *Humility, Charity and Veracity* and the three Poisons in the East: *Greed, Hatred and Delusion*. Virtues are what we aspire to; poisons are to be avoided. Smith describes the Virtues as follows

- *Humility:* The deeper meaning of humility is to treat your-self fully as one, but not more than one.
- *Charity:* If you treat your self fully as one, you have an obligation to make sure your fellow human beings are treated fully as one.
- *Veracity:* Huston Smith calls it, "seeing the world in its suchness", which means the ability to drop our "subjective" lens and see the word, "as objectively" as possible.

As I argue throughout this chapter, *veracity* presents the biggest challenge of all, because the paradigms that give rise to our cultural conditioning lie at the unconscious and sub-conscious; they are implicit in all of our actions and not always, if ever, made explicit. To make this point clear, consider the fundamental canons of the National Society of Professional Engineers' Code of Ethics.

Engineers, in the fulfillment of their professional duties, shall:

1. Hold paramount the safety, health, and welfare of the public.
2. Perform services only in areas of their competence.
3. Issue public statements only in an objective and truthful manner.
4. Act for each employer or client as faithful agents or trustees.
5. Avoid deceptive acts.
6. Conduct themselves honorably, responsibly, ethically, and lawfully so as to enhance the honor, reputation, and usefulness of the profession.

The first Canon is basically a general statement of *Charity*, the second Canon is a specific statement of *Humility*, Canons three, four and five are specific statements of *Veracity*, and the sixth and final Canon is a combination of all three Virtues. These Canons have been developed over the past 100 years or so, and to the best of my knowledge, their time-honored origin has never been articulated, but carried in the collective unconsciousness of society over the millennia.

The second great era centers on the Enlightenment (eighteenth century Europe) sandwiched between the Age of Reason (seventeenth century Europe) and the Social Movement termed Modernity (ninteenth century Europe and the United States), all of which gave rise to the Industrial Revolution. It began with Descartes and Newton, and it is marked by a paradigmatic shift from the physical to the mental (*cogito ergo sum*), and from the collective to the individual (from the pre-egoic to the egoic). It focuses on a priori universal laws, whether they are natural, physical or moral. It is an age that gave rise to major achievements in moral philosophy and ethical theory; among the more germane to the engineering profession are Right's Ethics (Locke), Duty Ethics (Kant) and Utilitarianism (Bentham and Mill).

The Enlightenment also marks the divergence between Eastern and Western cultural values; the paradigmatic shifts from the collective to the individual and from the physical to the mental did not take place in the East to the extent it took place in the West. I must emphasize that this discussion is not about intelligence. This is about a context that enabled Western Society to replace physical labor with machines that is based on new quantitative analyses and replicated empirical data; i.e. the development of the "scientific method."

This paradigmatic shift is best exemplified by the development of science and technology and how it influenced the Industrial Age. From one perspective, David S. Landes describes in great detail why the Industrial Revolution first occurred in Europe and not elsewhere [10]. To quote Landes:

> To be sure, in Europe as elsewhere, science and technology had their ups and downs, areas of strength and weakness, centers shifting with the accidents of politics and personal genius. But if I had to single out the critical, distinctively European sources of success, I would emphasize three considerations: (1) the growing *autonomy* of intellectual inquiry, (2) the development of unity in disunity in the form of a common implicitly adversarial *method*, that is, the creation of a language of proof, recognized, used, and understood across national and cultural boundaries; and (3) the invention of invention, that is the *routinization* of research and its diffusion.

Regarding autonomy, Landes also describes why, within Europe, the Industrial Revolution took place first in Britain. Here too, quoting Landes:

> Britain, moreover, was not just any nation… Remember that the salient characteristics of such a society is the ability to transform itself and adapt to new things and ways, so that the content of "modern" and "industrial" is always changing. One key area of change: the increasing freedom and security of the people. To this day, ironically, the British term themselves *subjects* of the crown, although they have long—longer than anywhere—been *citizens*.

Although originating within the Greek and Roman Empires, and associated with freedom, it was during the European Enlightenment, that people transitioned from being subjects of a king or queen to being citizens of a city and later, a nation. Such status carried with it rights (such as the ability to participate in the political process) as well as responsibilities (such as military service). Citizenship is the mark of the individual, and the hallmark of the European Renaissance,[14] the very essence of the egoic period.

We might also ask why the Industrial Revolution did not occur in the East, particularly in Japan. Here I refer to both David Landes [11] and Jared Diamond [12]. While each Asian country had it own unique set of circumstances in terms of natural resources, climate, geography, and the socio-political environment, many suffered from what Diamond calls "cultural isolationism" rather than embracing "cultural diffusion," the latter, a necessary ingredient for scientific and technological advancement. Beginning in 1633 and lasting until the Meiji Restoration in 1867–1868, Japan had closed the door to the outside world. In the words of Landes [13]:

> Japan had had enough of discovery and innovation, enough fire and blood. The aim now: freeze the social order, fix relations of social and political hierarchy, prevent disagreement and conflict.

The net result of cultural isolationism during this nearly 250 year period, is what I would call the "not invented here" syndrome. For Japan in particular, the culture of today[15] regarding Fukushima as described by the Chairman of the Independent Commission reporting to the Diet of Japan is also the culture of yesterday:

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[14] The European Renaissance took place between the fourteenth and seventeenth centuries…. A natural precursor to the Age of Enlightenment.

[15] The culture of the Japanese people today is not monolithic and the Chairman's remarks were focused on the root causes of the accident.

"reflexive obedience, reluctance to question authority, devotion to 'sticking with the program', groupism (collectivism) and insularity" [14].[16]

As said, the Industrial Revolution, a product of the Enlightenment, is an age wherein physical labor is replaced by mental analysis resulting in man-made machines that are conceived, built and operated from a (Newtonian-Cartesian) world-view or paradigm based on three premises:

- *Reductionism*: The world can be understood by reducing complicated systems to their parts.
- *Determinism*: The world consists of causal links or chains; or output is proportional to input.
- *Objectivism*: The world obeys universal laws; the results of observations are independent of the observer, which taken together with the first two premises, yield these universal laws of nature.

This world-view has served Western Society well by providing a particular lens through which to view physical reality. It results in a fragmented world with distinct parts or boundaries. Studying these fragments has developed much of the technological world we know today. It is important to stress that in this paradigm, it is assumed that there is good data, the system has a fixed boundary and that second order (nonlinear effects) can be neglected. One has only to look at a complex machine such at an automobile to see that each system, from the engine to the CD player, is researched, designed, developed and manufactured separately—and yet they all fit marvelously together as planned. It is hard to imagine understanding a physical world that is not amenable to such fragmentation. And as long as the roadway is free of ice, the automobile and the driver behave as expected!

These two eras have now taken Society (both East and West) into a third, which is still in the process of being defined. It is sometimes called the Post-Modern or Post-Industrial era. It may have begun with a new understanding of the physical world (quantum mechanics and relativity), the biological world (the double-helix and cloning), the political world (the nuclear weapons race and the space race) or the social-media world (the Internet and the Information Age). It is neither pre-egoic nor egoic, neither physical nor mental; it appears to be trans-egoic and emotional. I will explore this later in the chapter.

It is often said that society's ability to develop new technologies (biotechnology, information technology, nanotechnology and nuclear technology) has far outstripped its ability to deal with their impacts (both intended and unintended consequences). I believe, in part, it is the unconscious grip of the Newtonian/Cartesian enlightenment world view that has the United States paralyzed with respect to high level radioactive waste disposal for example,[17] in

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[16] The English version of the report has been criticized because these statements do not appear in the Japanese version.

[17] The "Not In My Back Yard" or NIMBY attitude is egoic based.

much the same way as the pre-egoic, Axial Age world-view (primarily echoes of Shintoism coupled with elements of Buddhism, Confucianism and Taoism) that have Japan paralyzed with respect to safety culture, in light of the events at Fukushima. I believe that the way to resolve these dilemmas is to make these implicit world-views, explicit.

9.5 Safety Culture, Ethics and Risk

As said above culture is concerned with, (1) The act of developing the intellectual and moral facilities, especially by education, and (2) The integrated pattern of human behavior that includes thought, speech, action and artifacts on man's capacity for learning and transmitting knowledge to succeeding generations.

With respect to safety culture in Japan, Reuters News Service, in a July 4, 2013 article entitled, "Japan says building nuclear safety culture will take a long time," begins with the statement:

> Japan's nuclear regulator said on Thursday that elevating safety culture to international standards will "take a long time", (just) days before new rules come into effect to avoid a repeat of the Fukushima nuclear disaster in March 2011.

The article quotes the new Japanese Nuclear Regulation Authority Chairman as stating:

> The new regulations include extremely stringent requirements that the operators would not be able to endure if they don't change their culture. We will need a long time to change this culture, but day-to-day efforts to meet those tough standards will in the end lead to improvement in the safety culture.

As described below, the difficulty in meeting these international standards cannot be overemphasized. The accidents at the Three Mile Island (1979) and Chernobyl (1986) nuclear power plants brought renewed international focus on the importance of a strong safety culture in the design, construction and operation of nuclear power plants internationally. Indeed, the International Atomic Energy Agency (IAEA) published a report [15] aimed at providing guidance to member states in their efforts to provide a sound safety culture for their (nuclear) organizations. The Forward to this report states:

> The concept of safety culture was first introduced by the International Safety Advisory Group (INSAG-4), formed by the IAEA. In their report [16] they maintained that the establishment of a safety culture within an organization is one of the fundamental management principles necessary for the safe operation of a nuclear facility. The definition recognized that safety culture is both structural and attitudinal in nature and relates to the organization and its style, as well as attitudes, approaches and the commitment of **individuals** (emphasis mine) at all levels in the organization.

The IAEA report goes to considerable length to describe the general concept of culture. Two important points made in the IAEA report are worth noting here. First, the nature of culture is very complex, and second, there is no right or wrong culture. Regarding the first point, culture is deep (not a superficial phenomenon), it is broad (it impacts virtually all aspects of life), and it is stable (it provides meaning and makes life predictable). Hence it is very difficult to change. And with respect to the second point, there is no better or worse culture, except in relation to what a group or organization is trying to do. Said another way, the operators at Fukushima were attempting to manage multiple core-melt accidents at once, but were looking for *collective* solutions from higher authorities when *individual* actions were required. As I will argue throughout this paper, it is this latter point that may have contributed to the accident at Fukushima and it is the former point that will make elevating safety culture to international standards a very difficult and prolonged task in Japan.

As also noted in the IAEA report, the levels of culture go from the very visible (explicit) to the tacit and invisible (implicit). The report describes three levels of culture, Artifacts and Behavior (explicit), Espoused Values (strategies, goals and philosophies—which can be elicited) and Basic Assumptions (unconsciously held and usually tacit). Of particular interest in understanding any culture, are the fundamental beliefs that are so taken for granted that most people in a cultural group subscribe to them, but not in a conscious way, i.e. they are implicit.

As to a more precise and succinct definition of safety culture, the IAEA report cites the U.S. Nuclear Regulatory Commission's Policy Statement on the Conduct of Nuclear Power Plant Operations [2], which defines safety culture as:

> The necessary full attention to safety matters and the **personal dedication and accountability of all individuals** (emphasis mine) engaged in any activity which has a bearing on the safety of nuclear power plants. A strong safety culture is one that has a strong safety-first focus.

The recently published U.S. Nuclear Regulatory Commission, Safety Culture Policy Statement (U.S. NRC 2012) [17] expands the focus to all regulated entities and defines safety culture as follows:

> Nuclear safety culture is the core values and behaviors resulting from a collective commitment by **leaders and individuals** (emphasis mine) to emphasize safety over competing goals to ensure protection of people and the environment.

Both the IAEA and the U.S. NRC emphasize that safety culture rests with individuals and leaders in any organization. The notion of the *individual* as opposed to the *collective* stems from the European Enlightenment, a cultural shift that took place in the eighteenth century: individual rights, individual duties and individual responsibilities that are essential to a strong safety culture, and which may be incongruent with the societal culture of Japan as articulated by the Commission Chairman cited above.

9.6 Uncertainty and Safety Philosophy

Perhaps, former United States Secretary of Defense, Donald Rumsfeld said it best [18]:

> Reports that say something hasn't happened are always interesting to me, as we know, there are known knowns. There are things we know we know. We also know there are known unknowns. That is to say, we know there are some things we do not know. But there are also unknown unknowns, the ones we don't know, we don't know.

Although the popular press and the late-night pundits found much humor in these statements, it is in fact just a "Truth Table" regarding our knowledge about the state of the world: what is knowable about the world and what is not, and our degree of knowledge about each. In terms of the initiating events at Fukushima, earthquakes that originate in Subduction Zones cause large tsunamis, a fact that has been known (a known-known) for some time. On the other hand, the return frequency and magnitude of such events, is a known-unknown; and so a safety philosophy is developed to account for the unknown.

Technically, a safety philosophy can account for two types of uncertainty: aleatory (random variations and chance outcomes in the physical world) and epistemic (lack of knowledge about the physical world) [19]. It is important to distinguish between random variations and chance outcomes, and lack of knowledge. More research can reduce epistemic uncertainty, however, aleatory uncertainty can only be estimated better, but not reduced with more research. In either case, the annual probabilities and the consequences can be expressed as probability distribution functions. The typical approach for evaluating the risk when consequences and probabilities are expressed as distributions in the risk equation shown in Appendix B is the use of Monte Carlo simulation. When these two types of uncertainty are included, the risk itself might also be quantified as a cumulative probability distribution function.

To cope with aleatory and epistemic uncertainty, a safety philosophy was developed from the inception of the nuclear age called *Defense-in-Depth* and is still in effect today. While there is no formal definition of Defense-in-Depth, examples of it are found at the nuclear power plant level, at the structural, system and component (SSC) level, and at the phenomenological level.[18] Moreover, where phenomenological uncertainties exist, safety margins are included leaving a big difference between estimates of capacity and load.

In reality,[19] there is also indeterminacy (e.g. a unique initiating event leading to accident sequences that may take many paths) and a high level of ambiguity (i.e., non-unique, alternative or multiple legitimate interpretations based on identical observation or data assessments). Ambiguity may come from differences in interpreting factual statements about the world or from differences in applying normative rules to evaluate the state of the world. Finally, there is the realm of the unknown-unknown.

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[18] Examples of the Philosophy of Defense-in-Depth can be found in Appendix B.

[19] I mean in real time, e.g. during the course of an actual accident.

9.7 Reflections on Fukushima Daiichi

And what of the unknown-unknown, e.g. how will people (the operators, the authorities and the general public) react when confronted with an accident the scope of Fukushima? A recent National Public Radio interview [20] included the following statements:

> The Japanese decision-making process, of group decision-making and not individual decision-making, might have been a hindrance for dealing with a situation like this… It's hard to know, but the timeframe demands of making decisions like this, that are multi-billion-dollar decisions, would be difficult in the Japanese culture to do as promptly as maybe it would be done here.

And later on:

> One critical decision was whether to pump seawater into the reactors. That would certainly ruin them, but it could also keep them cool and prevent meltdowns. It appears that the engineers on site hesitated for some hours before they went ahead and did that.

And yet another example had to do with containment venting… the operators had to wait several hours while the request for permission to vent went all the way up to the Prime Minister for approval [21]. Much has also been written about the withholding of information regarding radioactive material dispersion and radiation dose data (see for example, [22]), as well as ignoring new geotechnical data regarding the return frequency of large earthquakes and tsunamis (see for example, [23]).

Taken at face value, these news reports lead me to conclude that individual and societal cultural conditioning was at play; and that this cultural conditioning was inapposite to the safety culture required for the conduct of operations at a nuclear power plant undergoing such a severe event. As said, the embodiment of our cultural conditioning resides as much in the unconscious and sub-conscious domain as it does in the conscious domain, i.e. that we are largely unaware of our motivations and oftentimes intentions.

One aspect of cultural conditioning has to do with responsibility and authority. In some cases, decisions can be made in advance and operators carry them out in conformance with plant procedures and severe accident management guidelines. This would be their responsibility. However, when operators are faced with situations beyond the scope of procedures and guidelines, decisions should be made at the level appropriate to the act. That is, operators should be given the authority to make decisions appropriate to the act they need to perform. Today's military model calls for just this (see for example, [24]). On-the-scene commanders at all levels have the ability and responsibility to make decisions when confronted with dynamic environments, as opposed to historical or conventional military operations, where centralized headquarters in the field made almost all decisions. In some cases very low-level personnel can and are expected to make decisions in response to unexpected circumstances, whether to mitigate unexpected risks or to exploit unanticipated opportunities (see for example, [25]).

As discussed above, cultural conditioning in the East is based on 2,500 years of collective, pre-egoic, traditions. Cultural conditioning in the West has its toots in the egoic, stressing individual responsibility and authority. Each underlies the safety culture in the respective domains.

9.8 Where Do We Go from Here?

As stated in the introduction, this chapter has revolved around three questions:

1. What would it take to improve the quality of risk analysis and emergency planning so that this terrible accident and the subsequent loss of public confidence can be avoided in the future?
2. Can a risk analysis paradigm be developed that incorporates the cultural conditioning of people and organizations responsible for nuclear energy?
3. Can a global safety culture be developed while still preserving the societal culture of host nations?

In Appendix C, I describe the Station Blackout scenario as quantified in NUREG 1150 for Unit 2 of the Peach Bottom Nuclear Power Plant, a General Electric boiling water reactor (BWR-4) unit of 1,065 MWe capacity housed in a Mark 1 containment. This report, published in 1991 [26] was an updated version of the same analysis published in 1975 [27]. This nuclear reactor is basically the same as the nuclear reactor systems at Fukushima Daiichi, Units 1–4. The dominant internally and externally initiated accident sequences leading to core-melt for Peach Bottom in NUREG-1150 consists of three station-blackout scenarios, where the timing of two of them matches the sequence of events at Fukushima Daiichi (the spent-fuel pools notwithstanding). And yet, given the robustness of the analysis, the diesel generators at Fukushima Daiichi were not adequately protected from a large tsunami, in spite of warnings to the contrary, as we discussed above.

We might conclude that the *risk as analysis* paradigm described in Appendix B works well when the system under consideration has adequate historical or actuarial data on failure rates, and empirical data on public health and environmental impact. Moreover, the system must be fairly well defined, has (assumed) fixed or rigid boundaries and where second order or nonlinear effects are (assumed) small. In terms of a nuclear power plant, as long as the plant functions within its design basis, or accidents occur within its design basis envelope, we might call this “safe”.

Because challenges to public health and safety resulting from beyond design-basis events violate these assumptions, I believe a new paradigm for risk and ethical decision-making is required. And this brings me to the complex domain. Hence it is useful to describe here some of the basic differences between the science and technology of the Industrial and Post-Industrial Ages. The key distinction we draw is between systems that are “complicated” and systems that are “complex”.

The paradigm within which Industrial Age technologies are understood is based on an Enlightenment worldview. As said, this worldview is atomistic (reductionism), deterministic (cause and effect) and objectivistic (universal laws). In other words, the laws governing the behavior of these **complicated** systems can be:

- Understood by studying the behavior of their component parts,
- Deduced from cause and effect (a search for causal links or chains), and
- Determined independent of the observer, that is, only deduced from "objective" empirical observations.

The context within which our Post-Industrial Age Technologies and their underlying science are understood is based on a nonlinear worldview. This worldview gives rise to **complex** systems that are characterized by **at least** one of the following [28]:

- *Holistic/emergent*—the system has properties that are exhibited only by the whole and hence cannot be described in terms of its parts,
- *Chaotic*—small changes in input often lead to large changes in output and/or there may be many possible outputs for a given input, and
- *Subjective*—some aspects of the system may only be described subjectively.

It is often said that for complex systems, "the whole is greater than the sum of its parts". What this means is that there is an *emergent quality* (sometimes called an emergent property) that is not exhibited by the parts alone. Examples include electric power transmission grids, the disposal of high-level radioactive waste, and the response of social systems to severe natural phenomena. I believe that the new issues regarding national and international security also fall into this category. In each case, the system is simultaneously a whole and a part of a larger whole, a characteristic of complex systems.

It should be made crystal clear that the impacts of human activities on both society and the environment (from the development of the steam engine to the development of the jet engine) have always been complex. In the past, however, the only undesirable consequences of an Industrial Age technology, such as a nuclear power plant, that were considered in a PRA were geographically local (public health effects out to one mile or 25 miles) or they were observable in "real" time (a hydrogen explosion). This gave the impression that the current risk paradigm is accurate because locality and observability were two characteristics of the impact. This lens is changing, and yet our practices are still based on the same paradigm. That is, a nuclear power plant accident has "global" impacts (an accident at one plant affects the operation of all plants) and manifests very quickly (e.g. loss of public confidence worldwide). In the case of disposal of radioactive waste, the undesirable consequences are almost imperceptible (e.g. the migration of high-level radioactive waste takes place over geological timescales or millennia). Moreover, these impacts may be temporally persistent and/or irreversible (e.g. the degradation of public welfare due to nuclear proliferation).

Thus, as a result of the complexity inherent in Post-Industrial Age Technology, societal and environmental impacts are no longer geographically local, nor perceptible in real time, nor reversible. Rather, complexity can produce impacts that are geographically global (a malicious human act), imperceptible in time either manifesting very quickly (on the Internet) or very slowly (high level radioactive waste disposal), or irreversible (release of radioactivity due to a core-melt accident). We are like the driver of a modern automobile, cruising along on the Interstate (in a linear world), and now suddenly, we are faced with "black ice"!

The impacts we have described above lead to unprecedented ethical issues as reflected in the three questions above. Moreover, questions such as: "What constitutes an acceptable risk and why?" take on new meaning in the face of challenges to the ecology of life. There is a growing belief, as noted by Donald Rumsfeld's quote above, that not only is the future unknown, it is unknowable. Moreover, because these complex ethical issues are arising so much faster than ever before, and because there has been little time to develop normative processes for decision-making, there is even greater ambiguity. The unknown-unknown looms large in the domain of *Risk as feelings*.

What we are pointing to, for lack of a better description, is a *Cultural Risk Analysis*. This would entail making explicit the implicit cultural conditioning of individuals, and organizations/institutions, and their relationship to the society in which they abide. Such a Cultural Risk Analysis would illuminate cases where the underlying societal culture runs counter to the demands of safety culture, such as for nuclear power. If aspects of the societal culture are left implicit, they just don't underlie the safety culture, they will undermine it. If made explicit, it becomes possible for the safety culture to be designed and constructed in a way that accounts for, accommodates or even overcomes the conflicts between the two cultures.

Such a Cultural Risk Analysis would then require an analysis of cultural conditioning, much the same way we analyze the machine. This would mean understanding how underlying assumptions, values, and beliefs come from culturally defined sources and not "objective facts".[20] However, there is one major difference; people are "complex" emotional, mental, physical and spiritual human beings. Humans are not "complicated" machines and so are not amenable to a linear reductionist approach.

Human beings have emergent properties, namely feelings and thoughts that do not reside in any one part of the body. Humans may respond differently to the same stimulus on any given day. And there are no "closed form" analytical solutions to describe human behavior; it is, for the most part subjective. Coincidentally with the development of these new complex technologies, there has been growing empirical evidence that in the realm of human decision-making, the emotional precedes the cognitive [29], and that motivation and intention derive from the unconscious–emotive and subconscious-mental [30]. These findings have found their way into such fields as Behavioral Economics [31] and Risk Perception [32], among others (An extensive literature review can be found in [33]). And a number of consulting companies have developed analytical methods in an attempt to quantify the "Risk Culture" of Business Organizations. In this case, the focus is on comparing the "self-interest" of the individual employees versus the corporate interest.

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[20] By "objective facts", I mean empirical observation and data. Evolution and Global warming are two areas where cultural conditioning and scientific observations and data are in conflict.

Developing a framework for a Cultural Risk Analysis, i.e. to carry out a cultural analysis, requires a paradigmatic shift in human consciousness similar to the one that took place in the Enlightenment. And this will be extremely difficult because it is a shift requiring both the rational (cognition) **and** the emotional (feeling). It will require both risk-as-analysis **and** risk-as-feelings; it will require both moral reasoning **and** emotional morals. As any good engineer knows (at least those who have taken my class), a redundant and diverse system has order of magnitude higher reliability if the system is built of "AND" gates rather than "OR" gates.[21]

Perhaps Thomas Kuhn [34] said it best, "…that is why a law that cannot even be demonstrated to one group of scientists may occasionally seem intuitive to others. Equally, it is why, before they can hope to communicate fully, one group or the other must experience the conversion we have been calling a ***paradigm shift.***" And, "Just because it (***a paradigm shift***) is a transition between incommensurables, the transition between competing paradigms cannot be made a step at a time, forced by logic and neutral experience. Like the gestalt switch, it must occur all at once (though not necessarily in an instant) or not at all."

Appendix A: The Conventional Approach to Risk Assessment

Risk analysis, to date, has been used primarily as a *retrospective* process. It was developed by the U.S. Space Program in the 1950's and 1960's with the advent of Failure Modes and Effects Analysis (FMEA) in an attempt to both understand and correct missile and rocket launch failures. Risk assessment was introduced to the nuclear power establishment with the publication of the Reactor Safety Study (WASH-1400) in 1975, but only after 75 or so nuclear power plants already had been designed, built and operated in the U.S. and reached a level of maturity with the publication of NUREG 1150 in 1990. Risk management only came to prominence after the accident at Three Mile Island-Unit 2 in 1979. More recently, the NRC has developed a regulatory approach called "Risk-Informed Decision Making" that utilizes risk assessment as one input into design and operational changes requested by the nuclear utilities in the US. The NRC believes that the current approach to risk assessment for nuclear power plants is mature enough to warrant its use in decision- making.

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[21] Consider a system, S, with sub-systems A and B. If A **AND** B must fail, the failure rate of S is AB. If A **OR** B must fail, the failure rate of S is A + B. If the failure rate of A is 0.1 and B is 0.1, then AB is 0.01 and A + B is 0.2, rendering the **AND** configuration, an order of magnitude more robust!

In their seminal paper, Kaplan and Garrick [35] lay the foundation for our current risk assessment model by asking three questions: (a) What can go wrong? (b) How likely is it to happen? (c) What are the consequences? The first question is answered by defining an accident sequence beginning with an initiating event, followed by multiple failures (or events) and an "end state." This is commonly called an accident sequence. The answer to the second question is the frequency or annual probability of that sequence occurring. Lastly, the end state defines the consequences and answers the third question. Posing risk in this fashion has led a number of practitioners to quantify risk as a convolution or summation over accident sequences of consequences multiplied by annual probability. This approach results in an operational or instrumental definition of risk as an expected value. Hence one of the common operational definitions of risk is the "expected value of an undesirable consequence" as:

$$Risk = \sum_{i=1}^{n} x_i f_i \tag{9.1}$$

Here, i is the ith sequence, while x_i and f_i are the consequence and annual probability associated with the ith sequence. When actuarial data is available, the annual probability becomes the frequency of the ith sequence. Hence risk may then be expressed as an "average annual probability of consequence" such as mission failure rate, or chronic exposure rate, or core damage frequency, or acute fatality rate.

The quantification of the annual probability for each sequence for engineered systems is determined by the construction of fault and event trees. As shown in Fig. 9.1, the fault tree (upper tree) is basically a logic diagram for a system, sub-system, component or structure in which the "Top" event is the annual probability of failure, given by p_i in the event tree (the lower tree). The branches of the event tree (lower tree) signify success (yes) or failure (no) for each event in the sequence. The symbol $\mathbf{E_1}$ stands for the initiating event and the symbol $\mathbf{F_s}$ stands for the final state. Associated with each final state is a consequence, x_i. If the consequence involves a release of material into the environment (e.g. radioactive material, toxic chemical, etc.) with ensuing health effects or environmental degradation, models for environmental fate and transport, exposure and dose/response are required to determine the consequences for each sequence. This approach to risk assessment is indicative of a linear or reductionist approach, in that all sequences are assumed to be independent of one another, and is deterministic in that there is a "causal" relationship between each input and output.[22]

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[22] An exception is the so-called "common mode" failure due to, for example, an earthquake or manufacturer's defect. But even here, the basic fault and event tree structure is maintained, and the failure probabilities are modified accordingly.

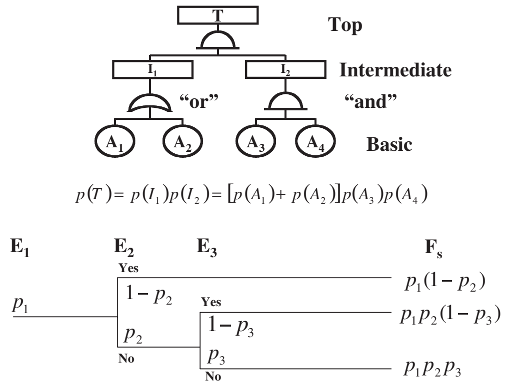

Fig. 9.1 Generic fault tree (*upper*) and event tree (*lower*)

Appendix B: Defense in Depth

Some examples of the concept of Defense in Depth are:

At the nuclear power plant level

- Plants are designed to prevent accidents from occurring (Prevention), are provided with Engineered Safety Features (ESFs) to mitigate the consequences of an accident, should one occur (Mitigation), and have Emergency Plans to evacuate people and interdict food stuffs, should there be a release of radioactive material (Emergency Planning).
- Plants are designed with Multiple Barriers to prevent or mitigate fission product release: the ceramic fuel matrix, the metallic fuel clad, the primary system (vessel and piping) and the containment building.

At the structural, system and component (SSC) level

- Single Failure Criterion: A single failure means an occurrence that results in the loss of capability of a component to perform its intended safety functions. Multiple failures resulting from a single occurrence are considered to be a single failure. Fluid and electric systems are considered to be designed against an assumed single failure if neither (1) a single failure of any active component (assuming passive components function properly) nor (2) a single failure of a passive component (assuming active components function properly), results in a loss of the capability of the system to perform its safety functions [36].
- Redundancy and Diversity: One of the keys to satisfying the single failure criterion. It might mean a power operated valve in series with a check valve, or an electric driven pump in parallel with a steam driven pump.

At the phenomenological level

- Safety Margins: Design with large difference between estimates of capacity and load. Examples include: 10 CFR 50—Appendix K–ECCS Evaluation Criterion; Licensing Basis Accidents; 10 CFR 100 Appendix A—Seismic and Geologic Siting Criteria for Nuclear Power Plants

Appendix C: The Accident Sequence at Fukushima Daiichi

In both WASH-1400 (1975) and NUREG 1150 (1990), a risk assessment was carried out for Unit 2 of the Peach Bottom Nuclear Power Plant, a General Electric boiling water reactor (BWR-4) unit of 1065 MWe capacity housed in a Mark 1 containment. It began commercial operation in July 1974. This is basically the same as the nuclear reactor systems at Fukushima, Units 1–4. The dominant internally and externally (seismic) initiated accident sequences leading to core-melt for Peach Bottom in NUREG-1150 consists of three station-blackout scenarios, where the timing of two of them matches the sequence of events at Fukushima (the spent-fuel pools notwithstanding). They are summarized as follows:

- Loss of onsite and offsite ac power results in the loss of all core cooling systems (except high-pressure coolant injection (HPCI) and reactor core isolation cooling (RCIC), both of which are ac independent in the short term) and all containment heat removal systems. HPCI or RCIC (or both) systems function but ultimately fail at approximately 10 h because of battery depletion or other late failure modes (e.g., loss of room cooling effects). Core damage results in approximately 13 h as a result of coolant boil-off.
- Loss of offsite power occurs followed by a subsequent failure of all onsite ac power. The diesel generators fail to start because of failure of all the vital batteries. Without ac and dc power, all core-cooling systems (including HPCI and RCIC) and all containment heat removal systems fail. Core damage begins in approximately 1 h as a result of coolant boil-off.

Given the vulnerability to station blackout, how is it that the Fukushima Units were not adequately protected against a station blackout, regardless of the severity of the earthquake, and the tsunami following? Part of a "healthy" safety culture, is to go meta to the aggregate of accident sequences, which means that the philosophy of "defense in depth" must be extended to the level of "safety function." Active or passive safety systems or operator actions are required to provide the necessary functions to bring a reactor to "cold-shutdown." Said another way, there are basically four functions needed in case of an accident:

1. Stop the chain reaction or "scramming" the reactor: this means redundant and diverse methods for bringing a critical reactor to a sub-critical state.
2. Insure adequate cooling to remove decay heat: this means providing passive or active, redundant and diverse systems to maintain coolant under a range of accident scenarios and conditions.
3. Insure the integrity of the primary system: this means maintaining a coolant path from the reactor to the "ultimate" heat sink, maintaining primary pressure and
4. Insure an "ultimate" heat sink.

References

1. Onishi N (25 June 2011) “Safety myth” Left Japan ripe for nuclear crisis. New York Times. Available at: http://www.nytimes.com/2011/06/25/world/asia/25myth.html?pagewanted=all&_r=0. Accessed 19 July 2014
2. U.S. Nuclear Regulatory Commission (January 24, 1989) Policy Statement on the Conduct of Nuclear Power Plant Operations. Federal Register notice. Available at: http://www.nrc.gov/about-nrc/regulatory/enforcement/54fr3424.pdf. Accessed 19 July 2014
3. Slovic P, Finucane ML, Peters E, MacGregor DG (2004) Risk as analysis and risk as feelings: Some thoughts about affect, reason, risk and rationality. Risk Analysis 24(2): 311-322
4. Roeser S (2006) The role of emotions in judging the moral acceptability of risks. Safety Science 44:689-700
5. Roeser S (2011) Nuclear energy, risk and emotions. Philosophy of Technology 24:197-201
6. Roeser S (2011) Moral emotions and intuitions. Palgrave Macmillan, Basingstoke. [Online] Available at: http://www.palgraveconnect.com/pc/doifinder/10.1057/9780230302457. Accessed 19 July 2014
7. Taylor C (1997) The ethics of authenticity. Harvard University Press, Cambridge
8. Jaspers K (1953) The origin and goal of history (trans: Bullock M). Yale University Press, New Haven, CT
9. Smith H (1991) The world’s religions. Harper, San Francisco
10. Landes DS (1999) The wealth and poverty of nations: Why some are so rich and some are so poor, Chapters 14 and 15. W.W. Norton & Company, New York
11. Landes DS (1999) The wealth and poverty of nations: Why some are so rich and some are so poor, Chapters 22 and 23. W.W. Norton & Company, New York
12. Diamond J (1997) Guns, germs and steel: The fates of human societies. W. W. Norton & Company, New York. I am particularly influenced by Chapters 12 and 13 and the 2005 Edition that contains a new chapter on Japan.
13. Landes DS (1999) The wealth and poverty of nations, Why some are so rich and some are so poor, Chapters 22 and 23. W.W. Norton & Company, New York, p 356
14. Fukushima Nuclear Accident Independent Investigation Commission (June 2012) Report (in English). National Diet of Japan
15. International Atomic Energy Agency (December 2002) Safety culture in nuclear installations: Guidance for use in the enhancement of safety culture. IAEA, Vienna. IAEA-TECDOC-1329
16. International Nuclear Safety Group (1991) Safety culture. IAEA, Vienna. Safety Series, No. 75-INSAG-4
17. U. S. Nuclear Regulatory Commission (Dec 2012) Safety culture policy statement. NUREG/BR-0500, Rev. 1
18. U. S. Department of Defense (12 Feb 2002) News briefing - Secretary Rumsfeld and Gen. Myers. Available at: http://www.defense.gov/transcripts/transcript.aspx?transcriptid=2636. Accessed 19 July 2014
19. National Research Council (1996) Understanding risk: Informing decisions in a democratic society. Washington, DC, The National Academies Press
20. National Public Radio (5 Jul 2011) What went wrong in Fukushima: The human factor. http://programs.wypr.org/news/what-went-wrong-fukushima-human-factor?quicktabs_1=1. Accessed 19 July 2014
21. Wald ML (19 May 2011) U.S. was warned on vents before failure at Japan’s plant. N.Y. Times. Available at: http://www.nytimes.com/2011/05/19/science/earth/19nuke.html. Accessed 19 July 2014
22. The Oregonian Editorial Board (16 Aug 2011) Editorial: Data so alarming it was ignored. Available at http://www.oregonlive.com/opinion/index.ssf/2011/08/data_so_alarming_it_went_unann.html. Accessed 19 July 2014

23. Onishi N, Glanz J (26 Mar 2011) Japanese rules for nuclear plants relied on old science. New York Times. Available at: http://www.nytimes.com/2011/03/27/world/asia/27nuke.html?pagewanted=all. Accessed 19 July 2014
24. Builder CH (1989) The masks of war: American military styles in strategy and analysis: A RAND Corporation research study. Johns Hopkins University Press, Baltimore
25. Biddle S (2004) Military Power: Explaining Victory and Defeat in Modern Battle. Chap. 3. Princeton University Press, Princeton
26. U.S. Nuclear Regulatory Commission (1991) Severe accident risks: An assessment for five U.S. nuclear power plants. NUREG-1150
27. U.S. Nuclear Regulatory Commission, (1975) The reactor safety study. WASH-1400
28. American Association for the Advancement of Science (2 Apr 1999) Complex systems. Science 284(5411): 1-212
29. Lewis T, Amini F, Lannon R (2001) A general theory of love. Vintage Books, New York
30. Barron DS (Jan 2009) There's no such thing as a negative emotion, rev. Outskirts Press, Denver
31. Gilovich T, Griffin D, Kahneman D (eds) (2002) Heuristics and biases: The psychology of intuitive judgment. Cambridge University Press, New York
32. Slovic P (2010) The feeling of risk. Earthscan, London
33. Lloyd's (Mar 2010) Behaviour: Bear or bull, Lloyd's emerging risk report, Lloyd's, London. Available at: http://www.lloyds.com/~/media/Lloyds/Reports/Emerging%20Risk%20Reports/EmergingRiskreportBehaviour_March2010_v2.pdf. Accessed 19 July 2014
34. Kuhn T (1996) The structure of scientific revolutions, 3rd edn. University of Chicago Press, Chicago
35. Kaplan S, Garrick BJ (1981) On the quantitative definition of risk. Risk Analysis 1(1): 11-27
36. U.S. Nuclear Regulatory Commission (13 Jan 1998) Title 10, Code of Federal Regulations, Part 50, Appendix A. 63 FR 1897. Available at: http://www.nrc.gov/reading-rm/doc-collections/cfr/part050/part050-0001.html. Accessed 19 July 2014

Chapter 10
The "Structural Disaster" of the Science-Technology-Society Interface

From a Comparative Perspective with a Prewar Accident

Miwao Matsumoto

Abstract This chapter attempts to shed fresh light on the structural causes of the Fukushima accident by illuminating the patterns of behavior of the agents involved in a little-known but serious accident that occurred immediately before World War II. Despite the expected incalculable damages caused by the Fukushima Daiichi nuclear power plant accident, critical information was restricted to government insiders. This state of affairs reminds us of the state of prewar Japanese wartime mobilization in which all information was controlled under the name of supreme governmental authority. This paper argues that we can take the comparison more seriously as far as the patterns of behavior of the agents involved are concerned. The key concept that is employed for that argument is the "structural disaster" of the science-technology-society interface, the causes of which can be divided into two different categories, organizational errors and technological trajectory. Through the lens of "structural disaster", the possibility of functional disintegration coupled with structural interdependence and secrecy is drawn for investigation relevant both in wartime and in peacetime. This paper will contextualize the sociological implications of the possibility for all of us who face the post-Fukushima situation based on exploration into the hidden prewar accident with particular focus on a subtle relationship between success and failure.

Keywords Structural disaster · Secrecy · Fukushima · Wartime mobilization · Science-technology-society interface

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10.1 Introduction

The Fukushima Daiichi nuclear power plant accident was extremely shocking, but what is even more shocking in the eyes of the present writer is the devastating failure in transmitting critical information on the accident to the people when the Japanese government faced unexpected and serious events after March 11, 2011. Secrecy toward outsiders seems to have caused this failure: secrecy to the people who were forced to evacuate from their birthplaces, to the people who wanted to evacuate their children, to the people who have been suffering from tremendous opportunity loss such as giving up entering college, and others. It is virtually impossible to enumerate individual instances of suffering and aggregate them in an ordinarily calculable manner. Despite such expected incalculable damage, critical information was restricted to government insiders. This state of affairs seems to show similar tendencies to the state of prewar Japanese mobilization in which all information was controlled under the name of supreme governmental authority [1].

One might consider such a comparison to be merely rhetorical. This chapter argues that we can take the comparison more seriously as far as the patterns of behavior of the agents involved are concerned. It is true that the prewar Japanese military regime was oriented toward mobilization for war while the postwar regime has been prohibited from mobilization for war purposes of any kind by the constitution. In this respect there is a large discrepancy between the prewar and postwar regimes as to their purpose. However, the surprising but telling similarity of the patterns of behavior embedded in the regimes is evident if we look into the details of a hidden accident that took place just before the outbreak of World War II (abbreviated to WWII hereafter).

This chapter attempts to shed fresh light on the structural causes of the Fukushima Daiichi accident by illuminating the patterns of behavior of the agents involved in the little-known but serious accident involving naval vessels that occurred immediately before WWII with a particular focus on the subtle relationship between success and failure in the complex science-technology-society interface. The chapter will then contextualize the similarity and draw its sociological implications for all of us who face the post-Fukushima situation. The conceptual tool that is employed here to that end is the “structural disaster” of the science-technology-society interface.

10.2 The “Structural Disaster” of the Science-Technology-Society Interface

The “structural disaster” of the science-technology-society interface is the concept developed to give a sociological account of the repeated occurrence of failures of a similar type [2]. In particular, it is developed to clarify a situation where novel and undesirable events happen but there is no single agent to blame and no place to allocate responsibility for the events and to prescribe remedies. The reason for denominating this failure as the failure of the science-technology-society interface rather than that of science, or of technology, or of society is worthy of attention to understand the development of my argument. For example, if nuclear physics is completely successful in understanding a chain reaction, technology such as nuclear engineering could fail in controlling the reaction as in the case of Chernobyl.[1] Or if nuclear engineering is almost completely successful in containing radioactive materials within reactors, social decision-making could fail as in the case of Three Mile Island (TMI).[2] Or if society is completely successful in setting goals for the development of renewable energy technologies, science and/or technology could fail as in the case of Ocean Thermal Energy Conversion (OTEC).[3]

In a word, the success or failure of science, of technology, and of society cannot be overlapped automatically [9, 10]. In particular, there seems to be something missing in-between, which has unique characteristics of its own. The concept of "structural disaster" is intended to explore this state. What is in-between could be institutional arrangements, organizational routines, tacit interpretations of a formal code of ethics, invisible customs, or the networks of interests of different organizations. The "structural disaster" consists of one or more of the following elements [11]:

1. Adherence to erroneous precedents causes problems to be carried over and reproduced.
2. The complexity of a system under consideration and the interdependence of its units aggravate problems.
3. The invisible norms of informal groups essentially hollow out formal norms.
4. Quick fixes for problems at hand lead to further such fixes for temporary counter measures.
5. Secrecy develops across different sectors and blurs the locus of agents responsible for the problems to be addressed.

This chapter focuses on, among other things, the interdependence of heterogeneous agents, which come into play in the science-technology-society interface and give rise to secrecy in a specific social condition. This chapter will make clear the interdependence by tracing it back to the hidden prewar accident, which will give us an important clue to the understanding of the Fukushima Daiichi accident from the perspective of "structural disaster" as defined above. To understand the social context of this hidden prewar accident, it is necessary to move away from the current social condition of the post-Fukushima situation to the prewar wartime mobilization of science and technology, within which the clarification of this hidden accident can be properly pursued. After the clarification, we will move back to the current situation surrounding the Fukushima Daiichi accident, to present the sociological implications of the hidden accident for the Fukushima Daiichi accident and for potential future extreme events.

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[1] For a sociological investigation into the relationships between the Chernobyl and Wind scale incident, see [3]. For a different view on the relationships, see [4].

[2] For a pioneering sociological investigation into TMI, see [5]. Also see [6, 7].

[3] On a sociological account of an unanticipated social consequence of OTEC, see [8].

10.3 The Basic Points About the Fukushima Daiichi Accident from the Perspective of "Structural Disaster"

To elucidate the problem of secrecy in the Fukushima Daiichi accident, several basic points can be noted from the perspective of "structural disaster," which should be kept in mind in approaching the hidden accident that happened much earlier than the Fukushima Daiichi accident. First, there seems to have arisen a repeated occurrence of similar patterns of behavior that have run through various different instances and in the end have given rise to secrecy. It is true that the emergency situation during and after such an extreme event as the Fukushima Daiichi accident can provide a good reason to expect confusion and delay in transmitting information. But the degree and range of confusion and delay went far beyond those to be expected from an emergency situation alone.

For example, the System for Prediction of Environmental Emergency Dose Information (abbreviated to SPEEDI hereafter) was developed with the assistance of more than ten billion yen to make the early evacuation of the people affected smoother and safer. The first recommendation from the Japanese government for evacuation was made on March 12. The prediction obtained from SPEEDI was made public for the first time on April 26, despite the fact that its prediction had been made shortly after the accident. As a result of this secrecy, the affected residents were advised by the government to evacuate without reliable information at the critical initial phase when they were exposed to a high level dose. All they could do was to trust the government or not. SPEEDI had been awarded the first nuclear history award by the Atomic Energy Society of Japan in 2009 [12], but its prediction was never made public when it was needed.

A similar behavior pattern of the government and the resulting secrecy and serious suffering can be observed in various other cases in the accident, such as the delayed venting of the nuclear reactors in the Fukushima Daiichi nuclear power station, the deregulation for recycling decontaminated mud for concrete production, and the rise and fall of dose levels allowed for children in primary school and for workers in the station. In light of structural causes implied in the "structural disaster", organizational errors seem to have intervened behind this state of affairs: TEPCO's disobedience of the directive by the prime minister, the malfunction of the so-called "double check" system within Ministry of Economy, Trade and Industry (METI), miscommunication between nuclear engineers of the makers of the reactors and TEPCO officials, and others. If we look into the details of the Fukushima Daiichi accident as embodying "structural disaster," organizational errors of this kind should be scrutinized, elaborated on, and extended as one of the crucial causes of "structural disaster." This is the first point to be noted in approaching the hidden accident that happened much earlier than the Fukushima Daiichi accident and in obtaining a broader perspective.

Second, we need to carefully place the specifications of six nuclear reactors at the Fukushima Daiichi power station in a technological trajectory, within which

Table 10.1 Specifications of the nuclear reactors at the Fukushima Daiichi power station

Reactor unit no.	1	2	3	4	5	6
Type	BWR	BWR	BWR	BWR	BWR	BWR
Container vessel	Mark I	Mark I	Mark I	Mark I	Mark I	Mark II
Output ($\times 10^4$ kW)	46	78.4	78.4	78.4	78.4	110
Makers	GE	GE/Toshiba	Toshiba	Hitachi	Toshiba	GE/Toshiba
Domestics (%)	56	53	91	91	93	63
Year Built	1971	1974	1976	1978	1978	1979

Source [13]

we might be able to properly understand what "structural disaster" implies (see Table 10.1).

There are two reasons for paying attention to the technological trajectory to understand the Fukushima Daiichi accident as "structural disaster." First, every reactor there had a long history of successful operation extending over 30 years since its start in the 1970s, which forces our attention to turn to the possibility of a more "structural" cause of the accident beyond picking up individual ad hoc troubles and errors. Second, as the ratios of domestic production indicate, the reactors at the Fukushima Daiichi power station embody the turning point leading from licensed production to self-reliant production. For these reasons, there could exist common characteristics throughout the reactors in question at the Fukushima Daiichi power station and it is possible that such characteristics are somehow related to the "structural disaster" of the science-technology-society interface as manifested in the accident.

In a word, the causes of "structural disaster" can be divided into two different categories, organizational errors and technological trajectory, as the first step to explaining the Fukushima Daiichi accident.[4] If we can substantiate these two elements in understanding other independent cases as "structural disaster," then we will be able to have a stronger position to learn lessons from the Fukushima Daiichi accident as a "structural disaster" and to extend their implications for potential future extreme events. What follows is an independent substantiation of these two elements by examining the hidden accident happened long before the Fukushima Daiichi accident with a focus on a complex relationship between success and failure in the science-technology-society interface and secrecy in the interface.

The hidden accident long before the Fukushima Daiichi one is a very perplexing accident of the naval turbine developed by the Imperial Japanese Navy, which occurred immediately before the outbreak of WWII. This accident enables us to redefine the complex relationship between success and failure in the science-technology-society interface both in peacetime and wartime. The accident was treated as top secret because of its timing. The suppression of information about the accident means that it has not been seriously considered as an event in the sociology of science and technology up to now. However, the description and

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[4] On organizational errors in the context of technological failures, see [14–17] regarding the Fukushima Daiichi accident. For a pioneering study referring to the dynamic aspect of technological trajectory in the history of technological change, see [18].

analysis of this accident will suggest that technological development can depart significantly from a unidirectional process. This also implies that we need to revise our view of the science-technology-society interface beyond a simplistic dichotomous understanding in terms of success or failure.

The steam turbine was invented, and finally patented in 1884, by British engineer C.A. Parsons, who in 1894 obtained a patent for the marine turbine [19].[5] After Parsons' original invention, it was supposed that the marine turbine had become a reliable, mature technology in the prewar period. The hidden accident of the naval turbine that occurred immediately before WWII, however, throws doubt on the validity of a unidirectional and one-dimensional view of such a development trajectory for technology. To confirm this doubt, it is necessary to outline the development trajectory of the Japanese type naval turbine by making clear the locus of the complex relationship between success and failure.

10.4 The Development Trajectory of the Kanpon Type and Its Pitfalls

The technology taken up here is the Kanpon type turbine, Kanpon being the Technical Headquarters of the Navy. The Kanpon type turbine was developed by the Imperial Japanese Navy about 1920 to substitute entirely self-reliant technologies for imported ones. This naval turbine provides the key to understanding the connection between success and failure. The reason is that the Kanpon type was the standard turbine for Japanese naval vessels from 1920 to 1945, and as regards its blades a serious but almost inexplicable and little-known accident occurred immediately before WWII.[6] The first question to approach the core of the connection between success and failure lies in the background against which the Kanpon type turbine was developed.[7]

From the time of the first adoption of the marine turbine in the early twentieth century (1905) after intensive investigations and license contracts, the Imperial Japanese Navy accumulated experience in the domestic production of marine turbines. Throughout this process, the Navy carefully monitored the quality of British, American, and various other Western type turbines and evaluated them.[8]

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[5] As for the procession of events before 1884, see [20].

[6] Kanpon is the abbreviation of the Kansei Honbu, which means the Technical Headquarters of the Imperial Japanese Navy.

[7] Studies on the innate connection between success and failure of the science-technology-society interface have scarcely been undertaken from the sociological point of view. See [21] for a shortened version of this chapter.

[8] The British type originated in Parsons and the American type in Curtis turbines, respectively. The first demonstration of the Parsons turbine at the Naval Review in 1897 caused a sensation [22]. With respect to the Curtis turbine, see [23]. On detailed descriptions and analyses of these dual strategies of the Navy outlined here, see [24, pp. 54–63]. As for a more general background of the relation between the Navy and private companies, see [24, pp. 74–78].

Table 10.2 Synopsis of geared turbine failures of naval vessels from 1918

Date	Ship name	Ship type	Specification	Turbine type
3 Oct 1918	Tanikaze	Destroyer	Blade fell out	Brown-Curtis
30 Nov 1918	Minekaze	Destroyer	All blades fell out	Brown-Curtis (HP) Parsons (LP)
26 Feb 1919	Sawakaze	Destroyer	Blade sheared and dropped off	Brown-Curtis (HP)
30 Apr 1919	Tenryu	Cruiser	Blade sheared	Brown-Curtis
21 Nov 1919	Tatsuta	Cruiser	Blade smashed	Brown-Curtis
6 Feb 1920	Nire	Destroyer	Blade sheared	Brown-Curtis (HP) Parsons (LP)
Apr 1920	Kawakaze	Destroyer	Blade sheared	Brown-Curtis
28 Sep 1920	Shimakaze	Destroyer	Blade breakage	Brown-Curtis (HP) Parsons (LP)
20 Dec 1920	Kuma	Cruiser	Blade breakage	Gihon
18 Mar 1922	Sumire	Destroyer	Blade damaged	Zölly

Source [25, 26]. The same naval vessels and naval vessels of the same class suffered similar failures and breakdowns many times. These repeat failures and breakdowns are omitted here. The secondary failures and breakdowns caused by the initial ones are also omitted altogether. Gihon in the table is the multiple-flow turbine designed by the predecessor of the Technical Headquarters of the Navy. Geared turbines made possible an increase of one order of magnitude in revolutions per minute, from 100–200 to 1,000–2,000, which might have affected turbines designed for 100–200 rpm.

As a result, a reduction gearing adopted by the Navy for the first time in 1918 contributed greatly to the total efficiency of the main turbines.

However, quite unexpectedly, the introduction of reduction gearing caused one failure after another from 1918 (see Table 10.2).

What was most important to the Navy was the fact that all the geared turbines causing failures and breakdowns were Western types as shown in Table 10.2. And the license contracts with the makers of the two leading turbines, the Curtis and the Parsons types, were due to expire in June 1923 and in August 1928, respectively. Considering the failures and breakdowns in light of this situation, the Navy started to take official steps to develop its own type.[9] For the purpose of replacing imported turbines, the new Kanpon type turbine was developed, and achieved standardization in design, materials, and production method “that is independent of foreign patents” ([26, pp. 133–134]. The Kanpon type turbine was also expected to achieve cost reduction and flexible usage for a wide range of purposes, which would be made possible by standardization.

Thus the Kanpon type turbine was developed and established as the standard turbine for Japanese naval vessels due to the failures and breakdowns of imported

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[9] In February 1921, a turbine conference was organized by the director of the Military Affairs Bureau of the Navy to drastically reconsider the design, production method, materials, and operation method of geared turbines. As a result, the configurations, materials, strength, and installation of turbine blades were all improved. In addition, in August 1922, the Yokosuka arsenal of the Navy undertook an experiment on the critical speed of turbine rotors in accordance with the Military Secret No. 1148 directive in order to determine the normal tolerance of turbine rotors in terms of revolutions per minute. The above descriptions are based on [26, 27].

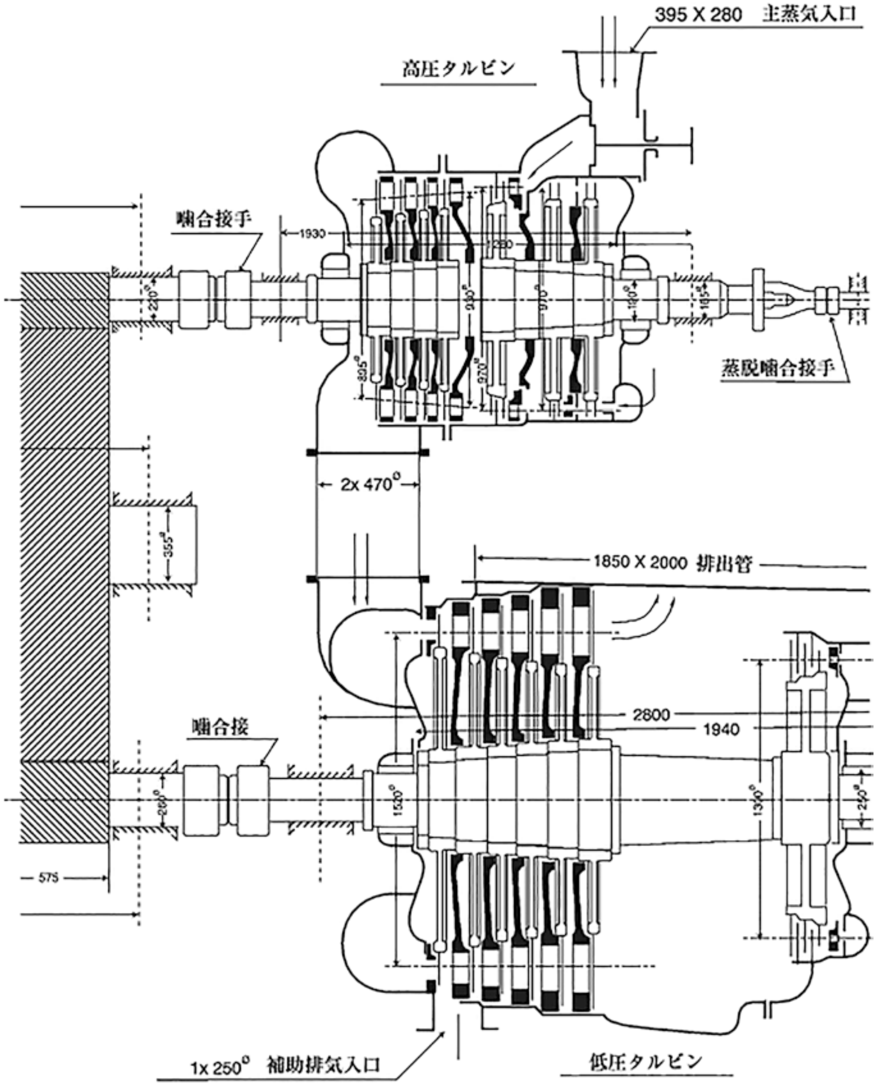

Fig. 10.1 Plane view of the first Kanpon type turbine (*Source* [28])

turbines experienced by the Navy. The first Kanpon type turbine was installed in destroyers built in 1924 (see Fig. 10.1).[10]

All Japanese naval vessels continued to adopt this Kanpon type turbine until 1945. Everyone regarded it as a landmark that showed the beginning of adoption of self-reliant technologies. This is because, as the Shipbuilding Society of Japan wrote in its official history of naval architecture and marine engineering, "there

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[10] For the detail of this first Kanpon type turbine, see [24], Chap. 3. Also see [28].

had been no serious trouble with the turbine for more than ten years since the early 1920s, and the Navy continued to have strong confidence in their reliability." [29, Vol. 1, p. 668].

What follows is an important counterargument to this account, by calling attention to the missing failure linking success and failure, a pitfall inherent in the trajectory. The detailed description and analysis of the hidden but serious incident of the established Kanpon type turbine that occurred immediately before WWII will show how important and meaningful this pitfall is for the trajectory of Japan's technological development, its organizational errors, and its science-technology-society interface. This is particularly because, as will be clarified below, the pitfall was profoundly related to the functional disintegration of the military-industrial-university complex caused by an unbalanced secrecy, one of the key factors leading to "structural disaster." The military-industrial-university complex hereafter means an institutional structure made up of the governmental sector, particularly the military, the private industrial sector, and universities—mutually autonomous in their behavior but in combination expected to contribute to national goals.[11]

10.5 The Accident Kept Secret

In December 1937, a newly built destroyer encountered an unexpected turbine blade breakage accident. Since the accident involved the engine of standard design, it caused great alarm. A special examination committee was set up in January 1938 to investigate the accident. The committee was called Rinkichō in Japanese. This chapter will refer to the accident as the Rinkichō accident hereafter. Today, there are five non in-house books containing references to the Rinkichō accident. The first reference to the accident appeared in 1952, and the last in 1981.[12] The publication dates and the authors/editors of the references are all

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[11] See [24, p. 50]. There is no implication herewith that the complex was designed in Japan by the "rich nation, strong army" policy in a top-down manner. Rather the complex in Japan had an endogenous origin. See [24], Chap. 3. As for the "rich nation, string army" policy, see [30]. The endogenous origin of the complex might also be detected in Britain as shown by the connection between physics and engineering in the life of Lord Kelvin. See [31]. For a study on the complex with reference to American science and technology, see [32].

[12] In 1952, seven years after WWII ended, the first reference appeared in [33] compiled under the leadership of Michizō Sendō who was an engineering Rear Admiral of the Navy. Four years later, the second reference appeared in [34] written by Masanori Itō who was a Mainichi newspaper reporter and was also a graduate of the Naval Academy. The third reference [35] that appeared in 1969 gives the most authentic history of the failure among the five books. Eight years later, in 1977, the fourth reference appeared in [29]. The editor-in-chief was a former engineering officer of the Navy, and the editorial committee of the society also included several other engineering officers of the Navy. Of the five books, this reference provides the most detailed description of the technical aspects of the failure, which will be examined below based on newly discovered primary source materials. In 1981, the last reference [36] appeared in *Kaigun* (The Navy) compiled by the Institute for the Compilation of Historical Records relating to the Imperial Japanese Navy.

Table 10.3 References to the Rinkichō accident

Year of reference	Author/Editor
1952	Former engineering rear admiral of the navy
1956	Mainichi newspaper reporter (Graduate of the Naval Academy)
1969	War history unit of the national defense college of the defense agency
1977	Japan shipbuilding society (editor-in-chief and several members of the Editorial committee were former technical officers of the navy)
1981	Institute for historical record compilation on the navy

different, but all were written by parties connected with the Imperial Japanese Navy (see Table 10.3).

The accounts given in these references agree for the most part on their main points that the cause was soon identified, resulting in no serious consequence. These references make up a kind of success story. And it is extremely difficult to look into further details of the failure because little evidence is provided to prove what is stated by these references. It appears that the accident was kept secret because it occurred during wartime mobilization.

To confirm this, an examination of government documents from around the time of the accident is in order. The government documents consulted here are the minutes of Imperial Diet sessions regarding the Navy. The minutes of the 57th Imperial Diet session (held in January 1930) to the 75th Imperial Diet session (held in March 1940) contain no less than 7,000 pages about Navy-related discussions. These discussions include ten naval vessel incidents summarized in Table 10.4.

It is noteworthy in these discussions that the Fourth Squadron incident of September 1935, one of the most serious incidents in the history of the Imperial Japanese Navy, was made public and discussed in the Imperial Diet sessions within a year (on May 18, 1936).[13] The Rinkichō accident occurred on December 29, 1937, and was handed down informally within the Navy and counted as a major incident on a par with the Fourth Squadron incident.[14]

However, more than two years after the Rinkichō accident there is no sign in the documents that it was made public and discussed in Imperial Diet sessions. As will be noted in detail, reports on the accident had already been submitted during the period from March to November 1938 (the final report was submitted on November 2). Nevertheless the Imperial Diet heard nothing about the accident or any detail of measures taken to deal with it. The Rinkichō accident was so serious that it would have influenced the decision on whether to go to war with the U.S.

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[13] The *Tomozuru* incident of March 11, 1934 was the first major one for the Imperial Japanese Navy. Only one year and a half after this, a more serious incident occurred on September 26, 1935—the Fourth Squadron incident.

[14] Based on interviews by the present writer with Dr. Seikan Ishigai (on September 4, 1987; June 2, 1993) and with Dr. Yasuo Takeda (on September 25, 1996; March 19, 1997).

Table 10.4 Discussions in the imperial diet regarding naval vessel accidents, etc.: January 1930–March 1940

Date	Description
February 13, 1931	Questions about the cause of the collision between the cruiser *Abukuma* and *Kitakami*. (Shinya Uchida’s questions were answered by the Minister of the Navy, Abo, at the Lower House Budget Committee, the 59th Imperial Diet session)
March 2, 1931	Questions about the measures taken before and after the collision between the cruiser *Abukuma* and *Kitakami* during large-scale maneuvers in 1930 and the responsibility of the authorities. (Tanetada Tachibana’s questions were answered by the Minister of the Navy, Abo, at the House of Lords Budget Committee, the 59th Imperial Diet session)
March 17, 1933	Questions about the Minister of the Navy’s view on the expenditure (12,000 yen) on repairs to the destroyer *Usugumo* and on the fact that the destroyer struck a well-known submerged rock. (Shinya Uchida’s questions were answered by the Minister of the Navy, Ōsumi, at the Lower House Budget Committee, the 64th Imperial Diet session)
March 2, 1935	Request for information about the results of investigation into a scraping incident involving four destroyers, apparently on training duty in Ariake Bay, reported in newspapers. (Yoshitarō Takahashi’s questions were answered by the Minister of the Navy, Ōsumi, at the Lower House Budget Committee, the 67th Imperial Diet session)
May 18, 1936	Request for information about the seriousness of the collision between submarines I-53 and I-63 and the amount of money drawn from the reserve as a remedy. (Kanjirō Fukuda’s questions were answered by the Accounting Bureau Director, Murakami, at the Lower House plenary session, the 69th Imperial Diet session)
May 18, 1936	Request for detailed information about the degree of damage to two destroyers due to violent waves in September 1935. (Kanjirō Fukuda’s questions were answered by the Accounting Bureau Director, Murakami, at the Lower House plenary session, the 69th Imperial Diet session)
February 6, 1939	Brief explanation of the accident of submarine I-63. (The Minister of the Navy, Yonai, explained at the House of Lords plenary session, the 74th Imperial Diet session)
February 7, 1939	Brief explanation of the accident of submarine I-63. (The Minister of the Navy, Yonai, explained at the Lower House plenary session, the 74th Imperial Diet session)
February 25, 1939	Request for a brief explanation of the sinking of a submarine due to collision during maneuvers. (Takeo Kikuchi’s questions were answered by the Director of the Bureau of Military Affairs, Inoue, at the House of Lords Budget Committee, the 74th Imperial Diet session)
February 1, 1940	Brief report on the completion of the salvage of the sunken submarine I-63. (The Minister of the Navy, Yoshida, reported at the House of Lords plenary session, the 75th Imperial Diet session)

and Britain. The Fourth Squadron incident was also serious enough to influence the decision in that it dramatically disclosed the inadequate strength and stability of the hull of the standard naval vessels designed after the London naval disarmament treaty concluded in 1930.[15] But it was made public and discussed in Imperial Diet sessions. In this respect, there is a marked difference between the handling of the two incidents. Regarding the Fourth Squadron incident, the Director of the Naval Accounting Bureau, Harukazu Murakami, was forced to give an answer to a question by Kanjirō Fukuda (Democratic Party) at the 69th Imperial Diet session held on May 18, 1936.[16]

Although his answer gave no information regarding the damage to human resources (all members of the crew confined within the bows of the destroyers died), it accurately stated the facts of the incident and the material damage incurred, which amounted to 2.8 million yen in total. Even the damage due to the collision between cruisers about five years earlier in Table 10.4 was only 180,000 yen. The answer from a naval official clearly attested that the Fourth Squadron incident was so extraordinarily serious as to oblige him to disclose this fact to the public.[17] It should be noted here that remedial measures for the problem of the turbines of all naval vessels disclosed by the Rinkichō accident were expected to cost 40 million yen [38].

Nevertheless, no detailed open report of the Rinkichō accident was presented at the Imperial Diet. This fact strongly indicates that the Rinkichō accident was top secret information, which was not allowed to go beyond the Imperial Japanese Navy. What, then, were the facts? This question will be answered based on documents owned by Ryūtarō Shibuya who was an Engineering Vice Admiral of the Navy and was responsible for the turbine design of naval vessels at the time (these documents will be called the Shibuya archives hereafter).

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[15] The purpose of this treaty was to restrict the total displacement of all types of auxiliary warships other than battleships and battle cruisers, while that of the Washington naval disarmament treaty of 1922 was to restrict the total displacement of battleships and battle cruisers. This London treaty obliged the Imperial Japanese Navy to produce a new idea in hull design enabling heavy weapons to be installed within a small hull, which, however, proved to be achieved at the expense of the strength and stability of the hull, as the incident dramatically showed.

[16] “When the Fourth Squadron was conducting maneuvers in the sea area to the east of Japan, they encountered a furious typhoon. They were attacked by very rare high waves. Two destroyers were tossed about tremendously. As a result, their bows were damaged. The damage to the engines and armament was considerable—two million yen for the ship and 800,000 ¥ for its armament, a total of 2.8 million yen” [37, p. 86].

[17] The damage due to the collision between the cruisers *Abukuma* and *Kitakami* in terms of contemporary currency is based on the above-mentioned answer by the Navy minister Kiyotane Abo to a question by Viscount Tanetada Tachibana made on March 2, 1931 during the 59th Imperial Diet Session [37, p. 831].

10.6 The Hidden Accident and the Outbreak of War with the U.S. and Britain: How Did Japan Deal with the Problem?

The Shibuya archives are enormous, consisting of more than 4,000 materials on various subjects including casualties of the atomic bomb.[18] Even though we chose only the materials directly concerning the Rinkichō accident, it is impossible to present here a full analysis of all the details gleaned from these voluminous materials. Among these, this chapter focuses on the special examination committee established in January 1938. The purpose of the committee was as follows [39]:

> Problems were found with the turbines of Asashio-class destroyers…. It is necessary to work out remedial measures and study the design of the machinery involved and other related matters, so that such studies will help improvements. These research activities must be performed freely without any restrictions imposed by experience and practice in the past. The special examination committee has been established to fulfill this purpose.

Its organization was as follows [40]:

- General members who did not attend subcommittee meetings
  - Chair: Isoroku Yamamoto, Vice Admiral, Administrative Vice Minister of the Navy
  - Members: Rear Admiral Inoue, Director of the Bureau of Naval Affairs, the Ministry of the Navy and five other members

- First subcommittee for dealing with engine design and planning
  - Members: Leader: Shipbuilding Vice Admiral Fukuma, Director of the Fifth Department (including the turbine group), the Technical Headquarters of the Navy; and nine other members
- Second subcommittee for dealing with the maximum engine power and suitable load/volume
  - Members: Leader: Rear Admiral Mikawa, Director of the Second Department, the Naval General Staff; and eleven other members
- Third subcommittee for dealing with prior studies/experiments/systems and operations
  - Members: Leader: Rear Admiral Iwamura, Director of the General Affairs Department, the Technical Headquarters of the Navy; and ten other members

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[18] When Japan was defeated in 1945, most military organizations were ordered to burn documents they had kept. Many documents of the Imperial Navy were burned before the General Headquarters of the U.S. Occupation Forces ordered the government to submit documents regarding the war. Ex-managers and ex-directors of the Imperial Japanese Navy then held meetings and decided to undertake a research project to collect, examine, and preserve technical documents to the extent possible. The Shibuya archives were the result of this project and came into the hands of Ryūtarō Shibuya. The description of the background of the Shibuya archives is based on Shibuya Bunko Chōsa Iinkai, Shibuya Bunko Mokuroku (Catalogue of the Shibuya Archives), March 1995, Commentary.

Table 10.5 Members of the special examination committee by section

Section	Number
Administrative vice minister of the navy	1
Bureau of naval affairs	8
Naval general staff	5
Technical headquarters of the navy	15
Naval staff college	3
Naval engineering school	1
Total	33

Note Calculated based on [40]

Ignoring duplication of members belonging to different subcommittees and arranging the net members by section, we obtain the following result (see Table 10.5).

The accident, as mentioned above, concerned the breakage of turbine blades. Tracing back the history of the development of the marine turbine in Japan since 1918 when the Navy began to adopt geared turbines, we find that various failures occurred with main turbines. When we classify these failures during the period from 1918 to October 1944 by location, failures involving turbine blades account for 60 % of the total (see Table 10.6).[19]

The Imperial Japanese Navy had thus had many problems with turbine blades for many years and accumulated experience in handling them. Accordingly, it is unsurprising that the special examination committee took the accident as merely a routine problem from the outset based upon such a long and rich experience. In fact, the special examination committee drew a conclusion made up of two points, both of which were in line with such accumulated experience. First, the accident was caused by insufficient blade strength. Second, turbine rotor vibration made the insufficient strength emerge as a problem [41]. On the basis of this conclusion, a plan was worked out to improve the design of the blades and rotors of the Kanpon type turbines for all naval vessels. It was decided to change the form of the blades so as to make their stress concentration lower to enhance their strength [42]. The improvement of 61 naval vessels' turbines was indicated as the first step, in accordance with the voluminous previous reports of 66 committee meetings held over a period of 10 months [43].

However, the blade breakage in the accident was significantly different from that in the past. In impulse turbines, for instance, blades in most cases were broken at the base where they were fixed to the turbine rotor. In contrast, one of the salient features of the Rinkichō accident was that the tip of the blade was broken off. The broken off part amounted to one third of the total length of the blade.[20] Figure 10.2 is a photograph showing the locus of the breakage.

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[19] This classification assumes that if a problem at one location produces another problem at another location, the latter problem is not counted separately, but is considered part of the former.

[20] The breakage as described in the record written at that time is as follows: "Moving blades and the rivets on the tip of the 2nd and 3rd stages of the intermediate-pressure turbines were broken…. The break in every moving blade was located at 40–70 mm from the tip" [42].

Table 10.6 Turbine failures on naval vessels classified by location: 1918–1944

Location	Incidents	Percentage	Cumulative
Impulse blade and grommet	368	46.8	46.8
Reaction blade and binding strip	111	14.1	60.9
Reduction gear and claw coupling	80	10.2	71.1
Bearing and thrust bearing	66	8.4	79.5
Casing	46	5.9	85.7
Casing partition and nozzle	34	4.3	89.7
Blade wheel and spindle	22	2.8	92.5
Steam packing	20	2.5	95.0
Others	39	5.0	
Total	786	100.0	100.0

Source Based on [25, pp. 1–2]. Reaction blade means the blade of a traditional Parsons turbine (Cf., [25, p. 4].)

These facts indicated that the accident was significantly different from any previous routine problem. Yoshio Kubota, an Engineering Captain of the Navy who happened to be transferred to the Military Affairs Bureau in November 1938 when the special examination committee reported its conclusion, eventually noticed this point. It was not really permissible for a newcomer to the Military Affairs Bureau of the Navy to utter an objection to the latest conclusion of the special committee. In addition, six months before his transfer to the bureau, the Japanese government enacted the Wartime Mobilization Law on April 1, 1938 for the purpose of “controlling and organizing human and material resources most efficiently… in case of war” (Clause 1). Naval vessels came first in the specification of the law as “resources for wholesale mobilization” (Clause 2). Against this background of wartime mobilization, a naval engine failure caused by small tip fragments of the main standard engine was a very delicate matter for anyone to raise.[21] Despite the circumstances, Kubota strongly recommended that confirmation tests should be conducted again for naval vessels of the same type. He argued that if turbine rotor vibration was the true cause, then the failure would be repeatable when the engine was run continuously at the critical speed causing rotor vibration (nearly 6/10 to 10/10 of the full speed).[22]

The Navy finally decided to initiate continuous-run tests equivalent to ten-year runs on April 1, 1939. No failure occurred. This provided the Navy with the simplest practical rationale for cancelling the overall remedial measures for all naval vessels, which were expected to require huge amounts of extra money and

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[21] Reference [44, p. 412]. The author was in charge of drafting the national mobilization plan at the Cabinet Planning Board (Kikaku In) in the prewar period. For the Navy, war preparation updates started from August 1940. See [45, pp. 93–94]. Sugiyama was the Chief of the General Staff at that time.

[22] Records of an interview with Yoshio Kubota made by the Seisan Gijutsu Kyōkai (Association for Production Technology) on March 19, 1955 [46].

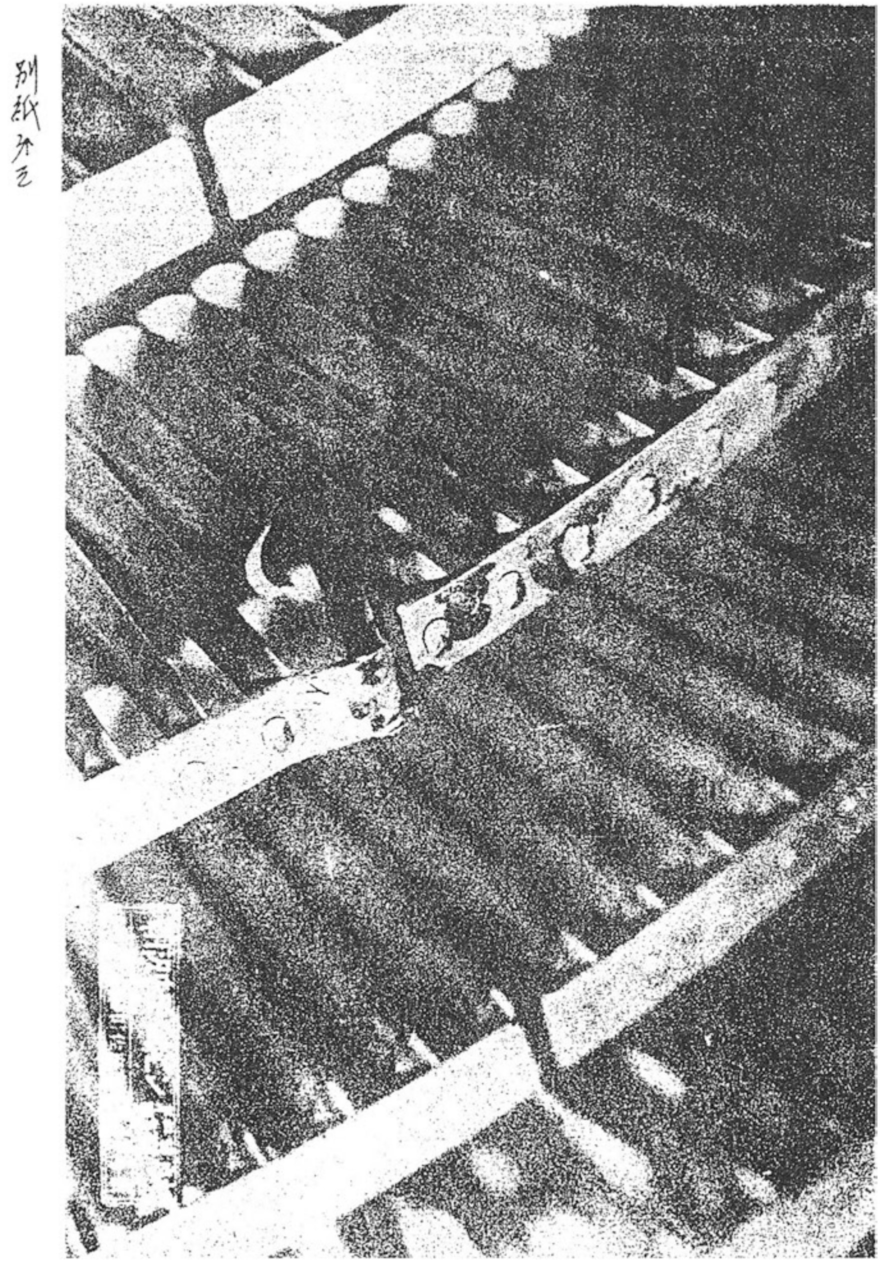

Fig. 10.2 Broken part of a blade in the Rinkichō accident (*Source* [42])

time.[23] An order was issued promptly to postpone the modification to the turbine blades and rotors of the Kanpon turbines for all naval vessels. At the same time, however, there was obviously an urgent need to consider the possibility of another cause and a study to identify the cause was restarted. The Maizuru Naval Dockyard conducted preliminary on-land tests and a more thorough one followed at the Hiro Naval Dockyard to confirm the conditions that would make the failure recur. However, the test was extremely difficult to carry out. There were two reasons for this. First, the complete test required the Dockyard to construct from scratch a full-scale experimental apparatus for a load test of vibration, which was only completed in December 1941, the month the war with the U.S. and Britain broke out. Second, the test turned out to be so large-scale, eventually extending to more than 35 main items, that it took far more time than expected. As a result, the schedule for identifying the cause, which was originally expected to be completed in November 1940, was extended to mid-1943.[24] Thus it is probable that all of Japan’s naval vessels had turbines which were imperfect for some unknown reason when the country went to war with the U.S. and Britain in 1941.

What, then, was the true cause for the accident? The true cause was binodal vibration. Previous efforts to avoid turbine vibration had been confined to one-node vibration at full speed since multiple-node vibration below full speed had been assumed to be hardly serious and unworthy of attention based on rule of thumb.[25] The final discovery of the true cause of the Rinkichō accident drastically changed the situation. It revealed that marine turbines are susceptible to a serious vibration problem below full speed. It was in April 1943 that this true cause was eventually identified by the final report of the special examination committee—almost one and half years after war broke out (see Fig. 10.3).[26]

Only three months before the submission of the report, a theoretical study made at the Hiro Naval Dockyard supported the conclusion that the true cause was binodal vibration.[27] The results of theoretical calculation, on-land confirmation testing, and the characteristics of the actual failure matched. The complete mechanism creating binodal vibration itself was still left for further studies. Even so,

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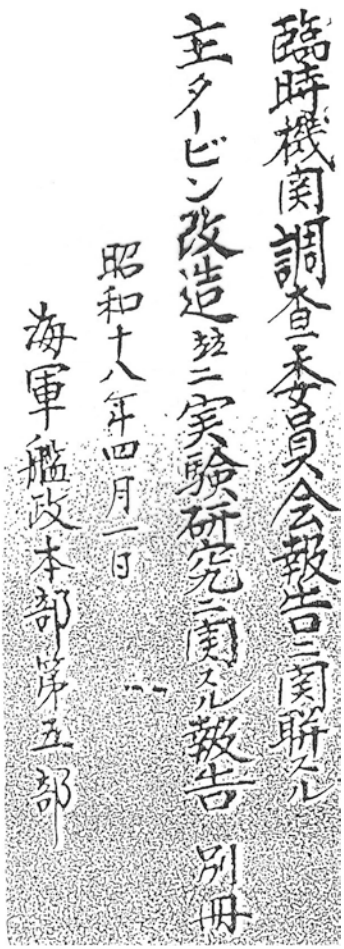
[23] These original remedial measures are kept in the Shibuya archives.

[24] The descriptions here are based on [47]. This is the final report of the special examination committee.

[25] In general, such was the standard of turbine design in the prewar period [48–50].

[26] According to this report, “Binodal vibration occurs when the product of the number of nozzles and the revolution of blades … equals the frequency of the blades at binodal vibration [47].” This means that a forced vibration caused by steam pulsation and a specific binodal frequency of blades resonate with each other, as a result of which binodal vibration occurs.

[27] It proved that even if uniform vertical and horizontal sections were assumed for the purpose of simplification, binodal vibration could produce the maximum stress at places less than three-fifths of the distance from the tip of a blade, which matched the place of the actual breakage in the failures [51]. Dr. Yasuo Takeda discovered this document on March 3, 1997, and it was added to the Shibuya archives.



臨時機関調査委員会報告ニ関聯スル
主タービン改造並ニ実験研究ニ関スル報告 別冊
昭和十八年四月一日
海軍艦政本部第五部

Fig. 10.3 The front page of the final report of the special examination committee (*Source* [47])

every result from the special examination committee that finally concluded in 1943 pointed to the same single cause: binodal vibration [52].[28]

Strictly in terms of the technology involved in the accident without hindsight, therefore, all the evidence suggests that the Japanese government went to war in

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[28] Shigeru Mori, a contemporary Navy engineer who graduated from the Department of Physics of the Imperial University of Tokyo seems to have tried to construct a model to identify the mechanism, whose details are not available now See [53]. When we look at other circumstantial evidence such as the fact that the blade breakage was limited to a relatively small number of turbines of particular newly built destroyers, it was still plausible that the strength of particular blades had something to do with the failure. The Navy therefore revised its design directive to ensure an enormous increase (from 0.4 to 1.5 mm) in the thickness of turbine blades just after the submission of the final report of the committee in April 1943. The original design directive had been issued on May 1, 1931, the documents of which are collected in the Shibuya archives. In interpreting this circumstantial evidence, the author is indebted to Dr. Ryōichirō Araki for

haste in 1941 notwithstanding the fact that it had unaccounted for, highly intricate, and serious problems with the main engines of all its naval vessels. And that fact was kept secret by the military sector from other sectors involved in the military-industrial-university complex, not to speak of the general public. The rarity of breakdowns of naval vessels due to turbine troubles during the war is a completely different matter, one of hindsight. Thus, the Rinkichō accident strongly suggests that practical results alone (for example, rarity of breakdowns of naval vessels due to turbine troubles) during wartime, possibly in peacetime as well, do not prove the essential soundness of the development trajectory of technology, and that of the science-technology-society interface and national decision-making along the trajectory.

10.7 The Sociological Implications for the Fukushima Daiichi Accident: Beyond Success or Failure

The sociological implications of this Rinkichō accident that happened much earlier than the Fukushima Daiichi accident are closely related to the reasons why we can call it a little-known "structural disaster." One of the reasons is that it was much more serious and complex than expected and therefore kept secret from outsiders. This fact requires us to reconsider the development trajectory of technology beyond the simplistic dichotomy of success or failure throughout peacetime and wartime. According to a standard view of the history of technology in general, Japan proceeded to a self-reliant phase with the establishment of the Kanpon type turbine in the 1920s, after improvements made to deal with various problems and failure incidents. In short, a successful self-reliant phase followed subsequent to improvements after various failures.

And it has been assumed up to now that this trajectory enabled Japan to go to war in 1941. According to the description and analysis of the Rinkichō accident given above, however, the trajectory becomes much more complex than the conventional "success story" account suggests, since there was a serious but little known missing phase, one of "self-reliant failure," which the Navy was unable to completely solve by the outbreak of the war. Considering this in association with the similarity in terms of technological trajectory such that the reactors of the Fukushima Daiichi power station embody the turning point leading from licensed production to self-reliant production, there is the possibility that the Fukushima Daiichi accident was a "self-reliant failure" in the sense mentioned above.

Footnote (continued)

technical advice. Considering this circumstantial evidence together, there were possibly two closely associated aspects in the failure. One is a universal aspect leading to the detection of binodal vibration. The other is a more local aspect possibly due to the testing and quality control of the strength of the particular broken blades. Whatever weight may be given to each aspect in the description and analysis of the failure, however, as the date of the final report indicates, it was only after April 1943 that both aspects were finally noticed. By then, about one year and a half had already passed since the outbreak of the war with the U.S. and Britain in 1941.

There is another reason why we can describe the Rinkichō accident as a little-known "structural disaster." The reason is that the recognition of binodal turbine blade vibration as the true cause was beyond the knowledge of the usual turbine designer of the day. This type of problem is supposed to have been unrecognized until the postwar period. In the postwar period, avoiding turbine blade vibration caused by various resonances still provided one of the most critical topics for research on turbine design.[29] The Imperial Japanese Navy certainly managed, after the serious technological and organizational errors of the Rinkichō accident that was kept secret from outsiders, eventually to detect the universal true cause during the war. But its complete solution seems not to have been found after the detection of the true cause.[30]

In short, the problem was detected in the prewar period, but its final solution was left until after the war.[31] Far beyond the simplistic dichotomy of success or failure throughout peacetime and wartime, this hidden and little known "structural disaster", an important snapshot of a serious failure of Japan's self-reliant prewar technology, gives a significant confirmation of the functional disintegration of the network of the relationships linking the military and industrial sectors. That is to say, the incident enables us to look at a secret military problem-finding and investigation, and pioneering but partial diagnosis without a well-informed industrial problem-solving process. This was the end state of the military-industrial-university complex in the prewar period in which a pitfall was present within the success in technological development, from which the postwar industrial reconstruction in Japan started.

This will provide an important guideline for characterizing and understanding the Fukushima Daiichi accident beyond the simplistic dichotomy of success or failure. This is because the kind of fresh account exemplified here, which goes

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[29] Cf., [54–59]. An article on the QE2's turbine reported that a similar failure occurred even in 1969. See [60].

[30] The same type of turbine blade breakage still occurred in the same class of destroyer more than one year after the final report of the special examination committee had been submitted. A destroyer of the same class was found to have had the same type of turbine blade breakage around "one-third of the blade from the tip" on July 21, 1944, an incident even less known than the Rinkichō accident [25, pp. 158–159]. Also see [61].

[31] Postwar industrial development, and the development of the steam turbine for commercial purposes, among other things, started from a careful re-examination of the binodal vibration problem left unsolved by the prewar/wartime military sector. For example, in 1953 Kawasaki Heavy Industries Ltd. invited three technical advisers to help develop an independent turbine technology for the future: Yoshitada Amari (ex-Engineering Rear Admiral of the Navy), and Kanji Toshima and Shōichi Yasugi (both ex-Engineering Captains of the Navy). They were all in the Technical Headquarters of the Imperial Japanese Navy at some stage of their prewar careers and were also concerned with the Rinkichō accident. And every detail of prewar turbine failures including the Rinkichō accident was inputted into an IBM computer and reanalyzed, from which the company obtained an exact normal tolerance for the strength of turbine blades and a design to avoid binodal vibration. Based on [62] and a letter from Yasuo Takeda, Kawasaki Heavy Industries Ltd. to Kanji Toshima, IHI. (n.d.). For a detailed description and analysis of the Rinkichō accident, see [24, pp. 159–172].

beyond a dichotomous narration, has tended to be unduly neglected up to now in the sociology of science and technology and particularly in relation to the sociological studies on extreme events such as the Fukushima Daiichi accident. As a matter of fact, the Rinkichō accident that occurred after a long history of successful technological development reminds us of its structural similarity to the Fukushima Daiichi accident that happened after a long successful operation of nuclear reactors closely associated with the myth of safety.

Another sociological implication that could be obtained from this hidden accident pertains to the social context of organizational errors involved in "structural disaster." As mentioned earlier, the social context of the Rinkichō accident is the wartime mobilization of science and technology, which was authorized by the Wartime Mobilization Law in 1938 and the Research Mobilization Ordinance in the next year. This formal legal foundation gave rise to one of the salient features of the wartime mobilization of science and technology, namely the structural interdependence of the military-industrial-university complex under the control of the military sector. The military sector controlled the overall mobilization, in which the industrial sector and universities had to obey orders given by the military. This was associated with an extremely secretive attitude of the military toward outsiders. According to Hidetsugu Yagi who invented the pioneering Yagi antenna, a crucial component technology of radars, and in 1944 became the president of the Board of Technology, the central governmental authority specially set up for the wartime mobilization of science and technology, the military "treated civilian scientists as if they were foreigners."[32]

Thus, even at the central governmental authority specially set up to integrate every effort for the wartime mobilization of science and technology, cooperation, not to speak of coordination, with the military sector was very limited and the military-industrial-university complex began to lose its overall integration. Particularly in terms of the relationship between the military and industrial sectors, functional disintegration went further. What is important here is the fact that this functional disintegration of the network of relationships linking the military and industrial sectors was taking place just at the time the strong structural integration of the complex was formally being reinforced by the Wartime Mobilization Law and the Research Mobilization Ordinance.

And this coupling of structural integration and functional disintegration during wartime mobilization provides a suitable background for redefining success and failure not only in prewar Japan's context but in the current context of the Fukushima Daiichi accident. The reason for this is that the social context of organizational errors involved in the Rinkichō accident provides us with an important insight such that if the Fukushima Daiichi accident is a "structural disaster" it could have some characteristics similar to the coupling of structural integration and functional disintegration. For example, functional disintegration of the network of relationships linking the government, TEPCO officials, and the relevant reactor designers of makers might

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[32] The statements by Yagi are based on [63]. These are Yagi's words on September 11, 1945, when interrogated by General Headquarters of U.S. Army Forces, Pacific Scientific and Technical Advisory Section.

be taking place just at the time the strong structural integration of the government-industrial-university complex was formally reinforced by the seemingly well-organized ordinances and laws revolving around the "double-check" system within a single ministry in the past and that between two ministries now, between METI and the Ministry of the Environment, ministry-bounded in either case.

10.8 Conclusion: Prospects for the Future

From the perspective of "structural disaster", there are two different kinds of similarities between the Rinkichō accident and the Fukushima Daiichi accident: one relating to technological trajectory, the other to the social context of organizational errors.

First, regarding similarity between the two accidents in terms of technological trajectory, both accidents took place in the stage of domestic or almost entirely domestic production of a technology once produced through license contracts after a successful operation of domestically produced technologies extending over 10–30 years. In that particular sense, both accidents could be categorized in the "self-reliant failure" type.

Second, there could be similarity between the two accidents in terms of the social context of organizational errors. This is because the coupling of structural integration and functional disintegration observed in the Rinkichō accident could similarly reside in the Fukushima Daiichi accident, particularly with respect to the relationships between the governmental and industrial sectors.

Of course, there are differences between the two accidents. Among other things, the difference in the way organizational errors came to be detected and corrected is noteworthy. In the Rinkichō accident, the conclusion once submitted by the final report of the special examination committee and authorized by the organization in question was dynamically cancelled by carefully observed facts regardless of the rank in the organization of those who pointed out the facts and the past experience accumulated in the organization. Such a dynamic reconsideration of alternative possibilities that upset the face-saving procedure within a specific organization triggered the restart of the examination leading to a drastically different conclusion. In the Fukushima Daiichi accident, in contrast, up until now there has been no sign showing the working of this kind of dynamic correction of organizational errors. At least looking at inside stories of TEPCO, Nuclear and Industrial Safety Agency (NISA), and other governmental bodies that have been disclosed one after another, one might rather well suspect the working of mutual "cover-ups" within and/or between those organizations in question, though the possibility of the dynamic correction of organizational errors might still be left open. This difference is noteworthy because, even with the working of such a dynamic correction of organizational errors, reconsideration of alternative possibilities, and restarting of development, the timing of the realization of the true cause of the Rinkichō accident was too late for Japan to check the soundness of national decision-making before going to war in haste in 1941.

In sum, putting together the similarity between the Rinkichō accident and the Fukushima Daiichi accident as “structural disaster” and their difference as to whether the dynamic correction of organizational errors and the reconsideration of alternative possibilities could work, there remains the possibility that the causes of “structural disaster” embedded in the Fukushima Daiichi accident will continue in a path-dependent manner. In such a case, the science-technology-society interface surrounding the Fukushima Daiichi accident will probably be unable to tolerate another impact that could be given by serious and unexpected events such as a second huge earthquake and tsunami and/or the difficulty of decontamination within some of the reactors in question and their abrupt uncontrollability.

One of the most important lessons from understanding the Fukushima Daiichi accident as “structural disaster” based on scrutinizing the hidden one that happened much earlier is how to avoid the worst state of this kind. That is to say, the seemingly structurally robust but functionally disintegrated science-technology-society interface due to secrecy should be changed. By the same token, while various communication activities to facilitate links between science, technology, and society had been carried out with public funds as represented in café scientifique before the Fukushima Daiichi accident, it turns out that there had been only one café scientifique on anything nuclear (held on July 24, 2010) out of 253 carried out in the Tohoku district including Fukushima prefecture. And yet the topic taken up there had nothing to do with any kind of risk from nuclear power plants, not to speak of extreme events such as the Fukushima Daiichi accident.[33] This implies that various activities supposed to facilitate well-balanced links between science, technology, and society in reality did nothing in advance about the communication of the negative aspect of nuclear power plants and therefore played no role in early warning against extreme events such as the Fukushima Daiichi accident.

As long as this kind of functional disintegration of the science-technology-society interface continues to exist and operate behind the façade of structural integration, such a state can lead to a similar dangerous weakness in quite a different and larger-scale social context. The possibility of functional disintegration through structural interdependence accompanied with secrecy and the suppression of negative information under the name of communication activities could constitute one of the important symptoms of “structural disaster.” This state should be changed by the will of the people who are suffering from the Fukushima Daiichi accident for the purpose of instituting a significant structural remedy, the remedy which is far beyond counter measures that only temporarily patch over individual troubles coming into sight at the moment and serve to save face of responsible agents concerned.

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[33] What is mentioned here is confirmed on November 18, 2011 through the following portal website on café scientifique in Japan: http://cafesci-portal.seesaa.net/.

References

1. TMM, No. 1119, June 25 (2011) sent by No Nukes Plaza Tokyo.
2. Matsumoto M (2002) Chi no shippai to shakai (The structural failure of the science-technology-society interface). Iwanami Publishing Co., Tokyo, pp 25-27
3. Wynne B (1996) Misunderstood misunderstandings: social identities and public uptake of science. In Irwin A, Wynne B (eds), Misunderstanding science?: The public reconstruction of science and technology. Cambridge University Press, Cambridge, pp 19-46
4. Collins H (2011) The third wave of science studies: the development and politics. Japanese Journal for Science, Technology & Society 20: 81-106
5. Perrow C (1984) Normal accidents: Living with high risk technologies. Basic Books, New York
6. Perrow C (1999) Normal accidents: Living with high risk technologies: With a new afterword and a postscript on the Y2K problem. Princeton University Press, Princeton
7. Walker JS (2004) Three Mile Island: A nuclear crisis in historical perspective. The University of California Press, Berkeley
8. Matsumoto M (2005) The uncertain but crucial relationship between a 'new energy' technology and global environmental problems. Social Studies of Science 35(4): 623-651
9. Latour B (1996) Aramis, ou L'amour des techniques. la Décourverte, Paris. English edition: Latour B (1996) Aramis or the Love of Technology (trans: Porter C). Harvard University Press, Cambridge, Massachusetts
10. Perrow C (2007) The next catastrophe. Princeton University Press, Princeton
11. Matsumoto M (2012) Kozosai (The structural disaster). Iwanami Publishing Co., Tokyo
12. Atomic Energy Society of Japan (2009) http://www.aesj.or.jp/awards/2008/2008-119-120.pdf. Ascertained on 21 Mar 2013
13. Tokyo Electric Power Company (2014) http://www.tepco.co.jp/nu/f1-np/intro/outline/outline-j.html. Ascertained on June 9 2014
14. Vaughan D (1996) The Challenger launch decision: Risky technology, culture, and deviance at NASA. The University of Chicago Press, Chicago
15. MacFarlane A (2003) Underlying Yucca mountain: The interplay of geology and policy in nuclear waste disposal. Social Studies of Science 33(5): 783-807
16. Eden L (2004) Whole world on fire: Organizations, knowledge, and nuclear weapons devastation. Cornell University Press, Ithaca
17. Jobin P (2013) Radiation protection after 3.11: Conflicts of interpretation and challenges to current standards based on the experience of nuclear plant workers. Paper presented at Forum on the 2011 Fukushima/East Japan Disaster, 13 May, 2013, Berkeley.
18. Constant II E (1980) The origins of the turbojet revolution. The Johns Hopkins University Press, Baltimore
19. Parsons CA (1984) Improvements in mechanism for propelling and controlling steam vessels, Patent Record No.394 A.D.1894 (Kept by Tyne & Wear Archives Service in Newcastle upon Tyne)
20. Scaife WG (1991) Charles Parsons' experiments with rocket torpedoes: The precursors of the steam turbine. Transactions of the Newcomen Society for the Study of the History of Engineering and Technology 60: 17-29
21. Matsumoto M (2013) Structural disaster long before Fukushima: A hidden accident. Development & Society 42(2): 165-190
22. Legett D (2011) Spectacles and witnessing: constructing readings of Charles Parsons's marine turbine. Technology and Culture 52(2): 287-309
23. Somerscale EFC (1992) The vertical Curtis steam turbine, Transactions of the Newcomen Society for the Study of the History of Engineering and Technology, 63: 1-52
24. Matsumoto M (2006) Technology gatekeepers for war and peace. Palgrave Macmillan, Basingstoke
25. Seisan Gijutsu Kyōkai (ed) (1954) Kyū kaigun kantei jōki tābin koshō kiroku (Record of the problems and failures of naval turbines of the Imperial Japanese Navy) Seisan Gijutsu Kyō kai (for private distribution), Tokyo

26. Shibuya R (1970) Kyū kaigun gijutsu shiryō (Technical materials of the Imperial Japanese Navy). Association for Production Technologies (for private distribution), Tokyo, Vol. 1, Chapter 4
27. Murata S (n.d.) *Asashio* Gata Shu Tābin no Jiko (An accident of the main turbines of the *Asashio*-class), Manuscript, p 6
28. Hakuyō Kikan Gakkai Hakuyō Kikan Chōsa Kenkyū Iinkai (The Research Committee of the Marine Engineering Society of Japan) (ed) (n.d.) Nippon hakuyō kikan shi Jōki tābin hen Sōkō (An unpublished manuscript of the history of marine engineering in Japan: The steam turbine), Appended tables
29. The Shipbuilding Society of Japan (ed) (1977) Shōwa zōsen shi (The history of shipbuilding in the Showa period), Hara Shobō, Tokyo
30. Samuels RJ (1994) Rich nation, strong army: National security and technological transformation of Japan. Cornell University Press, Ithaca
31. Smith C, & Wise MN (1989) Energy and empire: A biographical study of Lord Kelvin. Cambridge University Press, Cambridge
32. Leslie SW (1993) The cold war and American science: The military-industrial-academic complex at MIT and Stanford. Columbia University Press, New York
33. Sendō M (ed) (1952) Zōsen gijutsu no zenbō (A conspectus of warship construction technology)
34. Itō M (1956) Dai kaigun o omou (On the Imperial Japanese Navy)
35. The War History Unit of the National Defense College of the Defense Agency (ed) (1969) Kaigun gunsenbi (The Military Equipment of the Navy). Tokyo
36. The Institute for the Compilation of Historical Records relating to the Imperial Japanese Navy (1981) Kaigun (The Navy)
37. Kaigun Daijin Kanbō Rinji Chōsa Ka (Temporary Research Section, the Minister of the Imperial Japanese Navy's Secretariat) (ed) Teikoku gikai kaigun kankei giji sokki roku (Minutes of Imperial Diet sessions regarding Navy-related subjects), Bekkan 1, 2. Reprinted edition: (1984) Vol. 3, Part 1. Hara Shobō, Tokyo
38. Shibuya R (n.d.) Jūgo zuihitsu (Essays). sono 4
39. The Minister of the Navy's Secretariat (1938) Military secret No. 266. Issued on January 19, 1938
40. Rinkichō Report (1938) Top secret No. 35, Appended sheets. Issued on November 2, 1938
41. Rinkichō Report (1938) Top secret No. 35. Issued on November 2, 1938
42. Rinkichō Report (1938) Top secret No. 1. Issued on February 18, 1938
43. Rinkichō Report (1938) Top secret No. 1. Issued on February 18, 1938 through Top secret No. 27. Issued on October 13, 1938
44. Ishikawa J (ed) (1982) Kokka sōdōin shi (The history of national mobilization), Compiled materials, Vol. 3. Kokka Sōdōin Shi Kankō Kai, Fujisawa
45. Sanbō Honbu (ed), Sugiyama memo (Sugiyama memorandum). Reprinted: (1967) Vol. 1. Hara Shobō, Tokyo
46. Kubota Y (1981) 85 nen no kaisō (Reminiscences of 85 years). for private distribution, Tokyo, pp 50-51
47. Kaigun Kansei Honbu Dai 5 Bu (1943) Rinji Kikan Chōsa Iinkai Hōkoku ni kansuru Shu Tābin Kaizō narabini Jikken Kenkyū ni kansuru Hōkoku (Report on the Remedy and the Experimental Research of the Main Turbines in connection with the Rinkichō Report), Bessatsu. April 1, (1943)
48. Sezawa K (1932) Vibrations of a group of turbine blades. Zosen Kyōkai Kaihō 50: 197-206.
49. Pigott SJ (1937) Some special features of the S.S.Queen Mary. Engineering 143: 387-390
50. (1940) Turbine-blade fatigue testing. Mechanical Engineering 62(12): 919-921
51. Engineering Lieutenant Nozaki (1943) Tābin yoku no shindō ni kansuru kenkyū (A theoretical study on turbine blade vibration). January 15, 1943
52. Ono K (1943) Tābin yoku no kyōsei shindō ni kansuru kinji keisan (An approximate calculation on the forced vibration of turbine blades. Engine Laboratory, Department of Sciences, Naval Technical Research Institute, August 1943

53. Mori S (1969) Waga seishun (My youth). Shizuoka Newspaper, August 29, August 30, September 1, 1969
54. Trumpler Jr. WE, Owens HM (1955) Turbine-blade vibration and strength. Transactions of the American Society of the Mechanical Engineers: 337-341
55. Andrews F, & Duncan JP (1956) Turbine blade vibration: Method of measurement and equipment developed by Brush. Engineering: 202-208, August 17, 1956
56. Luck GA, Kell BC (1956) Measuring turbine blade vibrations: Development of barium titanate transducers. Engineering 31: 271-273
57. Leist K (1957) An experimental arrangement for the measurement of the pressure distribution on high-speed rotating blade rows. Transactions of the American Society of the Mechanical Engineers: 617-626
58. Wahl AM (1957) Stress distribution in rotating disks subjected to creep at elevated temperature. Journal of Applied Mechanics: 299-305
59. Visser NJ (1960) Turbine blade vibration. VMF Review 2: 61-62
60. Report on *QE2* turbines. Shipbuilding and Machinery Review, March 13, 1969: 24-25
61. Matsumoto M (1999) A hidden pitfall in the path of prewar Japanese military technology. Transactions of the Newcomen Society 71(2): 305-325
62. Takeda Y (n.d.) Kawajū wa Kanpon Shiki Tābin no Point o Dōshite Toraetaka (How did the Kawasaki Heavy Industries Ltd. assimilate the points of the Kanpon Type Turbine?); Kawasaki Tābin Sekkei Shiryō (Kawasaki Turbine Design Materials), Dai 2 Bu (October, 1955)
63. Report on Scientific Intelligence Survey in Japan, 1945, Vol. III (GHQ/SCAP Records Box No. 8354 ESS (1)-00727), Appendix 3-A-1

Chapter 11
Three Mile Island and Fukushima

Some Reflections on the History of Nuclear Power

J. Samuel Walker

Abstract This article draws comparisons between the Three Mile Island accident in 1979 and the far more severe accident at Fukushima. It cites lessons that were learned from Three Mile Island and suggests how they improved the performance of the nuclear power industry in the United States. The article also draws other, perhaps less apparent, lessons from the history of nuclear power.

Keywords Three Mile Island · Nuclear industry · Radiation hazards · Nuclear Regulatory Commission

The accidents that occurred at the Three Mile Island (TMI) Unit 2 plant in Pennsylvania in March 1979 and the Fukushima Daiichi plants in Japan in March 2011 are generally and correctly regarded as two of the three most serious in the history of commercial nuclear power (Chernobyl, of course, is the third). For that reason, both accidents need to be carefully studied and appropriate lessons need to be learned. Although TMI and Fukushima differed in causes and consequences, they provide powerful incentives to investigate what happened and to draw conclusions that, if properly applied, can help to prevent, or at least mitigate the effects of, nuclear power accidents in the future.

Any account of TMI and Fukushima must recognize their important dissimilarities. TMI is usually and erroneously described as a disaster. Although it was a gut-wrenching crisis and although a significant portion of the core melted, it did not result in large

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releases of dangerous forms of radiation. The plant emitted several million curies of noble gases after the accident, but they present slight hazards to human health. Only small amounts of volatile radioactive isotopes that pose the greatest risks escaped into the environment. The accident released less than 20 curies of iodine-131 and no strontium-90, cesium-137, or plutonium. Careful epidemiological studies of a cohort of about 32,000 people who lived within a 5 mile radius of the plant have shown no increase in the incidence of cancer or other diseases that could be attributed to the accident. Most of the approximately 144,000 people who voluntarily evacuated returned to their homes within a few days and schools re-opened two weeks after the accident.

By contrast, Fukushima released radioactive iodine, strontium, cesium, and plutonium to the environment. The off-site quantities were larger, more widespread, and more worrisome than the amounts that escaped from TMI. The *Washington Post* reported in April 2011, that "experts predict no long-term health consequences on residents in the region," and that assessment has continued to hold. Nevertheless, the local population has suffered from the stress and trauma of a mandatory evacuation and all the trials of dislocation, uncertainty, and anxiety. For those reasons, Fukushima qualifies as a disaster, though far short of the magnitude of Chernobyl.

Despite those differences, there are critical lessons to be learned from what occurred at TMI that apply to Fukushima and to nuclear power in general.

1. Accidents can and probably will occur in unexpected ways. The TMI-2 accident was largely a result of mistakes on the part of the operators in the control room. Their training did not prepare them for the loss-of-coolant accident that began when the pressure-operated relief valve (PORV) stuck open and allowed the escape of coolant from the core. The instrument panel in the control room provided little useful information on what was happening in the core. The operators feared that the pressurizer was in danger of "going solid" from an excess of water, and therefore, they cut the flow of water to the core from the emergency core cooling systems to a trickle. In that way, they unwittingly transformed what should have been a minor incident into a massive meltdown. At Fukushima, of course, the original causes of the accident were the earthquake and tsunami, which were of perhaps unprecedented and certainly unanticipated magnitude. The worst effects occurred because the diesel generators that were designed to provide back-up power to the plant were submerged by the tsunami. Plant designers and engineers take elaborate precautions to guard against accidents as severe as TMI and Fukushima, but in those cases, their efforts were not enough. It seems axiomatic that other accidents are likely to happen in unexpected ways, and designers, engineers, and builders must do their utmost to ensure that plants can withstand such occurrences or at least minimize the consequences. Extending the margin of safety as much as possible is advisable, perhaps essential. At TMI, the overdesign of the pressure vessel almost certainly kept it from failing after the core meltdown and might well have prevented a more serious accident.
2. When accidents occur, they have to be thoroughly investigated and frankly evaluated. After TMI, extensive and hard-hitting investigations were conducted

by the President's Commission on the Accident at TMI (usually referred to as the Kemeny Commission after its chairman, John G. Kemeny), Congress, the state of Pennsylvania, and the Nuclear Regulatory Commission (NRC). The reports of those investigations, including the one sponsored by the NRC, made no effort to spare the feelings or the sensitivities of the NRC or the nuclear industry. They came down hard on the NRC for failing to do a better job of regulating and the industry for failing to do more to ensure the safety of the plants it built and operated. There was no doubt in anyone's mind at the NRC or in the field of nuclear power that broad reforms were needed if the industry was to survive. However painful it was to be targets of unvarnished criticism, the NRC and the industry took it well and moved on to make impressive progress in both safety and performance.

3. A closely related lesson is that lessons need to be learned, remembered, and heeded. Before TMI, the NRC and the nuclear industry believed that they had resolved questions regarding reactor safety and that nuclear plants were well-protected against a severe accident. TMI was a shocking and humbling experience, and both the NRC and the industry took the lessons of the experience to heart. It was clear from the sequence of events during the accident that although the safety equipment in the plant performed according to design, there were glaring flaws in what were known as "human factors." The NRC made important changes in its regulations to address, among other things, significant shortcomings in operator training, control room design, instrumentation, and communications. Likewise, the industry took a series of steps to fix the weaknesses the accident revealed, including programs to make operator training more rigorous. The action with perhaps the greatest impact was the creation of an industry-funded organization, the Institute of Nuclear Power Operations (INPO), which came to serve as the conscience of the industry and to exert effective peer pressure to bring about necessary changes. The result was that industry performance in the areas of both safety and reliability was vastly improved. For example, the capacity factor across the industry increased from less than 60 % in the 1970s to more than 90 % in the early 2000s. This is not to say that all problems in the nuclear industry were solved. There were still serious lapses—two prominent examples were the embarrassment of sleeping control room operators at the Peach Bottom plant in Pennsylvania in 1987 and the discovery of a football-sized cavity in the head of the pressure vessel at Davis-Besse in Ohio in 2002. Nevertheless, the application of key lessons learned from TMI was a major factor in improving nuclear power safety in the United States.

These lessons of TMI, at least in retrospect, are fairly obvious. But there are also other lessons from the history of nuclear power that are perhaps less apparent and that have important implications for the future of nuclear power in the United States and abroad.

1. Nuclear power will always be judged by standards that are different and more demanding than those applied to other sources of energy or societal risk. This is in part an appropriate response to the possibility of a catastrophic accident

at a nuclear plant. But it is also a function of unique fears of nuclear power. The news media and the public seem far more uncomfortable with the small (though real) likelihood of a disastrous nuclear meltdown than with the well-documented costs in human health and lives of other forms of energy. This pattern also applies to elements of societal risk in general. In 1978, a public opinion sampling of college students and members of the League of Women Voters in Oregon asked them to rank thirty sources of risk "according to the present risk of death from each." Both groups rated nuclear power as number one, ahead of smoking, motor vehicles, motorcycles, handguns, and alcoholic beverages. There is every reason to believe that the same poll would produce similar results in 2011. One indication is that media coverage in the United States of the effects of the Fukushima earthquake and tsunami tended to devote far more attention to the meltdowns at the nuclear plant than to the tragedy that took place throughout the region. Despite the severity of the damage to the plants, at least they remained standing and the amounts of radiation they released, while disturbing, were not catastrophic. This was not the case for the homes, schools, hospitals, factories, and other structures that were flattened by the earthquake and tsunami and in which thousands of people perished.

2. An important reason for the fear of nuclear power is exaggerated public anxiety about radiation. This was made vividly clear after Fukushima when citizens bought out supplies of potassium iodide and Geiger counters from stores—in California! This might have been a reasonable action for residents of Japan, given the uncertainties about the condition of the plants, but it hardly seemed necessary for those who lived on the other side of the Pacific Ocean. The reasons for acute public fear of even low-level radiation are rooted deep in history and have a great deal to do with media coverage. For a period of more than 65 years after Hiroshima, radiation hazards were a source of an abundance of sustained publicity, and, as a result, of uniquely intense public fears. In many cases, the news stories were ill-informed and distorted. Even when media reports on radiation were balanced and accurate, the information they conveyed was frequently unsettling. The distinction between accounts of radiation effects and those of other technological hazards with some similar characteristics, such as dangerous chemicals, electrical shocks, fossil fuels, dam failures, food additives, and genetic engineering, was more quantitative than qualitative. Radiation was different in remaining a regular source of headlines for decades. After Hiroshima, the many ramifications of nuclear energy were big news, and the effects of radiation were a major part of the story. The nature of radiation risks generated public apprehension, but the prevalent anxieties were greatly enhanced by the visibility that radiation issues commanded. Although most experts agreed that public fears of low-level radiation far exceeded the risks of exposure, those fears were hardly unreasonable based on the information or impressions that the public gleaned from the popular media.
3. A final lesson from the history of nuclear power is the importance of knowing something about the history of nuclear power. For example, practically every news story that refers to the early history of the industry quotes a statement

> made in 1954 by the chairman of the Atomic Energy Commission, Lewis Strauss, that nuclear power would be "too cheap to meter." This is cited as evidence of how optimistic or how foolish nuclear advocates were as the nuclear power industry got under way. The problem is that nobody, not even Lewis Strauss, believed that nuclear power would be so cheap. Strauss was engaging in a flight of fancy that was not consistent with the views of nuclear experts or the electric power industry then or later. Yet this statement has become part of a misleading mythology about the early history of the technology. Another more recent example is the continuing belief or assumption that TMI was a disaster, or worse, that radiation releases were far greater and the health effects far more extensive than the federal government, the state government, or the nuclear power industry has ever admitted. This charge has no basis in evidence, but it remains an article of faith among some people and makes at least occasional appearances in media reports.

It is essential to get the history of the nuclear power industry and of radiation protection right if we are to deal intelligently and effectively with the serious challenges presented by the Fukushima accident. It is also essential if we are to make informed choices about the options available to us, including a full accounting of the risks and benefits of all energy sources, to meet the growing demands for electrical power in the future.

Part III
Basis for Moving Forward

Chapter 12
Implications and Lessons for Advanced Reactor Design and Operation

Yoshiaki Oka and Dietmar Bittermann

Abstract This chapter describes the implication and lessons from reactor design and operation points of view. After introduction of safety principles and safety designs of LWRs, lessons of the accident, new regulatory requirements and improvements in Japan, essential technologies for preventing and mitigating severe accidents are described.

Keywords Severe accidents · Regulatory requirements · External events · Passive systems · Hydrogen mitigation · Containment venting systems · Melt stabilization measures · Severe accident instrumentation

12.1 Short Reflection of Basic Safety Issues

In contrary to other technologies, for nuclear facilities, the basic safety rules have been introduced from the very beginning. In addition, the safety requirements and designs especially of LWRs have been improved from the lessons of accidents and incidents that occurred during the history of this technology.

In order to assure the function of the four classical safety barriers—fuel matrix, fuel rod, primary circuit and containment—the defense-in-depth safety concept is applied. The strategy for defense-in-depth is twofold:

- to prevent accidents, and
- if prevention fails, to limit their potential consequences and prevent any evolution to more serious conditions.

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The fundamental safety goals that shall be achieved with the support of the provisions taken within the framework of the defense-in-depth concept are: control of reactivity, cooling of fuel elements, and activity retention.

The safety goal “reactivity control” means among others that a nuclear reactor should have inherent safety characteristics. The reactor should be designed to have negative reactivity feedback characteristics. The power coefficient of the reactor should be negative for automatic decrease without operator actions. The reactivity coefficients of fuel temperature and coolant voiding should be kept negative for the purpose. After a reactor trip it should be kept in a sub-critical state in the long term and sub-criticality should be ensured during handling, storage and transport of fuel elements.

The safety goal, “cooling of fuel elements,” means to ensure heat removal from the core and the fuel storage pool under all operating and accident conditions and replenishing of coolant for the core and the fuel storage pool. In addition the integrity of coolant retaining systems should be ensured by pressure and temperature limitation in the relevant safety components and systems.

The safety function, “activity retention,” should be provided by means of isolation provisions with the function of confinement of activity within the pressure-retaining boundary and connecting systems. An important activity confinement function is dedicated to the containment and other relevant buildings such as the reactor and the auxiliary building.

According to the IAEA document INSAG 10 [1], five levels of defense should be considered. The levels 1–3 define the design basis. Levels 4 and 5 define the beyond design basis area. An overview on the levels and the main means of action is depicted in Table 12.1.

Level 1

The safety provisions at Level 1 are taken through the choice of site, design, manufacturing, construction, commissioning, operating and maintenance requirements such as:

Table 12.1 The levels and the main means of action for the defense-in-depth safety concept in INSAG 10 [1]

Level	Goal	Main means of action
1	Prevention of abnormal operation and failures	Conservative design and high quality in construction and operation
2	Control of abnormal operation and failures	Control, limiting and protection systems and other surveillance features
3	Control of accidents within the design basis	Engineered safety features and accident procedures
4	Control of severe conditions including prevention of accident progression and mitigation of the consequences of a severe accident	Complementary measures and accident management
5	Mitigation of the radiological consequences of significant external releases of radioactive material	Offsite emergency response

- The clear definition of normal and abnormal operating conditions;
- Adequate margins in the design of systems and plant components, including robustness and resistance to accident conditions, in particular aimed at minimizing the need to take measures at Level 2 and Level 3;
- Adequate time for operators to respond to events and appropriate human-machine interfaces, including operator aids, to reduce burden on the operators;
- Careful selection of materials and use of qualified fabrication processes and proven technology together with extensive testing;
- Comprehensive training of appropriately selected operating personnel whose behavior is consistent with a sound safety culture;
- Adequate operating instructions and reliable monitoring of plant status and operating conditions;
- Recording, evaluation and utilization of operating experience;
- Comprehensive preventive maintenance prioritized in accordance with the safety significance and reliability requirements of systems.

Furthermore, Level 1 provides the initial basis for protection against external and internal hazards (e.g. earthquakes, aircraft crashes, blast waves, fire, flooding), even though some additional protection may be required at higher levels of defense.

Level 2

Level 2 incorporates inherent plant features, such as core stability and thermal inertia, and systems to control abnormal operation (anticipated operational occurrences), taking into account phenomena capable of causing further deterioration in the plant status. The systems to mitigate the consequences of such operating occurrences are designed according to specific criteria (such as redundancy, layout and qualification). The objective is to bring the plant back to normal operating conditions as soon as possible.

Diagnostic tools and equipment such as automatic control systems can be provided to actuate corrective actions before reactor protection limits are reached; examples are power operated relief valves, automatic limitation systems on reactor power and on coolant pressure, temperature or level, and process control function systems which record and announce faults in the control room. On-going surveillance of quality and compliance with the design assumptions by means of in-service inspection and periodic testing of systems and plant components is also necessary to detect any degradation of equipment and systems before it can affect the safety of the plant.

Level 3

Engineered safety features and protection systems are provided to prevent evolution towards severe accidents and also to confine radioactive materials within the containment system. Active and passive engineered safety systems are used. In the short term, safety systems are actuated by the reactor protection system when needed.

To ensure a high reliability of the engineered safety systems, the following design principles are adhered to:

- Redundancy;
- Prevention of common mode failure due to internal or external hazards, by physical or spatial separation and structural protection;

- Prevention of common mode failure due to design, manufacturing, construction, commissioning, maintenance or other human intervention, by diversity or functional redundancy;
- Automation to reduce vulnerability to human failure, at least in the initial phase of an incident or an accident;
- Testability to provide clear evidence of system availability and performance;
- Qualification of systems, components and structures for specific environmental conditions that may result from an accident or an external hazard

Level 4

The broad aim of the fourth level of defense is to ensure that the likelihood of an accident entailing severe core damage, and the magnitude of radioactive releases in the unlikely event that a severe plant condition occurs, are both kept as low as reasonably achievable (ALARA).

Such plant conditions may be caused by multiple failures, such as the complete loss of all trains of a safety system, or by an extremely unlikely event such as a severe flood.

Measures for accident management are also aimed at controlling the course of severe accidents and mitigating their consequences.

Essential objectives of accident management are:

- to monitor the main characteristics of plant status;
- to control core sub-criticality;
- to restore heat removal from the core and maintain long term core cooling;
- to protect the integrity of the containment by ensuring heat removal and preventing dangerous loads on the containment in the event of severe core damage or further accident progression;
- regaining control of the plant if possible and, if degradation cannot be stopped, delaying further plant deterioration and implementing on-site and off-site emergency response.

The most important objective for mitigation of the consequences of an accident in Level 4 is the protection of the confinement.

Specific measures for accident management are established on the basis of safety studies and research results. These measures fully utilize existing plant capabilities, including available non-safety-related equipment.

Measures for accident management can also include hardware changes. Examples are the installation of filtered containment venting systems and the inerting of the containment in boiling water reactors in order to prevent hydrogen burning in severe accident conditions.

Adequate staff preparation and training for such conditions is a prerequisite for effective accident management.

Level 5

Off-site emergency procedures are prepared in consultation with the operating organization and the authorities in charge and must comply with international agreements.

Both on-site and off-site emergency plans are exercised periodically to the extent necessary to ensure the readiness of the organizations involved.

Safety Culture

The idea of safety culture should be an inherent understanding of any organization in the international nuclear industry, which is focused on safety. For better understanding two definitions may serve.

INSAG-4 definition: *Safety culture* is that assembly of characteristics and attitudes in organizations and individuals which establishes that as an overriding priority, nuclear plant safety issues receive the attention warranted by their significance.

NRC definition: A good *safety culture* in a nuclear installation is a reflection of the values, which are shared throughout all levels of the organization and which are based on the belief that safety is important and that it is everyone's responsibility.

12.2 Lessons Learned and Recommendations Derived

The overview of the TEPCO's Fukushima Daiichi nuclear power station (NPS) accident is depicted in Fig. 12.1 [also see Chap. 2 in this volume—eds.]. The essential lessons from the accident are described in [2]. The lessons learned concerning the reactor design and operation states of view and the recommendations dedicated thereof are described in this section.

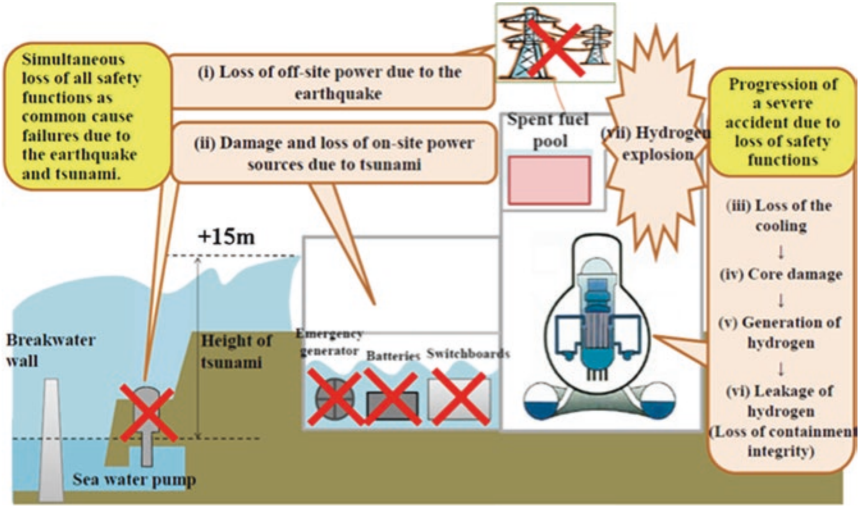


Fig. 12.1 Lessons learned from the Fukushima Daiichi nuclear power station accident [3]

12.2.1 Natural Hazards

Lessons

The accident was caused by the big tsunami. It flooded the reactor and turbine buildings. The emergency diesel generators (DGs) lost their function and all AC power supply was lost. The loss of function of the emergency diesel generators were caused by flooding of power supply panels and diesel generators themselves as well as loss of heat sink of the DG cooling by the flooding of sea water pumps.

The anti-seismic design of the plant worked well by the improvements after the big earthquakes in Kobe and Chūetsu-oki. The movements of multiple regions in the seabed caused the big earthquake of March 11, 2011. The acceleration on the base mat of the reactor building is, however, predicted well by the standard acceleration for safety grade system.

The safety systems did not lose function by the earthquake. The height of the tsunami was, however, underestimated. It is the most important direct reason for the initiation and progression of the accident. The tsunami was caused by the slides along the boundary of continental plates. The interaction of tsunami waves from multiple origins appears to make the waves high.

Recommendation

It is necessary to develop imagination of natural hazards and its combinations that may potentially cause severe accidents. For example, big hurricanes and typhoons cause extreme high tides that floods large area. The combination of external fires, tsunami and earthquakes may cause difficulty in the availability of the emergency power supply, cooling water and accessibility of the plants.

12.2.2 Emergency Power Supply

Lessons

The external power of the TEPCO Fukushima Daiichi plants was lost by the failure of transmission lines by the earthquake. The emergency DGs and some batteries were flooded. Both AC and DC power were lost. The capacity of the remaining batteries was exhausted. The safety systems and instrumentation systems lost their functions. Units 5 and 6 of the site survived with the electricity from an air-cooled emergency DG. The loss of DC power caused difficulty for the operators to know the condition of the plants and conduct timely actions.

Recommendation

It is necessary to enhance the reliability of both AC and DC power supply against external events and provide sufficient power in case of severe accidents. In case that they are lost, alternative power supplies need to be provided for the plant.

12.2.3 Loss of Heat Sink

Lessons
Loss of ultimate heat sink is the important lesson of the accident as well as loss of emergency power. Damage of seawater pumps by the tsunami caused multiple failures of functioning of pumps and heat exchangers needed for cooling and dumping heat into the sea.

Recommendation
Provision of protective measures such as bunkering of important components and/or alternative cooling devices as well as the water source is necessary.

12.2.4 Hydrogen Detonation

Lessons
The reactor building of Units 1, 3 and 4 were destroyed by hydrogen detonation. The building of unit 2 was not destroyed, because the blow- out panel of the reactor building dropped down by the detonation of Unit 1. The hydrogen detonation of Unit 1 building scattered the debris on the site and made preparation of securing activities for Units 2 and 3 difficult.

The primary containment vessels (PCVs) were inerted by nitrogen. Recombiners of hydrogen were equipped. The temperature and pressure of PCVs became high above the design conditions. The leakage of hydrogen from PCVs occurred at the penetrations and the gasket seals of the flange. It accumulated within the reactor buildings. Venting of PCVs caused hydrogen leakage to the piping connected to the stack.

The detonation of the reactor building of Unit 4 was thought to be caused by the leakage through the piping of stand-by gas treatment system (SGTS) connected to the common stack. The air operated valve of the SGTS piping failed open by the loss of power as well as the loss of air driving the valve as the backup. It caused the leakage of hydrogen from Unit 3 to Unit 4 that was not in operation at the accident [2].

Recommendation
The provision against hydrogen leakage at severe accidents should be elaborated and the respective measures should be performed.

12.2.5 Measurement at Severe Accidents

Lessons
Important reactor parameters such as water level, pressure and temperature could not be measured due to the loss of DC power after the tsunami. The water level, the most important safety parameter of LWRs was measured erroneously after

core melt down because of the change of the reference water level by evaporation due to the high containment temperature. It erroneously showed that the water level existed in the middle of the core. The wrong information confused the actions and harmed the reliability of the TEPCO information to the public. Mental bias of the specialists hoping the survival of the plants also decreased the reliability. It should be noted that the water level monitor did not work well at TMI-2.
Habitability of the main control room (MCR) was deteriorated at the accident. The air ventilation system of the MCR with charcoal filters lost the function.

Recommendation
Important reactor parameters as well as radiation level, radioactivity and hydrogen concentration in PCV need to be measured for management of severe accidents.

12.2.6 Management of Severe Accident

Lessons
The employees and workers at site had to conduct accident managements under extreme circumstances such as darkness, high radiation, loss of reactor monitoring and communication ability, scattered debris by earthquake, tsunami, and hydrogen explosions. Working under such conditions was not prepared at all. The command of TEPCO headquarters also suffered from difficulty in understanding the situations and making decisions.
The containment venting procedure is written in the manual that the director of the plant orders it. But it was negotiated with the central government and took time to be conducted. The seawater injection was halted by the order of the TEPCO headquarter, but it was continued by the decision of the plant director. There was confusion of command.

Recommendation
There should be a clear definition of information, decision responsibility and actions dedicated to the organizations involved during the management process in case of extreme situations or a severe accident.

12.3 Recommendations and Requirements Derived from Lessons Learned

All important organizations which are engaged in nuclear safety regulation have analyzed the Fukushima accident and have identified lessons learned and proposed recommendations which evolved from these lessons. These bodies were, for example, IAEA, NRC, ENSREG, ANS and Japanese organizations such as AESJ.

New regulatory requirements for commercial light water nuclear power plants were developed in Japan in July 2013, taking into account the lessons learned from the accident at Fukushima Daiichi Nuclear Power Station [3]. Major improvements include:

- Enforcement of resistance against earthquake and tsunami,
- Reliability of power supply,
- Measures to prevent core damage by postulating multiple failures,
- Measures to prevent failure of containment vessel,
- Measures to suppress radioactive material dispersion,
- Strengthen command communication and instrumentation,
- Consideration of natural phenomena in addition to earthquakes and tsunamis, for example volcanic eruptions, tornadoes and forest fires,
- Response to intentional aircraft crashes,
- Consideration of internal flooding, and
- Fire protection

These improvements are specifically required to be installed within the current Japanese reactor fleet as basic requirement for an allowance of further operation.

12.4 Examples for Potential Countermeasures and/or Technologies to be Applied

On basis of the identified lessons and countermeasures, some examples are described in more detail in the following sections of this chapter. There are three main areas selected as follows:

- External events,
- Design of buildings, systems and components, and
- Severe accident issues

12.4.1 External Events

There are some common countermeasures proposed for all external events which are considered to be generally applied for all extreme external events as follows:

- Develop an approach to regulate hazards from extreme natural phenomena;
- Periodically redefine and re-analyze the natural event design basis.

Since external events in most cases lead to a combination of initiating events such as earthquake and tsunami or earthquake and fire, such combined effects have to be systematically considered in the design. One proposal which could be considered as a good approach is recommended by Sustainable Nuclear Energy Technology Platform (SNETP) [4] as follows:

- Extending even further the in-depth safety approach to any type of hazards, in particular external ones, and accounting for any mode of combination of them;
- Systematically include the design extension conditions (beyond design basis accidents) in the defense-in-depth approach at the design stage.

According to SNETP, there is also the need for future studies and development in the following area:

- Development of approaches to natural hazard definition, techniques and data, and development of guidance on natural hazards assessments, including earthquake, flooding and extreme weather conditions;
- Development of guidance on the assessment of margins beyond the design basis and cliff-edge effects for extreme natural hazards;
- Development of a systematic approach to extreme weather challenges and a more consistent understanding of the possible design mitigation measures;
- Development of the approach for assessment of the secondary effects of natural hazards, such as flood or fires arising as a result of seismic events;
- Enhancement of probabilistic safety analysis (PSA) for natural hazards other than seismic (in particular extreme weather) and development of methods to determine margins and identify potential plant improvements;
- Overall enhancement of PSA analysis, covering all plant states, external events and prolonged processes, for PSA levels 1 and 2.

12.4.1.1 Earthquake

It is proposed from several organizations to increase the seismic design criteria for the evaluation and assessment of beyond design external events. There are some proposals available, such as those from Ref. [5], to increase the seismic design criteria to 1 degree of magnitude e.g. 0.2–0.3 g. Yet, there is no final decision that can be commonly agreed upon within the nuclear community. This is one of the tasks that have to be worked on by the respective organizations in the future.

It is now common understanding that a periodically redefinition and re-analysis of the earthquake design basis should be performed in the future. The regulatory basis has to be provided by the respective organizations.

In Japan, Nuclear Regulatory Authority (NRA) strengthened the examination of active faults. Seismic design needs to take into account of the faults that was active after 126,000 years ago (Late Pleistocene). If necessary, activity of the faults is examined up to 400,000 years ago. The ground acceleration should be determined taking the three-dimensional underground structures, which may amplify the acceleration. The safety-class structures and buildings should not be built on the active faults. The ground acceleration increases with the length of active faults. The length of faults needs to be determined including the examination of nearby seabed. Big earthquakes such as the movement between continental plates also need to be considered separately. The basic earthquake ground motion is determined from these points. It changes with the site of the nuclear power plants. Strengthening the seismic design of the plants is conducted after the approval of NRA.

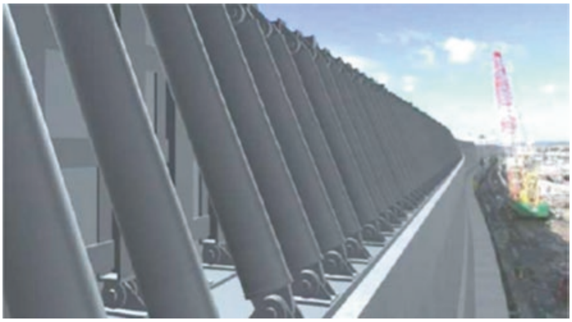


Fig. 12.2 Installation of a seawall to prevent site inundation [3]

12.4.1.2 Tsunami

The common countermeasures described above are also proposed for tsunami events.

As an example the standards set by the Japanese NRA define a “Design Basis Tsunami” as one that exceeds the largest ever recorded. It requires protective measures such as seawalls. The standards also require “structure, systems and components (SSCs)” for tsunami protective measures to be classified as class S, the highest seismic safety classification to ensure that they continue to prevent inundations even during earthquakes.

The examples of multi-layered protection measures against tsunami are installation of a seawall to prevent site inundation and installation of water-tight doors to prevent the flooding of buildings. An example for a seawall is shown in Fig. 12.2.

12.4.2 Design of Buildings, Systems and Components

12.4.2.1 Sites with More Than One Reactor

In case of multiple-unit sites, the following measures have to be considered:

- Strict separation of safety related systems and components, and
- Provision of a plant arrangement which prevents common cause failures for safety related systems and components,

There is no specific technology required; the design is related to well-known technologies that have to fulfill the specific design requirements.

The PSA should be the tool that enables identification of the areas that must be considered to strengthen the safety of multi-unit sites.

12.4.2.2 Off-Site and On-Site Electricity Supply

In case of an external event like an earthquake, the off-site electricity supply is very difficult or even impossible to maintain. This results not only from the direct effect on the grid structure like masts and cables, but also from the fact that other plants which feed into the grid may also be affected and consequently have to be shut down. Nevertheless, it should be evaluated whether it is possible to enforce the grid design, which may result in a higher chance for survivability of parts of the off-site grid connection.

Since the large uncertainty exists for the maintainability of the off-site grid in case of an earthquake, the way to substitute off-site electricity supply is mainly to provide mobile power supply systems or addition of diesel generators or other power sources such as gas turbines. These components must be protected against external events by bunkering or locating at positions which cannot be affected by e.g. tsunami waves.

NRA requirements for existing Japanese plants

In order to prevent common cause failures due to events other than natural phenomena, the measure against power failures is strengthened. For off-site power, independence of two circuits was not required before, but is required. For on-site AC power source, two permanently installed units, two more mobile units and storage of fuel for seven days are required. For on-site DC power source, one permanently installed system with a capacity for 30 min was required before, but increase of the capacity to 24 h duration and addition of one mobile system and one permanently installed system both with 24 h duration are required. Additionally, it is required that switchboards and other equipment should not lose their operational capabilities.

Loss of power supply and 3rd grid connection

To ensure that operational and safety-related components maintain their AC supply, in Germany nuclear power plants are forced to use a tiered back-up system: the main grid connection, the stand-by grid connection, the emergency power supply (ordinary back-up AC power source), and the emergency feed power supply (diverse AC power source). The different stages of the AC power supply allow it to cover different failures of the AC grid. An additional third grid connection is also available [6].

Robustness of emergency power supply

The measures to enforce the on-site power supply are in general the protection of the existing components against external events, to extend the capacity and timely availability, and provide diverse components.

In case of the Olkiluoto 3 Nuclear Power Plant (NPP) [7] the reactor plant electrical power system is divided into four parallel and physically separated subdivisions designed against external events. The power supply to equipment critical for safety of each division is backed up with a 7.8 MVA diesel generator. The Olkiluoto gas turbine plant can also supply the bus bars of the diesel generators. In case of the loss of all external power supplies, the malfunction of all four diesel generators at once, i.e. the complete loss of all AC power, the plant unit has two smaller diesel generators with an output of approximately 3 MVA each. These units are bunkered and can ensure power supply to safety-critical systems even in such a highly exceptional situation.

Another example is the “SUSAN” system of the Muehleberg NPP in Switzerland [8]. “SUSAN” is an acronym for “**S**pezielles **U**nabhängiges **S**ystem zur **A**bführung der **N**achzerfallswärme,” which means a special independent residual heat removal system. The main tasks are (1) to remove residual heat from the reactor pressure vessel (RPV) in the long term, (2) fast shutdown and isolation of the reactor and (3) limit and reduce the primary circuit pressure. The system is designed to resist design earthquake, protection against sabotage, flooding and airplane crash. The main system parts and equipment of SUSAN are located in a dedicated building, which is protected against impact from outside. Two 100 % emergency diesel generators are used to supply necessary pumps and systems with power in case of station blackout.

12.4.2.3 Bunkering of Buildings with Safety Related Systems

Emergency Feed Building

Recent German PWRs are equipped with a second four-fold emergency power supply (emergency diesel sets) [9]. These second emergency cooling systems can cool the reactor core (via steam generators) as well as the spent fuel pool (via auxiliary emergency cooling chain or emergency systems). Emergency diesel sets are equipped with diesel and water reserves conservatively lasting for at least 10 h and more. Emergency buildings (similar to regular emergency diesel housings) are also designed according to design basis regulations including flooding. A building arrangement of a typical emergency feed building is shown in Fig. 12.3. Air ventilation shafts and air suction holes are located in the upper part of the building, indicated by the circles in Fig. 12.3.

The emergency feed building is designed for airplane crash, explosion pressure wave, flooding, explosive gases, and earthquake, and is located separately from other buildings of the plant. It encloses the following:

1. Four additional EDGs (so called D2 Diesels): They serve for power supply in case of loss of offsite power (LOOP) and unavailability of the four main EDGs (D1 Diesels).

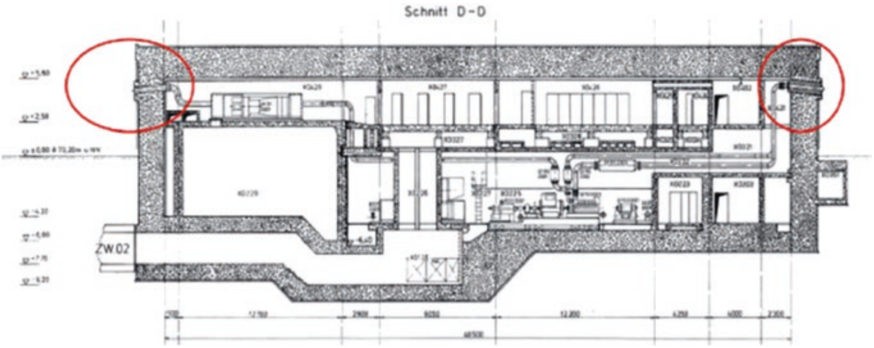


Fig. 12.3 Bunkered emergency feed building for recent German PWRs. The *circles* indicate air ventilation shafts and air suction holes located in the upper part of the building

2. Four trains of emergency feed water pumps: Directly driven by the D2 Diesels (but can also be power supplied by the D1 Diesels, if available): An emergency control room (RSS), including wash room, toilet, plant documentation.
3. Safety related instrumentation and control (I&C).
4. Safety related switchgears.
5. Dedicated heating, ventilation, air conditioning (HVAC) system (also powered by D2 Diesel).
6. Mobile equipment for secondary side bleed and feed.

Robustness of Cooling Chain in BWRs and PWRs

An example for the implementation of an additional cooling system and therefore for the robustness of the cooling chain of a BWR is described in the Stress test Report for German nuclear power plants [6].

An additional independent residual heat removal (RHR) system was installed in separated new building for Philipsburg 1 NPP, Brunsbuettel NPP both in Germany, Oskarshamm 1&2 NPP in Sweden, and Muehleberg NPP in Switzerland.

It serves as an independent heat sink for residual heat removal and power supply by diesels including cooling of the independent diesels in a separated new building. It is also possible to diversify, for example, by air-cooled cell cooling towers, wells etc. As another example, the ZUNA system of Gundremmingen 1&2 NPP may serve. This is a retrofitted, independent, additional residual heat removal and feed water system with a diverse heat sink by means of wet well cooling towers and diverse emergency power diesels (station blackout diesels). The ZUNA system is protected against external and internal events.

An example for the robustness of a fuel pool cooling system is the wet storage of spent fuel pool of Goesgen NPP in Switzerland [10]. The cooling during normal operation is provided by natural circulation. The temperature of the pool is 45 °C maximum with support of fans in case of high outside temperature and fully loaded fuel pool. The cooling in case of accidents is provided by natural circulation without need of electrical supply. The temperature of the spent fuel pool depends on the type of accident, but up to max 80 °C.

12.4.2.4 Passive Components and Systems Using Natural Forces

Passive components do not need external power since they rely on laws of physics such as gravity, heat transfer by temperature difference or pressure increase though heating of enclosed fluids.

Isolation Condenser

Isolation condenser (IC) is a passive system of BWRs for emergency cooling located above containment in a pool of water open to atmosphere. The scheme is

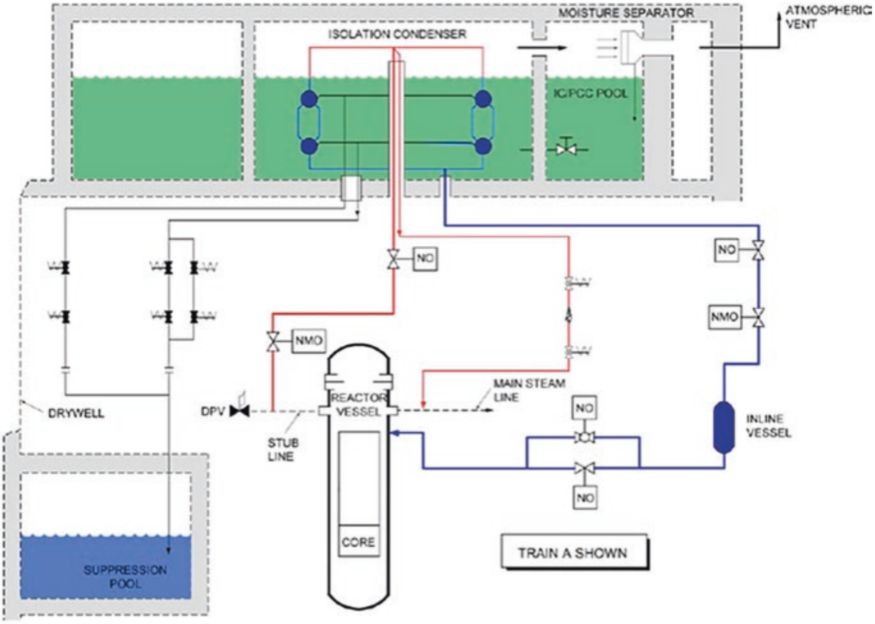


Fig. 12.4 Isolation condenser [11, 12]

shown in Fig. 12.4 [11, 12]. Under normal condition IC system is not activated, but the top of the IC is connected to the reactor's steam lines through an open valve. Steam enters the IC until it is filled with water. When the IC system is activated, a valve at the bottom of the IC is opened which connects to a lower area on the reactor. The water flows to the reactor via gravity, allowing the condenser to fill with steam, which then condenses. This cycle runs continuously until bottom valve is closed. In case of electricity failure, the valve closes automatically and operators have to open them manually. Fail-open valves and lines need to be installed for severe accidents.

Gravity Driven Cooling System

The gravity-driven cooling system (GDCS) injects water to the RPV by gravity. The GDCS pool locates at higher elevation than the RPV. Squib valves from the DC safety related power from batteries activate the system. The schematic diagram of ESBWR GDCS is provided in [11, 12].

Passive Containment Cooling System

Passive containment cooling system (PCCS) of ESBWR consists of a set of heat exchangers located in the upper portion of the reactor building. The steam from the reactor flows through the containment to the PCCS heat exchangers where the steam is condensed. The condensate drains backs from the PCCS heat exchangers where the steam is condensed to the GDCS pools. For more detail, refer to [11, 12].

The passive safety systems of ESBWR are discussed in [11, 12]. In the events where the reactor pressure boundary remains intact, the isolation condenser system(IC) is used to remove decay heat from the reactor to transfer it outside containment. In the events where the reactor pressure boundary does not remain intact and water inventory in the core is lost, the PCCS and GDCS work in concert to maintain the water level in the core and remove decay heat from the reactor and transferring it outside containment. When the water level of the RPV drops to a predetermined level, the reactor is depressurized and the GDCS is initiated. Both IC and PCCS heat exchangers are submerged in a pool of water large enough to provide 72 h of reactor decay heat removal capability. The pool is vented to the atmosphere. It is located outside of the containment. It will be refilled easily with low-pressure water sources via pre-installed piping.

Emergency Condenser

Emergency condensers (ECs) are used for residual heat removal from the RPV. The residual heat is released into the core flooding pool inside the containment, not outside of it as the isolation condenser. The schematic drawing of the ECs is shown in Fig. 12.5 [13]. Each of the four ECs consists of a steam line (to connection) leading from an RPV nozzle, and a condensate return line (lower connection) back to the RPV. Each return line is equipped with an anti-circulation loop. The ECs are connected to the RPV without any isolating element and

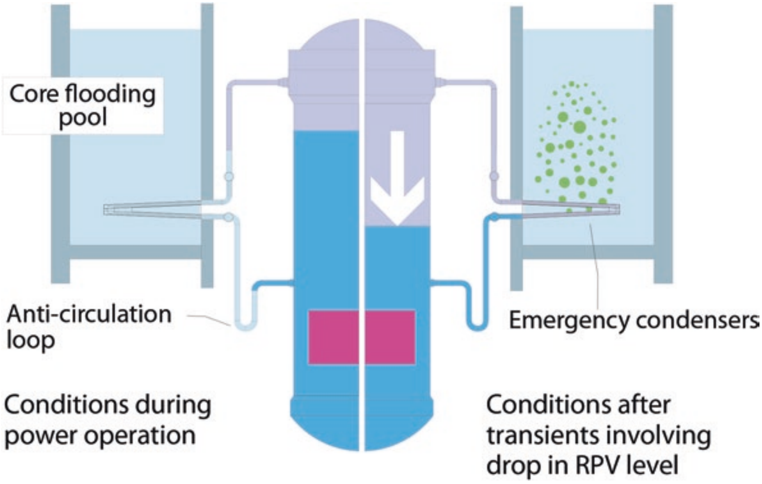


Fig. 12.5 Emergency condenser [13]

are actuated by a drop of the RPV water level. In the event of water level drop in the RPV, steam from the RPV enters the heat exchanger tubes of the ECs, located in the core flooding pools and condense inside the pipe. The condensate returns back into the RPV. This system assures core cooling even at high RPV pressure.

The ECs are used for the KERENA^{TM} (formerly SWR-1000) reactor, an advanced BWR in Germany. The cross section of the KERENA^{TM} reactor containment is shown in Fig. 12.6 [13]. Shielding/Storage pool is on top of the containment. It is used as a heat sink to remove the heat from the containment. The water inventory is sufficient to ensure passive heat removal for at least 3 days.

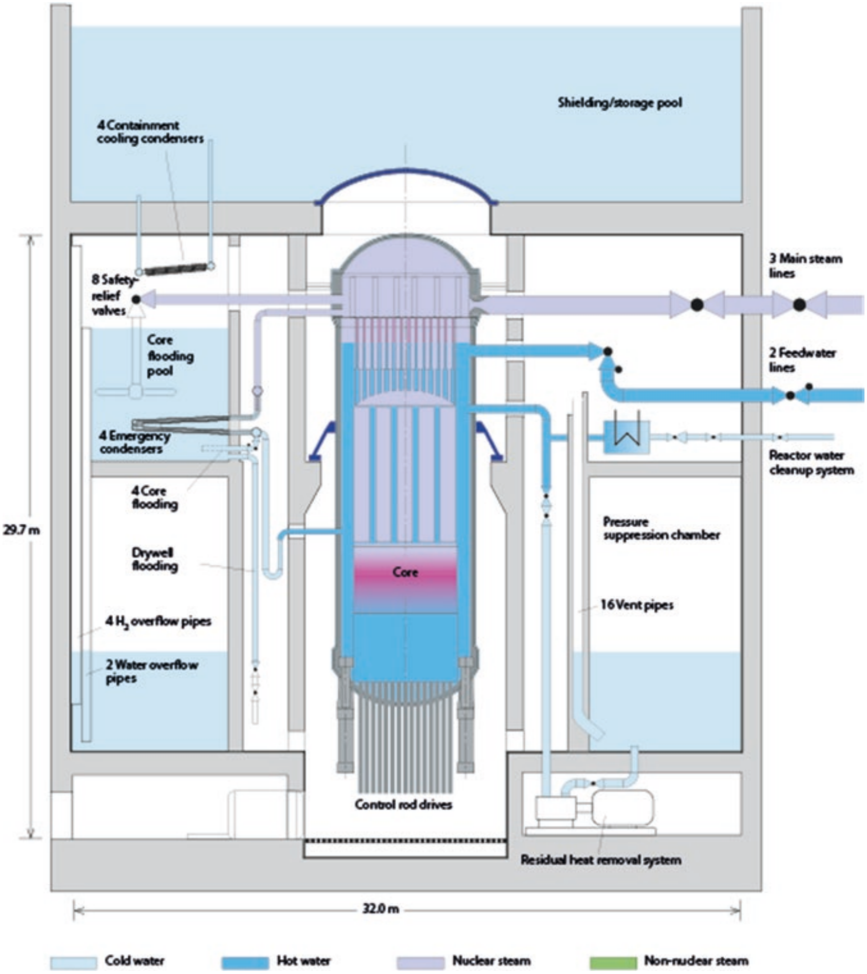


Fig. 12.6 Section through the KERENA reactor containment [13]

Containment Cooling Condenser

In case the ECs are in operation or when the safety relief valves are opened in case of LOCA, the water of the core flooding pool starts to evaporate and the pressure in the containment will increase. Containment cooling condensers (CCC) are installed above the core flooding pools as seen in Fig. 12.7.

The heat exchanger tubes are slightly inclined. Both inlet and discharge lines are connected to the shielding/storage pool and are open during normal operation. When the temperature increases inside the containment, the water in the CCC starts to heat up so that a natural circulation flow establishes in the system.

Passive Pressure Pulse Transmitter

The passive pressure pulse transmitters (PPPT) function without electric power supply, external media, or actuation via I&C signals. The PPPTs serve to initiate scram, containment isolation of main steam lines, and automatic depressurization of the RPV. The PPPT consists of a small heat exchanger connected to the RPV via a non-isolatable pipe, as shown in Fig. 12.8.

The secondary side of the heat exchangers is connected to a diaphragm pilot valve via a pipe. During normal operation the PPPTs are filled with water. In case of water level drop inside the RPV, the water level in the tube of the PPPTs drops as well. When the primary side of the heat exchanger is filled with steam it will condense and drains back into the RPV while in the secondary side of the heat exchanger the temperature rises until the water starts to evaporate. The design of the heat exchanger is such that the activation of the systems is done in the required time. By means of the increased pressure, a function is triggered via the diaphragm pilot valve.

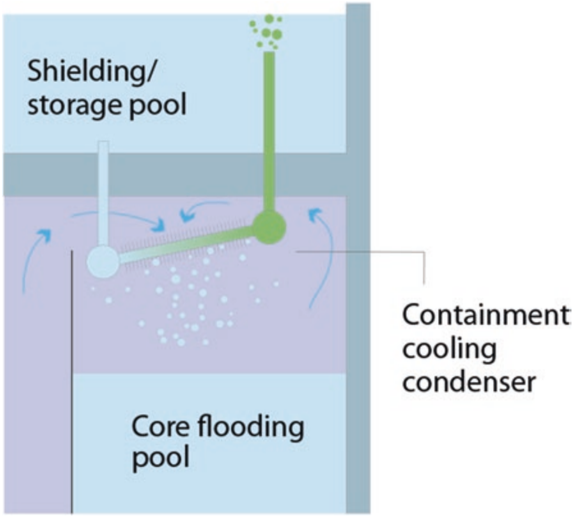


Fig. 12.7 Containment cooling condenser [13]

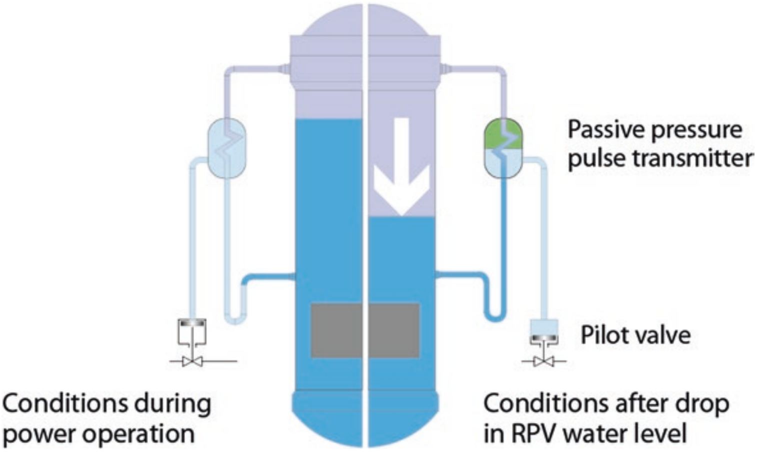


Fig. 12.8 Passive pressure pulse transmitter [13]

Passive Residual Heat Removal System

The passive residual heat removal system (PRHR) of advanced PWR, AP1000^{TM} provides reactor cooling by natural circulation through the core as shown in Fig. 12.9 [14].

The heat exchanger of PRHR is located in the in-containment refueling water storage tank (IRWST). The decay heat is transferred to the cooler water in the IRWST. The reactor coolant water in PRHR becomes cooler and denser and cools the core. The cycle continues until the water of the IRWST is depleted. Large amount of water is, however, stored in the IRWST. The decay heat is transferred to the water of IRWST in the containment vessel (CV) with PRHR and steam is generated. The IRWST is vented to the containment vessel and increase its pressure.

Passive Containment Cooling System

The passive containment cooling system (PCS) of AP 1000^{TM} is shown in Fig. 12.10 [14].

Passive containment cooling water storage tank (PCCWST) is located in the roof structure of the containment building. The water will be dispersed via gravity to the top of the CV from PCCWST. The water film covers the steel surface of the CV. The airflow through the annulus removes the heat from the CV by evaporation of the water.

The outside air flows into the outer annulus from the inlet louvers. It flows down and flows up in the inner annulus between the CV wall and the air baffle. Evaporating water is applied to the top of the CV from PCCWST. The steam is exhausted through the chimney area to the atmosphere. PRHR heat exchanger

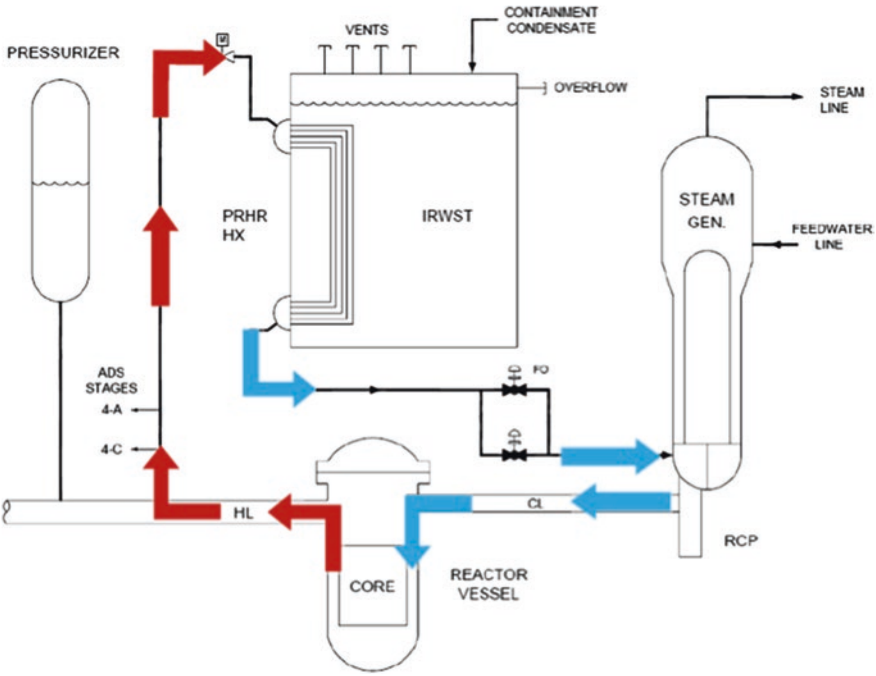


Fig. 12.9 Passive residual heat removal system (PRHR) [14]

transfers decay heat to the in containment refueling water storage tank to the containment atmosphere. The steam is condensed by PCS operation and returned via gravity-drain gutters to the IRWST again.

Advanced Accumulator

An advanced accumulator (ACC) is a passive device leading to a discharge characteristic of high and low flow rate using a vortex flow damper to cope with large break loss of coolant accident (LOCA) of a PWR [15–17]. High flow rate is required for the refill of RPV after large break LOCA, but low flow injection is necessary for reflooding of the core. The function was provided by an accumulator firstly and low head injection pump secondly in the current system. The switching off the systems is necessary. The new system of ACC operates at high flow rate firstly and low flow rate secondly by means of the vortex flow damper. It can eliminate the low head injection pumps and storage tank for safety injection of the present system.

A vortex chamber is provided at the bottom of accumulator tank as shown in Fig. 12.11. A standpipe is connected to the vortex chamber that is connected to the injection pipe. At high water level, water comes into both large and small flow pipes. Since the mass flow through the standpipe is large and is radially directed

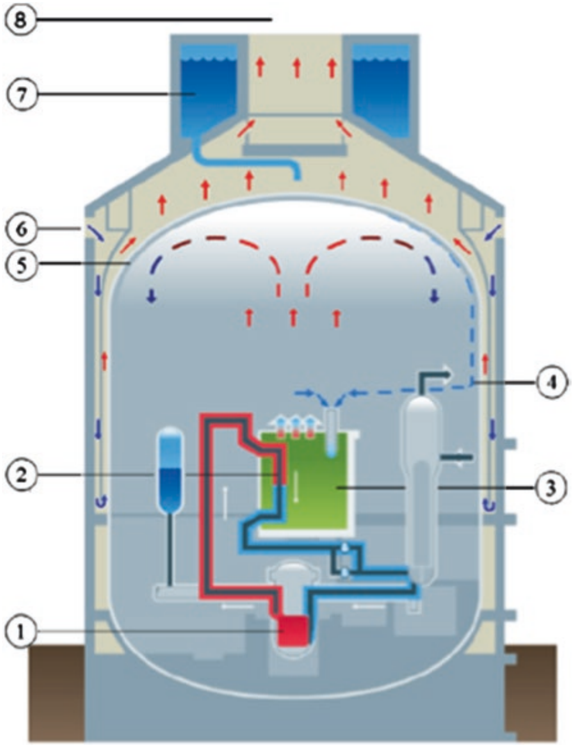


Fig. 12.10 Passive containment cooling system [14]. *1* Core, *2* PRHR, *3* IRWST, *4* Gutters, *5* CV, *6* Louvers, *7* PCCWST, *8* Atmosphere

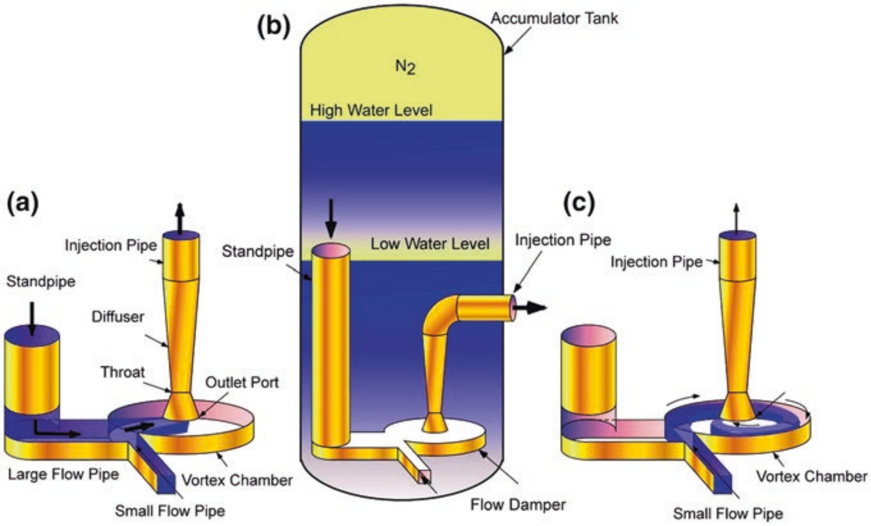


Fig. 12.11 Principle of advanced accumulator [17]. **a** Large flow rate (RV refilling). **b** Water levels in accumulator tank. **c** Small flow rate (core reflooding)

to the vortex chamber, it dominates the injection mass flow at the outflow without forming a vortex in the vortex chamber. Consequently the coolant is injected at high flow rate. At low water level, water stops flowing into the standpipe. The flow from the small flow pipe connected circumferentially to the vortex chamber forms a strong vortex in the vortex chamber. The coolant is injected with small flow rate due to the vortex.

12.4.2.5 Actual Japanese NRA Requirements Related to Buildings, Systems and Components

Installation of permanent backup facilities designed as "specialized safety facility" is required as the measures against intentional air craft crashes, etc.

Measures are strengthened for fire protection and internal flooding which trigger simultaneous loss of all safety function due to common cause.

Measures are required to prevent core damage even in the event of loss of safety functions due to the common cause. For example, a safety-relief valve(SRV) is opened by using mobile power sources to reduce the RPV pressure and water is injected using mobile water injection system.

Measures are required to prevent CV failures in the event of core damage. For example a filtered venting system is installed to reduce the pressure and temperature of CV and to remove radioactive materials. A system such as mobile pumps, hoses etc. are to be prepared to inject water into the lower part of the CV to prevent its failure. It is shown in Fig. 12.12.

In order to suppress radioactive materials dispersion in the event of CV failure, deployment of outdoor water spray equipment is required to douse the reactor building and prevent a plume of radioactive materials contaminating the atmosphere.

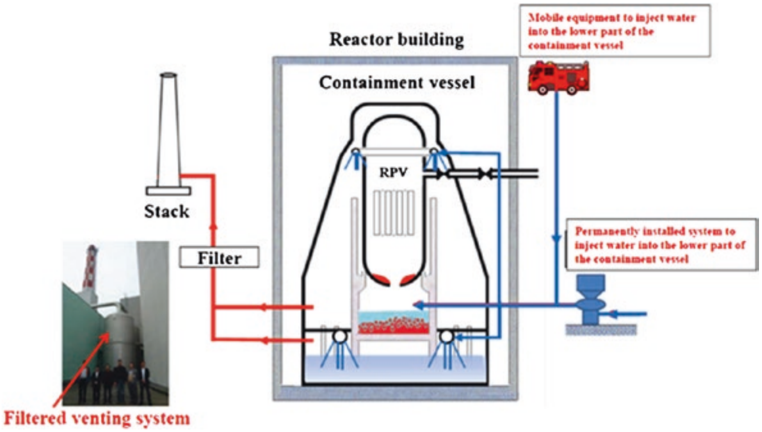


Fig. 12.12 Measures to prevent containment vessel failure [3]

12.4.3 Mitigation Measures Against Severe Accidents

12.4.3.1 Hydrogen Mitigation

Hydrogen and other flammable gases represent a key contributor to potential containment failure risk and therefore must be effectively eliminated. Reactor type as well as containment type, size and internal configuration and the selected melt mitigation strategy (in-vessel or ex-vessel molten corium cooling) are determining factors. Several provisions are generally available for mitigation of hydrogen risks, including containment venting, inerting, mixing, use of hydrogen igniters and passive autocatalytic recombiners (PAR).

After TMI-2 in 1979 attention was focused on the hydrogen produced by metal-water reactions in a degraded core accident. As a consequence, certain types of non-inerted operating plants installed electrical powered igniter system to control hydrogen build-up under severe accidents to prevent potential detonations at average uniform concentrations greater than 10 %. Later on, a new, simpler device called the passive autocatalytic recombiner (PAR) was developed, which is now considered as an appropriate system for the future.

The principle and concept of a passive autocatalytic recombiner is shown in Fig. 12.13 [20]. The PAR has a metal housing with a gas inlet at the bottom and a lateral gas outlet at the top. Catalysts are arranged in the bottom part of the housing. Housing protects the catalyst from direct spraying of water and aerosol deposition. H_2 molecules coming into contact with the catalytic surface react with ambient O_2. Reaction between H_2 and O_2 is an exothermic process with high activation energy (600–650 °C). By the use of catalysts the energy can be reduced to ambient condition. Reaction heat (exothermic process) reduces density of gas. It induces buoyancy-driven flow through PAR. Natural convection is increased by the chimney effect of PAR housing. Hot gas/steam mixture leaves PAR at the top.

The hydrogen issue in a PWR dry containment can be solved by 20–40 PARs distributed inside the containment. With this measure, the global hydrogen concentration can be limited to 10 vol. % and in case of deflagration the containment pressure can be kept below the design pressure. Global detonation is prevented [19].

BWR containments generally are inerted by nitrogen. Therefore only a few PARs in the drywell and wetwell are required which are able to limit the oxygen (from radiolysis) concentration below the flammability limit of 5 vol. %.

Acting in combination with igniters or pre-inerting, PARs deplete hydrogen in non-inerted containment atmospheres and oxygen in inerted atmospheres, such that no detonations or uncontrolled burning takes place that could cause failure of safety-related structures or components.

12.4.3.2 Containment Venting Systems

Motivation and objectives for filtered containment venting systems are to decrease the containment pressure in severe accident sequences when energy and fission

Fig. 12.13 Passive autocatalytic recombiner (PAR)

products are released into the containment, if the pressure exceeds a specified limit (prevention of late containment failure) and to limit the level of releases into the environment via the atmosphere. Different principles for containment venting systems are available such as dry filter systems and scrubber systems.

Dry Filter Method

The dry filter method (DFM) is a venting system that consists of the combination of two types of filters.

A metal fiber filter that retains airborne radioactive aerosols (aerosol filter) and a molecular sieve with doped zeolite for chemisorption of gaseous radioactive elemental iodine and its organic compounds (iodine filter).

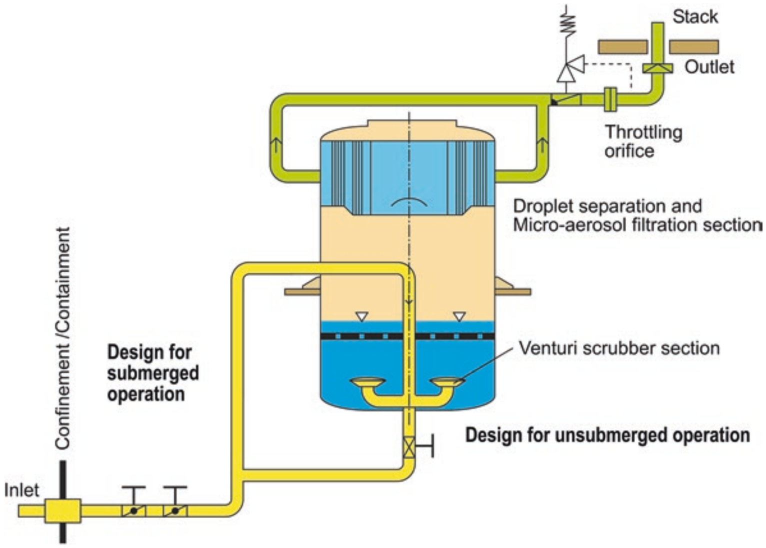


Fig. 12.14 Venturi scrubber

A droplet separator prevents water droplets from entering the filtered containment venting system (FCVS). The venting system can be actuated either remotely by opening containment isolation valves or by a rupture disc, depending on regulatory and/or customer requirements.

Scrubber System

This system is double-staged and uses the advantages of a high-speed venturi scrubber technology combined with highly efficient filter features. The system operates by passing the vented vapors from the containment atmosphere through a scrubber/filter vessel to remove high activity isotopes and aerosols to contain the radioactive releases. The filter unit is a wet scrubber system with chemical control. In the second cleaning stage, the micro-aerosol filter combination equipped with metal fibers helps to avoid significant long-term re-entrainment. The second part of the filter unit retains the aerosol particles that are usually too small for retention by any scrubber and droplet separation devices. A venturi scrubber is shown in Fig. 12.14 [20]. For both PWR and BWR dry filter or scrubber systems are installed in many nuclear power plants all over the world.

12.4.3.3 Melt Stabilization Measures

If a core in LWRs starts to melt and cannot be cooled within its original configuration, fuel, cladding and core structures will form a core melt within the RPV. In order to prevent the failure of the RPV or the containment, cooling mechanisms have to be implemented which will keep the core melt either within the RPV or within the containment. The stabilization and termination of the accident if it is successful with the coolability of the core melt in the bottom head is called In-Vessel melt Retention (IVR) and the same, if successful with the coolability of the melt on the concrete base mat or within a special coolable configuration (core catcher) is termed as ex-vessel melt retention.

In-Vessel Melt Retention

In-vessel melt retention (IVR) is the retention of core melt by thermally stabilization in the reactor vessel by RPV outside cooling. The principle of this concept of IVR is depicted in Fig. 12.15. Specific requirements of IVR are:

- It must be activated manually or coupled to severe accident signal.
- Flooding must be completed before corium relocation into the lower vessel head.
- At any melt-contacted location internal heat fluxes must be lower than local CHF limits on the outside.
- Suitable two-phase flow conditions must be established.
- Suitable water reservoir and flooding strategy; preferred water level in the pit near hot leg level.
- Elevated water reservoir with sufficient volume to cover the grace period, (period of no operator action necessary) for the unavailability of active measures.

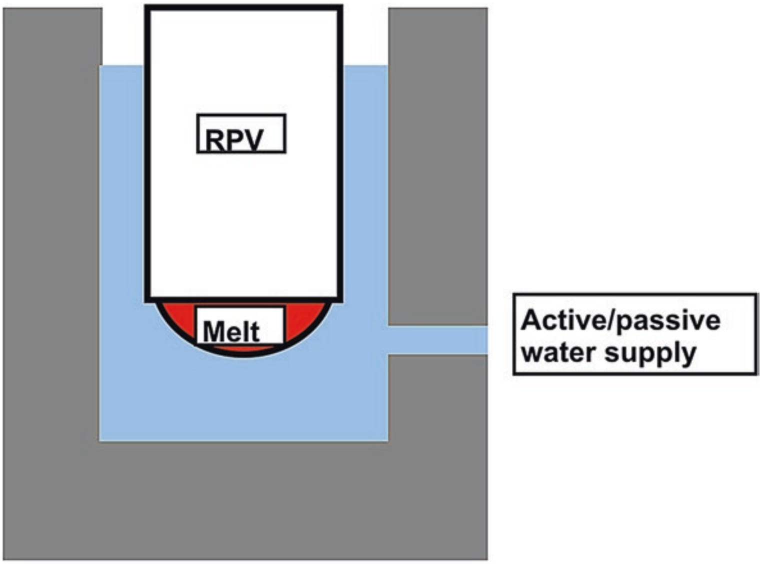


Fig. 12.15 Concept of in-vessel retention

Issues related to thermal regime of IVR have been studied in detail with dedicated experimental devices. The heat transfer distribution from a convective, volumetrically heated pool has been studied with facilities of various scale and geometry. The Rasplav [27] and MASCA [28] projects have employed real corium materials and thus played a significant role in confirming the applicability of the results obtained with simulant materials. Even though the heat transfer distribution from a molten metallic layer is relatively well known, there is still some uncertainty attached to the thickness of the metallic layer, which ultimately determines the magnitude of the focusing effect. However, when attempting to apply IVR to reactor with higher power density, the focusing effect during intermediate states becomes a major issue. Efforts are still needed for better understanding of the corium relocation process into the lower plenum, the formation of a molten pool there and the height of the metallic vs. oxidic layers as a function of time.

Ex-Vessel Melt Retention

Two PWR designs for which currently projects are under way rely on ex-vessel corium retention for the management and stabilization of corium within the containment: the EPR^{TM} and the VVER 1000. In these designs it is considered that in-vessel retention cannot be proven for large power reactors in all severe accident scenarios, therefore dedicated core catchers have been designed that can gather the corium and cool it safely without violating the containment basemat. The principle of ex-vessel melt retention (EVR) is shown in Fig. 12.16. Specific requirements are:

- Suitable water reservoir and flooding strategy (longer lead time than for IVR).
- Sufficient cavity size/volume.
- Openings for pit flooding must be protected against melt ingress.

Ex-vessel retention and coolability are also considered in a flooded pit for BWR's in Nordic Countries (Sweden, Finland) [25]. In these reactors, it is expected that after a vessel melt-through the corium will be fragmented in the flooded cavity and form a coolable debris bed.

Another proposal is the application of so called "EPRI concept" based on the provision of a certain spreading area for corium on the basemat and fragmentation of the melt through corium concrete interaction with water infiltration from above. It is assumed that this process will lead to a stable fragmented bed, which can be cooled and stabilized without penetration of the containment liner.

A concept was studied and tested by FZK (Research Center Karlsruhe), Germany, which relies on penetration of water through the melt from below which shall lead to a stable fragmented and coolable bed.

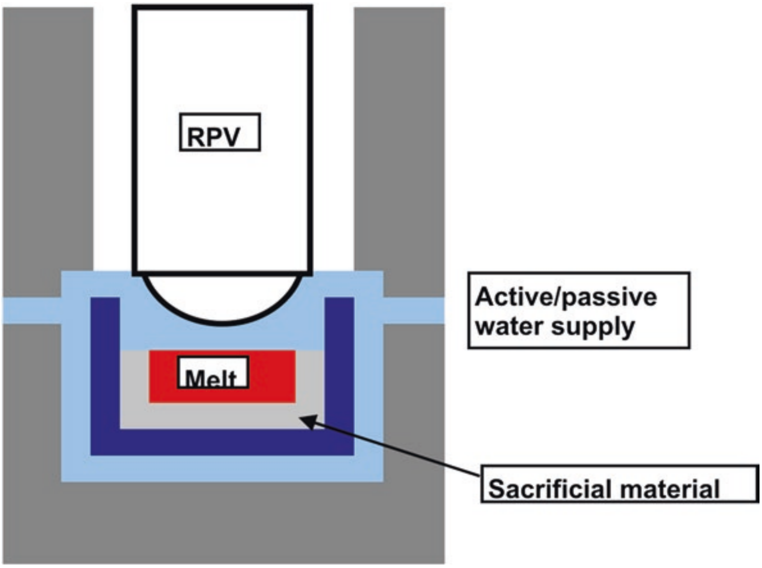


Fig. 12.16 Concept of ex-vessel retention

The operational principle or ex-vessel melt retention (crucible) is core melt collected and thermally stabilized within pit/cavity. It avoids most IVR-related concerns thanks to the addition of sacrificial material, which influences chemistry, stratification and heat fluxes.

Core Catcher Concepts

The EPR^{TM} melt retention (core catcher) concept

The scheme of the principle of the EPR^{TM} core catcher concept is shown in Fig. 12.17. For the stabilization and long-term cooling of the molten core, the EPR^{TM} relies on an ex-vessel strategy, which implies the spreading of the molten core on a large area with subsequent flooding and quenching. The resulting, high surface-to-volume ratio allows an effective cooling of the spread melt, even without crediting superficial fragmentation [21].

Melt relocation into the core catcher is promoted by a preceding temporary retention of the melt in the pit, with the admixture of sacrificial concrete. This results in an accumulation and pre-conditioning and enhances the ability of the melt to spread.

The principles of the main sequences are as follows:

- Temporary melt retention to accumulate and condition the core debris in the pit by means of sacrificial material (step 1).
- Spreading in one event into the core catcher after penetration of the melt plug (step 2).

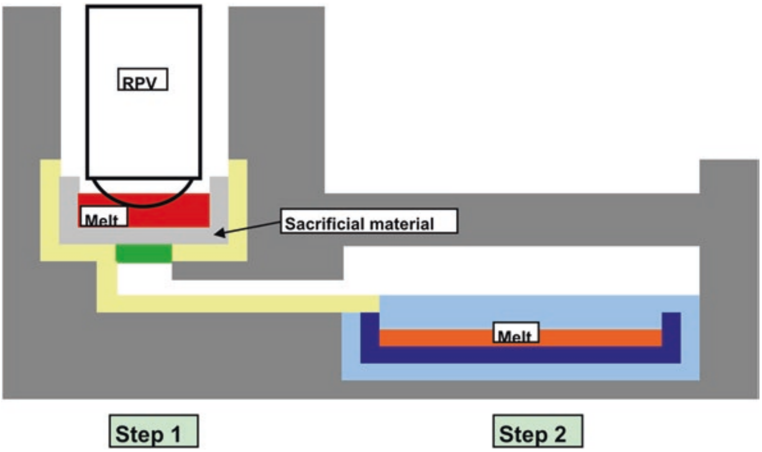
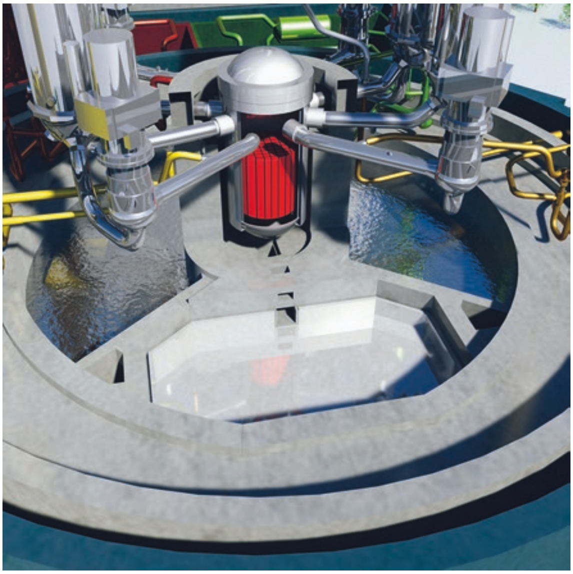


Fig. 12.17 Principle of the EPR^{TM} core catcher concept

Fig. 12.18 EPR^{TM}IRWST, spreading room and core catcher [7]



- Triggering of flooding valves which activate gravity- driven water overflow from the IRWST, Quenching and passive cooling of the melt by the evaporation or heat- up of water.

A picture of EPR^{TM} [7] IRWST, spreading room and core catcher is shown in Fig. 12.18. ATMEA, a 1000 MWe class PWR of Mitsubishi-AREVA also adopted this type of core catcher.

The VVER 1000 crucible concept

The core catcher of VVER 1000, a crucible concept is discussed in [22]. External heat fluxes to side/bottom can be adjusted by amount and type of added sacrificial material. Thermal-chemical interactions are not of concern; stabilization solely based on cooling and crust formation. Concept is used in VVER-1000 in China and India.

The crucible-type catcher comprises: a water-cooled steel vessel, a container with sacrificial material under the reactor bottom plate. The vessel performs the function of the main corium-retention barrier. The vessel comprises a vertical lateral part and a cone-shaped bottom with 12÷16° canting angle allowing the critical heat flux increase as compared to semi-elliptical or hemispherical bottom. The inner space of the vessel is sealed by a steel sheet preventing water penetration into the vessel prior to the molten corium relocation. Such a measure considerably reduces the probability of steam explosion. In a low probable case of a simultaneous water and corium relocation into the core catcher, the risk of steam explosion is reduced down to the negligible level by the honeycomb structure inside the catcher.

Other core melt stabilization concepts

European safety requirements are satisfied with limited modifications of the current ABWR [23]. The ESBWR proposes a so-called BiMAC (Basemat-internal Melt Arrest Coolability) concept located below the reactor pressure vessel [24]. It is a core catcher combined with passive containment cooling.

EPRI requirement

The EPRI requirement is used for the melt spreading, flooding and quenching on concrete in USA. “EPRI criterion” [26] requires that a spreading area should be larger than 0.02 m^2/MWth. Its function is based on water ingression and continued thermal cracking/fragmentation at the top. It is deduced from observations for volcanic magma flows. Its efficiency was first investigated for molten corium in the MACE/CCI test program at Argonne National Laboratory. The concept was developed for existing generation two (Gen-II) plants, but applied also in generation three (Gen-III) designs.

The basis for the “EPRI requirement” is as follows:

1. Decay heat considered to 1 % of thermal power
2. Removable “reference heat flux” from debris bed 1 MW/m^2
3. Assumption of a “conservative design factor” of 0.5

Using these figures the following specific number can be generated:

Area/thermal power = $0.01/(0.5*1\ \mathrm{MW/m^2}) = 0.02\ \mathrm{m^2/MW_{th}}$.

12.4.3.4 Severe Accident Instrumentation

A severe accident instrumentation concept consists of the availability of appropriate instrumentation in order to (1) perform operator actions, (2) inform about the progression of the accident and survey the effectiveness of the mitigation process, (3) survey the overall plant conditions including possible releases to the environment.

Table 12.2 Essential PWR parameters for severe accident management

Reactor
–RCS level
–RCS pressure
–Reactor power
–RCS injection flow
–Core exit temperatures
Containment
–Containment pressure
–Containment temperature
–Containment water level
–H_2/O_2 concentration
–Radiation levels
–Containment injection flow
–Containment spray flow

Table 12.3 Essential BWR parameters for severe accident management

Reactor
–RPV water level
–RPV pressure-reactor power
–RPV injection flow
–RPV metal temperatures
Primary containment
–Containment pressure/temperature
–Containment water level
–H_2/O_2 concentration
–Radiation levels
–Containment injection flow
–Drywell spray flow
Secondary containment
–Containment temperature
–Water level
–Radiation level

Instrumentation for Severe Accident Management

The essential parameters for severe accident (SA) management are shown in Table 12.2 for PWR and Table 12.3 for BWR.

Instrumentation for Containment Integrity

Important containment parameters relevant for severe accident management (SAM) strategy are combustible gas production (H_2, CO) and information on radioactivity content of aerosols, noble gases, iodine etc. The information is necessary for defining venting strategy, capability to derive the damage state of the core and the radioactivity level in the containment.

Measurement of combustible gas (H_2, CO) concentrations is necessary in order to get information about core degradation and location, and to succeed in mitigation measures. Containment pressure and containment temperature need to be measured to know pressure buildup in containment due to decay heat. Positions of core melt within the containment need to be known.

For identification of containment leak-tightness, measurement of specific parameters in adjacent compartments, for example, H_2-concentration, pressure build-up etc. is necessary.

Post Accident Sampling System

A post-accident sampling system (PRONAS) has been developed and is described in [18]. The technical features are:

1. Analysis of containment gases: Aerosol bound radionuclides; Non-aerosol bound (gaseous) iodine isotopes, radioactive noble gases (Xenon & Krypton)
2. In situ sampling technology
3. No loss of accuracy in pipes
4. High dilution technology enabling easy handling of the samples
5. Gases are diluted in modules and discharged from a sampling box
6. In situ micro sampling based on capillary pipe technology which requires no containment penetration valves
7. Design basis and SA qualified hardware
8. Entire measuring equipment outside containment
9. Capability for oxygen monitoring (for BWR)

12.5 Summary

The lessons learned from the Fukushima Daiichi accident support safety enhancements to cope with events that go beyond the design basis. Nevertheless the fundamental concepts of defense-in-depth still remain valid for nuclear safety. In case of higher uncertainties of external hazards, the effective implementation of the defense-in-depth requires additional means.

Concerning the structures, systems and components, technology and concepts exist which can cope with this type of accidents. With respect to severe accident mitigation, most of the technologies required to cope with Fukushima type accidents is considered to be already available, too.

External hazards
From the technological point of view it has to be stated that every measure that needs to be installed to cope with stricter requirements for both earthquake and

tsunami hazards is available. This is explicitly demonstrated by the already started or even finished measures for the enforcement of the plants up to now.

The main issue for the enforcement of the plants is to find out the design requirements which have to be considered concerning the beyond design basis conditions.

Enforcement of structures, systems and components

The main issue of multi-unit sites is to identify weak points of individual units. They are considered to be as follows:

- Common cause failures that lead to the failure of safety related systems and/or components, and
- Connections among units that may affect intact structures, systems or components from hazardous conditions of other units which consequently may lead to their failure

The PSA is considered to be the tool that enables to identify the areas which must be considered to strengthen the safety of multi-unit sites.

Since after an external event like an earthquake the offsite electricity supply is very difficult to guarantee, for such case the solution is mainly to use mobile equipment which is to be stored in the vicinity of the plant with the guarantee that it can be connected to the respective plugs at the plant under all circumstances. Only in cases where an offsite electricity source is very closely located to the plant site it can be considered to harden the source and the connection appropriately.

For the enforcement of onsite emergency energy supply many examples exist for bunkered systems, which were back-fitted and therefore are already provided for existing plants. So, the technology for such components is available; for example, diverse diesel generator systems with appropriate reliability for their function exist.

The main issue to strengthen the safety related structures, systems and components (SSC) in case of extreme external events is as follows:

- enforce the design of existing SSCs
- add alternative and/or additional SSCs
- use bunkered solutions
- provide passive components which need no electricity supply

For all these measures the technology is available and there exist a number of executed solutions for existing reactors. It is a matter of individual plant design what measure could be appropriate to strengthen existing SSCs considering also the impact on the economics effects of the plant.

Severe accident mitigation measures

The use of catalytic recombiner can be regarded as the most suitable hydrogen hazard mitigation strategy for nuclear power plants in the future because of its passive behavior, its well-known physical phenomenology, its efficiency under both beyond-design-basis and design-basis accident conditions, its start-up at low hydrogen concentration, and its simple use without supplementary constraints in normal operation.

All venting systems have passed a number of qualification tests and most of them were already installed in NPPs, meaning that they have successfully passed a licensing process. Decisive criteria for the selection of one of the systems have to be defined by the respective utilities under consideration of their regulatory requirements.

For existing reactors the back-fitting of RPV outside cooling is a very complex and expensive measure, and may be only possible from the technical point of view for very limited applications. It is expected that in most cases for the cooling an active system must be provided. In such cases it is proposed to use such an additional active system to inject water into the vessel instead injecting it for outside cooling. For existing BWRs, the method proposed by the Nordic countries could be a solution if it is assured that the cavity around the RPV can be filled with water passively and the water tightness of the compartment can be maintained.

In other cases, the proposal considering melt concrete interaction could be a solution, which may lead to an extension of the time the melt can be contained within the containment boundaries or even will be stabilized within the containment. For both solutions further effort of research and development is required.

Core catchers are mainly proposed for Generation 3+ reactor systems. Up to now already some concepts have been successfully developed and licensed, such as those for the VVER and EPR^{TM} reactors, and are implemented in ongoing projects.

Appropriate instrumentation qualified for severe accident conditions is one of the main prerequisites for an efficient severe accident management. In order to improve existing measures, it is required to consider this issue and implement severe accident related instrumentation for hydrogen monitoring or radioactivity monitoring. In addition the instrumentation that reliably indicates the state of the plant such as temperature, pressure and water level measurement have to be qualified for severe accident conditions at elevated temperatures and radioactivity doses.

It should be noted that management, command and control of severe accident for reducing the socio-psychological impact is important, although it is not addressed in this chapter.

References

1. International Nuclear Safety Advisory Group (INSAG) (1996) Defense in depth in nuclear safety, INSAG 10: A report by the International Nuclear Safety Advisory Group. International Atomic Energy Agency, Vienna
2. JANSI (Dec 2013) Lesson learned from accident investigation reports on the Fukushima Daiichi Accident and JANSI’s supporting activities. Available at: http://www.genanshin.jp/english/report/lessonslearned/data/F1jiko_kyokun.pdf#search=‘Lesson+learned+from+accident+investigation+reports+on+the+Fukushima+Daiichi+Accident+and+JANSI%E2%80%99s+supporting+activities’. Accessed March 28, 2014

3. Nuclear Regulator Authority of Japan (Aug 2013) New regulatory requirement for light-water nuclear power plants outline. Nuclear Regulatory Authority, Tokyo. Available at: http://www.nsr.go.jp/english/e_news/data/13/0912.pdf#search='New+Regulatory+Requirements+for+LightWater+Nuclear+Power+Plants'. Accessed March 28, 2014
4. Sustainable Nuclear Energy Technology Platform (SNETP) (Jan 2013) Identification of research areas in response to the Fukushima accident, Report of the SNETP Fukushima Task Group
5. Korea Atomic Energy Research Institute (29 Aug 2012) INPRO dialogues forum on global nuclear energy sustainability. KAERI, Seoul
6. European Union (2011) EU stress test: National report of Germany, Federal Ministry for Environment, Nature Conservation and Nuclear safety
7. TVO (2010) Nuclear Power Plant Unit Olkiluoto 3, Teollisuuden Voima Oyj
8. HSK (2007) Sicherheitstechnische Stellungnahme zur Periodischen Sicherheitsüberprüfung des Kernkraftwerks Mühleberg HSK. Available at: http://static.ensi.ch/1314202963/psu_muehleberg_2007.pdf. Accessed 27 July 2014
9. Mohrbach L (2011) The defense-in-depth safety concept: Comparison between the Fukushima Daiichi units and Geman nuclear power units. ATW International Journal of Nuclear Power 56 (4/5)
10. Appenzeller U (2013), External spent fuel storage facility at the nuclear power Plant in Gösgen. Presented at: Technical Meeting (TM) on Spent Fuel Storage Options, International Atomic Energy Agency, Vienna July 2-4, 2013. Available at: http://www.iaea.org/OurWork/ST/NE/NEFW/Technical-Areas/NFC/documents/spent-fuel/TM-45455/Agenda-14-SWITZERLANDExternalspent_fuel_storage_facility_at_NPP_Goesgen_Switzerland.pdf. Accessed 27 July 2014
11. IAEA (2009) Passive safety systems and natural circulation in water cooled nuclear power plants, IAEA-TECDOC-1624
12. Barrett AJ, Marquino W (2012) ESBWR response to extended station blackout and loss of all AC power. In: Proceedings of ICAPP'12, Chicago, USA, June 24-28, 2012
13. Zacharias T, Novotny C, Bielor E (2012) KERENA safety concept in the context of the Fukushima accident. In: Proceedings of ICAPP'12, Chicago USA, June 24-28, 2012, paper 12366
14. Vereb F, Winters J, Schultz T, Cummins E, Oriani L (2012) The AP1000 nuclear power plant innovative features for extended station blackout mitigation. In: Proceedings of ICAPP'12, Chicago USA, June 24-28, 2012, paper 12063
15. Shiraishi T (2009) Design feature and demonstration tests of advanced accumulator a new passive ECCS component of APWR, International summer school of nuclear power plants and young generation work shop, Tokai-mura, Ibaraki, Japan
16. Shiraishi T (2011) The advanced accumulator: a new passive ECCS components of the APWR, In: Saito T, Yamashita J, Ishiwatari Y, Oka Y (eds) Advances in light water reactor technologies. Springer, NewYork, Chapter 2.
17. Shiraishi T (2011) Design of the advanced accumulator for pressurized water reactor. Nuclear Engineering and Design 241: 3910-3924
18. AREVA PRONAS, Post-accident Sampling System Pronas, Marketing AREVA
19. International Atomic Energy Agency (2011) Mitigation of Hydrogen Hazards in Severe Accidents in Nuclear Power Plants. TECDOC 1161. IAEA, Vienna
20. Janke R (2012) AREVA's solutions for post-Fukushima safety enhancements, international forum. ATOMEXPO-2012, Moscow 4 June 2012
21. Bittermann D, Fischer M (2011) Development and design of the EPRTM core catcher. In: Saito T, Yamashita J, Ishiwatari Y, Oka Y (eds) Advances in light water reactor technologies. Springer, NewYork. Chapter 4.
22. Asmolov VG et al (2005) Crucible-type core catcher for VVER-1000 reactor. In: Proceedings of ICAPP '05 Seoul, KOREA, May 15-19, 2005 Paper 5238
23. Toshiba (July 2011) US-ABWR and EU-ABWR: Design, safety technology, operability features and their current deployment, Toshiba PSN-2011-0715

24. Hitachi (2013) ESBWR severe accident prevention and mitigation. Hitachi, INPRO Dialogue Forum Nov. 19-23, 2013
25. Chu CC, Sienicki JJ, Spencer BW, Frid W, Löwenhielm G (1995) Ex-vessel melt-coolant interactions in deep water pool: studies and accident management for Swedish BWRs. Nuclear Engineering and Design 155:159-213
26. EPRI Utility Requirements Document For Next Generation Nuclear Plants
27. The Organisation for Economic Co-operation and Development (OECD), Nuclear Energy Agency (NEA) (2013) OECD/NEA RASPLAV Project. Available at https://www.oecd-nea.org/jointproj/rasplav.html. Accessed 30 July 2014
28. Asmolov V, Tsurikov D (2004) MASCA project: major activities and results. Presented at CSNI Workshop, MASCA Seminar 2004, Institut de Radioprotection et de Sûreté Nucléaire (IRSN) Aix-en-Provence, France, 10-11 June 2004. The Organisation for Economic Co-operation and Development (OECD), Nuclear Energy Agency (NEA). Paper available at https://www.oecd-nea.org/nsd/workshops/masca2004/oc/papers/RF_ASM_M_Activities.pdf. Available 30 July 2014

Chapter 13
Understanding the Health Impacts and Risks of Exposure to Radiation

Taylor A. Choi, Sylvain V. Costes and Rebecca J. Abergel

Abstract In this chapter, the biological effects of exposure to radiation are summarized and explained from the perspective of the Fukushima Daiichi accident. First, a series of fundamental concepts in radiation biology are addressed to define the different types and sources of ionizing radiation, and resulting paths of human exposure. The health effects prompted by exposure to radiation are then broadly categorized and correlated with the nature of exposure and its extent. Finally, those concepts are revisited to assess the potential health impacts and risks endured by the workers and general population affected by the uncontrolled release of radiation around the Fukushima area. In the wake of the 2011 accident, a surge of public concern over the safety of nuclear energy and potential health risks from radiation exposure has re-surfaced. To evaluate, understand, and mitigate those health risks, it is essential that scientific data be meticulously gathered, rigorously analyzed, and accurately communicated. Taking a systematic knowledge-based approach to accurately capture the risks of exposure to radiation will not only alleviate mass confusion, but also help public health officials and emergency responders better prepare and implement logistics, should another such unfortunate event take place. The topics discussed in this chapter are intended to provide basic tools for understanding how health effects and risks related to radiation exposure are evaluated.

Keywords Health effects · Radiation exposure · Contamination · Radionuclides

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13.1 Introduction

In March 2011, the Great East Japan Earthquake and Tsunami led to the Fukushima Daiichi Nuclear Power Plant (NPP) accident, which released a large amount of radioactive material into the environment. While ionizing radiation is a ubiquitous and natural phenomenon that occurs all around us [1], a major release of radioactivity to the environment is always of concern, as it could result in acute and long-term health effects in surrounding populations.

Naturally occurring sources of radiation are broadly categorized into cosmic, terrestrial (e.g., earth's crust, soil, and construction material), and internal radiation [1, 2]. In addition, people are routinely exposed to man-made radiation from nuclear medical diagnostics (e.g., X-ray and Computerized Tomography scans) and treatment procedures, nuclear power plants, commercial flying, and even smoking [2]. However, scientific evidence from past events have demonstrated that any major uncontrolled release of radiation could be harmful and warrants immediate response to assess and minimize public health risks.

About two years after the Fukushima Daiichi NPP disaster, the World Health Organization (WHO) released a global report on 'Health Risk Assessment from the nuclear accident after the 2011 Great East Japan Earthquake and Tsunami based on preliminary dose estimation' [3]. Conducted by an independent team of international experts on radiation risk, this comprehensive study concluded that, for the general population inside and outside of Japan, the predicted risks were low and no observable increases in cancer rates above baseline were anticipated.

The WHO report was the first large analysis of the global health effects due to radiation exposure after the Fukushima Daiichi NPP accident [3]. As additional data are gathered and further monitoring and analysis of radiation levels are performed, a more accurate picture of the health risks will be drawn. This chapter is intended to briefly summarize important concepts in radiation biology that are the basis for understanding how health effects and risks related to radiation exposure are evaluated. The second part of this chapter then focuses on the health impacts resulting from the radiation release around the Fukushima Daiichi NPP. Rather than be an in-depth review of low-dose radiation, this chapter is intended to provide background information on low-dose ionizing radiation and integrate the information in order to better understand the effects of low-dose ionizing radiation from the perspective of the Fukushima Daiichi accident. For further reading on low-dose radiation, we refer readers to Appendix B.

13.2 Fundamental Concepts

13.2.1 Defining and Measuring Ionizing Radiation

Ionizing radiation transports sufficient energy to convert a neutral atom to a charged ion, which may result in harmful changes to the irradiated body. Common types of ionizing radiations include alpha (α) radiation, beta (β) radiation, gamma (γ) rays,

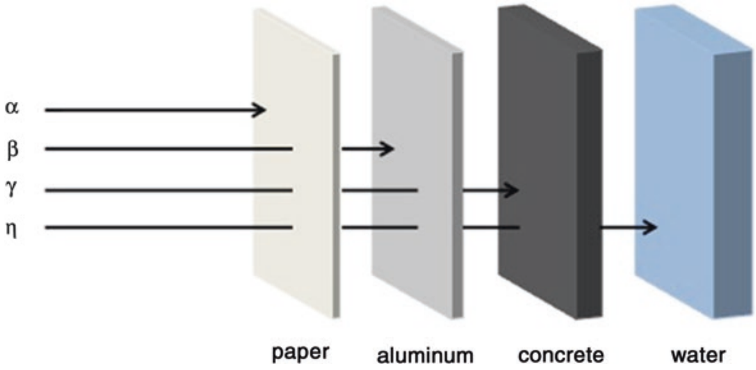

Fig. 13.1 Illustration of different types of ionizing radiation and energies

and neutrons [1, 2], as illustrated in Fig. 13.1. Alpha radiation consists of a heavy, positively charged helium nucleus. Alpha particles are short range, meaning they can be readily stopped with a sheet of paper, a few decimeters of thin air, or human skin [1]. Alpha particles pose a health risk if taken into the body through inhalation, ingestion, or wounds [4]. Beta radiation involves electrons and is more penetrating than α particles. Most β particles will pass through a sheet of paper but can be stopped with a thicker object, such as a sheet of aluminum or a pane of glass. Beta particles may also be a health risk if taken into the body. Gamma rays and X rays are penetrating electromagnetic radiation and carry no electrical charge. These non-particle rays easily pass through paper, glass, and the human body but can be stopped by concrete or lead [1, 5]. Neutrons are uncharged, indirectly ionizing radiation that can give rise to α, β, γ, and X-rays. They can be stopped by thick masses of concrete or water [5, 6].

Activity is a measure of the amount of radiation a source produces, while dose is a measure of the amount of radiation that reaches an irradiated matter [1]. The quantity of radioactivity is measured in becquerel (Bq), the unit of radioactivity defined by the International System of Units (SI) [2]. The curie (Ci), a non-SI unit of radioactivity, is sometimes used and is defined in terms of disintegrations per unit of time (1 μCi is equivalent to 2.2×10^6 disintegrations/min; 1 μCi = 37 kBq). One Bq corresponds to one atom decaying per second. But exactly how much is a Bq? At how many Bq will a genetic mutation or cancer occur? Becquerel is a very small unit. The human body contains between 5,000 and 10,000 Bq of natural radioactive elements (mainly potassium-40, ^{40}K). Smoke detectors typically contain about 30,000 Bq of americium-241 (^{241}Am). Patients are often exposed to radioactivity in kBq–MBq quantities during a medical diagnostics procedure and MBq–GBq quantities in therapeutics. The physical dose of radiation does not necessarily correlate to the degree of biological damage. For the same physical amount of radiation energy, alpha particles are biologically more harmful than gamma rays. In addition, tissues and organs exhibit different levels of radiosensitivity [1].

Table 13.1 SI and conventional units used in radiation biology

	SI unit	Conventional unit
Radioactivity	Becquerel (Bq)	Curie (Ci)
	1 Bq = 1 disintegration per second 1 Ci = 3.7×10^{10} disintegrations per second = 37 GBq	
Absorbed dose	Gray (Gy)	rad
	1 Gy = 1 J/kg = 100 rad	
Effective dose	Sievert (Sv)	rem
	1 Sv = 100 rem	
Linear energy transfer	Newton (N)	keV/μm
	1 N = 1 J/m 1 keV/μm = 1.6×10^{-13} N	

The absorbed dose is the mean quantity of radiation energy deposited per mass of tissue or organ (J/kg or Gy) [1, 2]. Initially defined in terms of rads by the International Commission on Radiation Units and Measurement (ICRU) in 1953, it has been replaced by the SI unit gray (Gy) [6]. Table 13.1 summarizes commonly used SI and conventional units.

Another important unit for ionizing radiation is the Linear Energy Transfer (LET). This parameter reflects the energy loss of charged particles per unit path length and is also referred in physics as the stopping power. LET can be described by the Bethe equation [7] and has a typical unit of keV/μm. LET makes the most sense for energetic ions found in cosmic radiation, which are referred to as high-LET radiation or HZE (High Z and Energy ions). These ions are relativistic, and with very high positive charge, deposit as much as hundreds to thousands of keV/μm via Coulomb interaction with surrounding electrons in the tissues they traverse [8]. In contrast, X-rays, γ-rays and electrons are often referred to as low-LET radiation (<10 keV/μm), which only makes sense for electrons, as photons do not interact via Coulomb interaction but via Pair production, Compton scattering, or photoelectric effects. Low-LET photons typically refer to the low-LET electrons produced via the interaction of photons with tissues.

The severity of biological damage varies with the type of radiation. It is interesting to note that very little difference is observed below 10 keV/μm, making ionizing radiation in the low-LET range a good reference for biological effects [8]. This has led radiation biologists and health physicists to define the effective (or biological) dose, measured in Sieverts (Sv), as the low-LET dose required to induce the same health effect as observed for a higher LET radiation [1, 9]. Therefore, one Sv corresponds to one gray (Gy) or Joule/kg (J/kg). The effective dose is calculated by multiplying the absorbed dose of a specific radiation type in Gy by a radiation weighting factor, referred to as the relative biological effectiveness (RBE) [2, 10]. For example, the RBE for high-LET α emitters is around 20 against 1 for γ rays, X rays, and β radiation [10]. Neutrons may have RBE of 5–20 depending on the energy and the endpoint. One Sv is a fairly high dose; an acute exposure of 0.5–1.0 Sv can cause acute radiation diseases. Cancer patients may be exposed to this level of radiation during radiotherapy [1].

13.2.2 A Perspective on Natural Versus Man-Made Radiation

The International Commission on Radiological Protection (ICRP) recommends an effective dose of 10 mSv as the annual dose reference level for humans [11]. The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) estimates that the global population receives an average annual effective dose of ~3.1 mSv (~2.4 mSv and ~0.7 mSv from natural background and anthropogenic radiation, respectively) [12]. Terrestrial radiation sources include primordial radionuclides such as uranium (^{238}U) and thorium (^{232}Th) [2]. Indwelling radon comprises about half of the overall average annual dose. Medical procedures (i.e., X-rays, CT scans) account for the majority of anthropogenic sources of radiation [13]. For occupational workers, the recommended annual dose limit to the whole body and extremities is 20 and 500 mSv, respectively [12]. While the dose rate from natural radionuclides in the body is independent of geographical location, the level of exposure to cosmic and terrestrial radiation can vary significantly depending on altitude [1]. For example, at 3,000 m above sea level, people receive five times more radiation dose than people at sea level [2].

13.2.3 Distinguishing External from Internal Exposure

Exposure to radiation may be classified into three categories: (i) body exposure due to the proximity of a radiation source, (ii) external contamination, and (iii) internal contamination.

All types of ionizing radiation may result in total or partial body exposure, with the severity of irradiation dependent upon the type and energy of the radiation. In contrast, external or internal contamination occurs when radionuclides or fission products settle on or penetrate human bodies via three primary routes [4, 14]:

- inhalation of airborne radionuclide particles
- ingestion of contaminated water and foodstuffs
- direct exposure via open skin from contaminated surface deposition

Numerous factors influence the potential health effects after contamination with radionuclides [3, 4, 10]:

- chemical nature of the radionuclide or radiation source
- the physicochemical characteristics of the radionuclide (radiological and biological half-life, particle size, chemical composition, solubility, etc.)
- the behavior of radionuclides after radionuclide intake into the body
- radionuclide dose and dose rate
- type of radiation
- radiation dose-response relationships for individual tissue following radiation uptake
- sensitivity of different tissues and organs
- age and health of the contaminated individual

The chemical nature of the ingested radionuclide strongly dictates the extent of absorption in the GI tract. For example, iodine and cesium are almost completely absorbed, whereas less than 0.1 % of plutonium and americium are absorbed. The distribution of incorporated radionuclides in the body also depends on the solubility of the particles. In general, absorption is greater after ingestion of soluble inorganic forms than after ingestion of inorganic forms of an element. For example, ingestion of ^{239}Pu as nitrate or citrate results in at least one order of magnitude greater absorption than as oxide particles. Similarly, intake of soluble radioactive materials via inhalation or open wounds results in greater absorption and deposition in other tissues. In addition, the pattern of radioactivity distribution (i.e., uptake and retention) throughout irradiated tissues may influence the degree of damage. This is particularly true for alpha emitters because of localized deposition of energy and their greater RBE compared with that of beta or gamma emitters. For example, α-emitting ^{239}Pu localizes in tissues and causes fibrosis, ulceration, loss of tissue function, and even death [10]. Ingestion of insoluble forms of radionuclides with α or β emission may be largely confined to the gastrointestinal tract, whereas radionuclides with γ emission may irradiate neighboring tissues. After 7 half-lives, less than 1 % of the original activity remains and after 10 half-lives, less than 0.1 % of the original activity remains [4].

13.3 Categorizing the Health Effects of Radiation

13.3.1 Direct Versus Indirect Effects

DNA damage or damage of other essential cellular components can occur by one of two mechanisms: direct or indirect effects. Different cell systems have different levels of sensitivity to radiation—actively replicating cells such as white blood cells are more sensitive to radiation than dormant cells or cells that do not regenerate as rapidly [15]. Mature cells in the brain, nerves and muscles are the slowest to regenerate and are thus least radiosensitive [4, 15].

Direct effects of ionizing radiation essentially affect DNA, which is directly ionized leading to a lesion. Indirect effects of ionization involve radiolytic decomposition of water in a cell. Water makes up most of a cell's volume and has a high probability of being affected when a cell is irradiated. Upon irradiation, water molecules break, producing hydrogen and hydroxide free radicals. These radicals can recombine to form water, or, in the presence of molecular oxygen, may form hydrogen peroxide, which will oxidize a variety of targets, including the DNA [15]. Typically for low LET, 60 % of DNA double strand breaks (DSB) are due to indirect effect. In contrast, high-LET radiation induces the majority of DSBs via the direct effect.

13.3.2 Acute Versus Chronic Effects

Biological effects of radiation are broadly categorized into acute or chronic effects. Acute effects arise as a result of exposure to high doses of radiation over a short period of time, whereas chronic effects are a result of exposure to low doses of radiation over an extended period of time. High dose radiation exposure can lead to death. Depending on the dose and dose rate, along with other contributing factors, irradiated cells can repair minor damages, reproduce despite incurred damages, mutate and pass down mutations, or die. Furthermore, people respond differently to the same radiation dose. The health and age of the individuals at the time of exposure seem to impact the response outcome [15].

Damages to skin are more likely to occur with exposure to low energy gamma, X-ray, or beta radiation. Acute high doses of X-ray or gamma irradiation can lead to impaired organ function or cell death. Erythema and blistering occur after acute doses of >3 and >12 Gy, respectively. Similarly, epilation (hair loss) can occur after acute doses of about 5 Gy. Depending on the dose (typically >4 Gy), sterility in males can be temporary or permanent. In females, sterility is usually permanent. Cataracts can occur at about 2 Gy [15]. At doses greater than 50 Gy, severe necrosis, impaired vision, ataxia, and/or coma may occur [12].

Whole-body dose exposure of 3–5 Gy is sufficient to damage bone marrow and may subsequently lead to death within 2 months. At 5–15 Gy, the GI and respiratory tracts are compromised and death can occur in 2–3 weeks. A whole-body dose of above 15 Gy can cause damage to the nervous system and result in death within 1–2 days. In contrast, low dose levels of ionizing radiation exposure typically do not cause immediate observable effects for individuals [15]. The biological impacts of low dose of ionizing radiation are still being debated and have been an active field of research in the world for many decades. The general consensus from epidemiological studies involving A-bomb survivors [16] is that cancer risk increases with dose for acute doses larger than 100 mSv. The A-bomb survivor data are, however, limited by the following: dose was delivered acutely and dose rate and exposure duration are other important factors to predict cancer incidence. However, if radiation dose is received over an extended period of time at low dose rates, stochastic effects such as cancer may ensue [4].

13.3.3 Deterministic Versus Stochastic Effects

Deterministic or non-stochastic effects are health effects in which severity varies with dose; they are believed to occur only after certain radiation dose thresholds are exceeded [3]. Examples of deterministic effects include erythema, cataracts, organ atrophy, fibrosis, and sterility. Deterministic effects have an individually variable dose threshold, and are complex to deduce a dose-response relationship [17]. Stochastic effects, on the other hand, are probabilistic adverse health effects of ionizing radiation that increase with increasing dose, without a threshold [3, 17]. Radiation risks from high dose rate or acute effects are primarily deterministic effects and are typically reported in Gy. Low dose rate or chronic effects are primarily stochastic effects, in particular, cancer [3, 4]. According to the WHO report, deterministic effects are not expected to occur in the general population, inside and outside of Japan, due to low radiation dose levels resulting from the Fukushima accident [3].

13.3.4 Homogeneous Versus Heterogeneous Irradiation

ICRP reviewed a limited number of studies comparing the biological effects of homogeneous and heterogeneous irradiation of tissues, and concluded the effect of uniformity of irradiation when contaminated with internal radionuclides through inhalation or ingestion was inconclusive [10].

The available information for irradiation of the lung, skin or liver, however, indicates that, in general, non-uniform alpha irradiation from internalized radioactive particles is no more hazardous, and may be less hazardous, than if the same activity were uniformly distributed [10, 18]. In one animal study, Chinese hamsters were burdened with different particle sizes of ^{239}Pu citrate or $^{239}PuO_2$ in order to compare the effects of particle size on local radiation dose and dose rate to the surrounding cells in inducing chromosome aberrations. The study suggested a correlation between biological response and the distribution of dose: more uniformly distributed ^{239}Pu citrate produced more chromosome aberration, suggesting that, in some cases, energy deposition or saturation at the cellular level is impacted by heterogeneity of plutonium distribution [19].

13.4 Correlating Radiation Exposure with Health Effects

As stated above, biological effects resulting from radiation exposure are highly correlated with received radiation dose and dose rate. Acute Radiation Syndrome (ARS), or radiation sickness, is the result of whole body exposure to very high levels of radiation, usually over a short period of time. While people who suffered from ARS include survivors of the atomic bombs and first responders after the Chernobyl NPP event in 1986, populations affected by radiation release and contamination schemes similar to those seen after the Fukushima accident are much more likely to experience chronic low dose effects. The following sections therefore focus on the health effects of exposure to low dose ionizing radiation and internal contamination with radionuclides.

13.4.1 Low Dose Ionizing Radiation

A low dose of ionizing radiation is generally defined as an acute exposure of <100 mGy (mSv) [20]. In the context of biology, the term “low dose” is the lowest dose of energy deposited in a single cell that results in cellular changes [21]. Interestingly, internalized radioactive materials deposited at low dose rates are not uniformly distributed at all levels of biological organization. The mechanisms of action for the biological responses induced by low doses of ionizing radiation are different from those induced by high doses. Responses estimated using linear extrapolation of high dose should be prudently interpreted since this method overestimates the real risk associated with these low dose and dose rate exposures. By and large, non-uniform distribution of low doses is less hazardous than single, acute whole-body exposures, as shown in DNA repair processes [11, 22].

Challenges lie in linking direct risk estimates for exposures at low doses. Radiation is a weak carcinogen and its effects are too small to quantify, as we are all exposed to natural background radiation at around this low level, which may mask any significant effects. Are internally deposited low dose radioactive materials more harmful than external exposures? There is no conclusive scientific evidence that shows fundamental differences between external and internal sources of radiation, or between artificial and natural radionuclides in their capacity to cause such damage. It is important to consider the location of target cells within tissues when considering doses from short-range internal emitters (e.g., alpha particles, low energy electrons) [23].

13.4.2 Linear-No-Threshold Model

There are conflicting schools of thought in the radiation community on stochastic health effects associated with exposures to low doses of ionizing radiation [20]. Current risk estimates and most radiation protection standards are based on the 'linear-no-threshold' (LNT) model [21]. The LNT hypothesis does not reflect the actual risk in the low-dose region, but provides a useful tool to conservatively control exposure [11]. According to this model, the effect of ionizing radiation is directly proportional to the dose, and even the smallest dose of radiation is associated with a small increase in cancer risk to humans without a threshold [24, 25]. The Biological Effects of Ionizing Radiation (BEIR) committee of the National Academy of Sciences (NAS) published a report in 2006 concluding that the available biological and biophysical data support the LNT risk model [24, 25].

In the same year, UNSCEAR issued a report citing that while the LNT hypothesis holds validity in radiation protection at low doses and low dose rates, it does not reflect the actual risk in the low dose region [12, 20, 21, 24]. In a subsequent 2012 study, UNSCEAR also concluded that there is no consensus on the impact of radiation exposure, particularly at low doses [26]. ICRP reached a conclusion similar to that of UNSCEAR and stated in their Recommendations guidance that current evidence does not support a universal threshold dose level, although a low-dose threshold is likely applicable for radiation-related cancers in certain tissue [5, 24, 27].

The French Academy of Sciences challenged the validity of the LNT model for assessing health risks at low doses [28]. The LNT model posits that carcinogenic risks remain constant in all biological reactions, regardless of dose or dose rate. The group pointed out that epidemiological studies did not show a significant increase of cancer incidence in humans for doses $\lesssim 100$ mSv. In addition, the LNT model fails to take into consideration the various biological mechanisms cells demonstrate when they are irradiated by ionizing radiation. The group concluded that the universal approach of the LNT model greatly simplifies the dose-effect relationships and may result in an overestimation of health risk at low doses since biological mechanisms and responses are different at low doses versus high doses [29, 30].

Some researchers subscribe to the once discredited hormesis concept, a hypothesis that receiving low ionizing radiation in doses just above the natural background level may induce beneficial biological responses [17]. The proponents of this hypothesis explain that a number of compensatory and reparatory mechanisms (e.g., stimulation of the immune response and DNA repair, and activation of apoptosis that eliminates damaged cells that would otherwise become cancerous) are stimulated in response to small doses of ionizing radiation [17, 31].

Stochastic effects are more likely to occur after acute exposure to internalized radionuclides than deterministic effects. At absorbed doses of ~1 Gy, deterministic effects may occur, including pneumonitis, erythema, vomiting and diarrhea, bone marrow failure, and cataracts. Some of these symptoms appear several hours after an acute absorbed dose, whereas others may take weeks or longer [4].

13.4.3 Chronic Exposure to Low Dose Radiation

The main concern associated with chronic exposure to irradiation at low doses is the induction of cancer [10]. Using the LNT model (see above), the risk of cancer is estimated to increase by 10 % for chronic health effects above 100 mSv [14]. However, several large cohort studies of nuclear medical technicians and nuclear industry workers suggest a slight increase in cancer risk at exposures below 100 mSv. Estimating adverse health effects, such as cancer risks of chronic low-level radiation exposure is complicated by other variables, such as diet, lifestyle, genetics, and overall health [32].

Is there a threshold below which radiation has no adverse effect? Some researchers believe that natural background radiation can be a carcinogenic factor. Others are convinced that small doses of radiation (natural or anthropogenic) are not harmful [33]. Still others, albeit a small community of researchers and health experts, prescribe to the hormesis model [32]. Because we all receive doses >1 mSv from our natural surroundings, correlating adverse biological responses to low radiation doses is difficult. Models associated with the different hypotheses are illustrated in Fig. 13.2.

13.4.4 Minimizing and Treating Exposure to Radiation

The first response to radiation exposure should be to treat acute radiation syndrome. Treatment of ARS focuses on reducing infections, maintaining hydration, and treating injuries and burns. Causes of death are often attributed to bone marrow destruction, which is why some patients may benefit from bone marrow recovery treatments. It is not possible to reverse acute exposure to radiation;

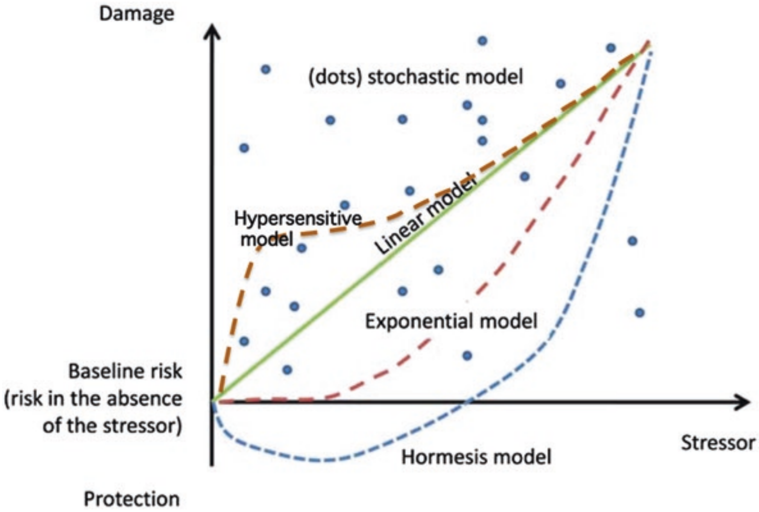

Fig. 13.2 Models discussed for evaluating the health effects of exposure to low-dose ionizing radiation. The baseline risk represents doses accumulated in excess of background natural sources (Adapted with permission from Biological effects of low-dose radiation: of harm and hormesis by Gori and Münzel, 2012, Eur. Heart J. 33:293)

however, it is important to minimize exposure in chronic exposure and internal contamination cases. Sources of radiation should be distanced or removed when possible, in order to reduce the radiation dose.

Currently available treatments vary as a function of the intake pathway, the level of contamination (mass and activity), the chemical and biological speciation of the radioisotope, as well as the intervention time after the incident. For contamination by inhalation, which primarily results from internalization of aerosols that display different chemical solubilities, treatment may include lung washing. For contamination by ingestion, treatments include gastric dressing, precipitation, and purging. For wound contamination, several treatments have been used including washing, surgical excision, and dressings with additional specific chelating gels.

Table 13.2 List of recommended treatments for representative radionuclides, adapted from [4]

Radionuclide	Recommended treatment
Americium	DTPA Chelation
Cesium	Prussian Blue
Iodine	Postassium iodide
Iron	Deferoxamine or EDTA Chelation
Potassium	Diuretics
Plutonium	DTPA Chelation
Radium	Strontium therapy
Strontium	Strontium therapy
Yttrium	DTPA Chelation

In all cases, where radioactive materials are deposited internally, a blocking or decorporation agent should be administered to prevent the settling or promote the removal of radioactive materials from tissues and organs. A comprehensive list or radionuclides and the corresponding treatment can be found in the NCRP Report [4]. Table 13.2 lists a few representative radionuclides and their corresponding recommended treatment.

13.5 The Fukushima Daiichi Nuclear Power Plant Accident

A series of natural disasters in Japan on March 11, 2011 resulted in an unanticipated extent of damage to infrastructure, including the meltdown of three of the six nuclear reactors at the Fukushima Daiichi NPP, and the subsequent release and deposition of radioactive materials into the environment [6, 9]. This uncontrolled release of radiation triggered a surge of public concern over the potential health risks of radiation exposure. Readers are referred to Chap. 3 for an in-depth analysis of the mechanisms of environmental contamination and to Chap. 4 for a description of decontamination strategies and waste management issues.

Immediately after the accident on March 11, 2011, the Japanese government ordered residents within a 3 km radius around the Fukushima Daiichi NPP to evacuate. As the seriousness of the accident became more apparent, evacuation areas were gradually expanded. On March 12, 2011, after the 1st explosion at the nuclear reactor No. 1, areas within a 20 km radius from the NPP were evacuated. On March 15, residents living in the 20–30 km range from the NPP were instructed to stay indoors. By the end of 2011, additional restrictions took effect, which impacted specific areas northwest of the NPP, corresponding to the migration pattern of radioactive particles after the accident. These restricted areas were rearranged into three zones according to the annual cumulative dose, with a confirmed annual integral radiation dose of less than 20 mSv in Zone 1, 20 mSv or more in Zone 2, and 50 mSv or more in Zone 3. The status of these zones, as of April 1, 2014, is depicted in Fig. 13.3.

13.5.1 Estimating the Exposure to Ionizing Radiation and Subsequent Impact

The general population in Japan receives an annual natural background radiation dose of about 2.1 mSv. This is comparable to the global natural background average of ~2.4 mSv (range of 1–13 mSv depending on geographical location and radon exposure) [34, 35]. Table 13.3 summarizes the annual doses received by the Japanese population as a function of source, in comparison with average doses estimated worldwide.

The effective dose over a lifetime from naturally occurring sources of radiation in Japan is about 170 mSv, which is higher than the estimated effective dose

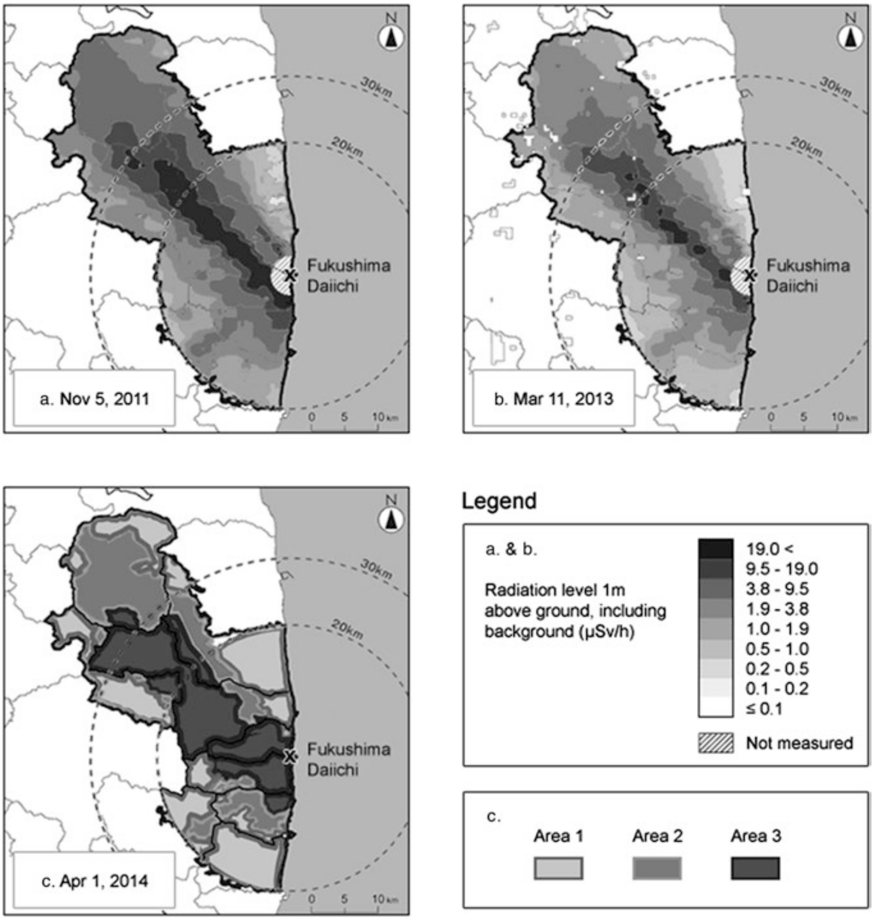

Fig. 13.3 Maps of radiation levels (**a** November 5, 2011 and **b** March 11, 2013), and evacuation areas (**c** April 1, 2014). Figure created using data available on the website of the Japanese Ministry of Economy, Trade and Industry

Table 13.3 Annual radiation exposure estimates in Japan and Worldwide [12, 36]

Source	Annual dose in Japan	Annual dose in the World
Natural background	2.1	2.4
Diagnostic radiology	2.20	0.62
Nuclear medicine	0.03	0.03
Fallout	0.01	0.01
Others (nuclear plant, aircraft, etc.)	0.01	0.01
Total	4.35	3.1

from the Fukushima Daiichi NPP accident for an average person living in the Fukushima Prefecture. The annual and lifetime doses to the thyroid from natural sources of radiation are about 1 and 80 mGy, respectively [34]. A post-incident health survey suggested that the received dose for nearly all the evacuees was low, with a maximum acute dose of ~25 mSv [10]. The mean annual radiation dose in 2012 attributed to the accident was 0.89–2.51 mSv. The mean dose rate attributed to the accident in 2022 is projected to be 0.31–0.87 mSv. In addition, annual internal exposure to fallout is estimated to be 0.0025 mSv [35].

An acute radiation dose of 100 mSv has been linked to an increase in the chance of developing cancer by a factor of 1.05, which is unlikely to be epidemiologically detectable [32, 35, 37]. The annual limit on the occupational effective dose for Japanese workers is 20 mSv/year and 100 mSv over 5 years [14, 38]. The emergency dose exposure was raised from 100 to 250 mSv/year, the established limit in emergency situations, in response to the gravity of the accident, as suggested by the ICRP [14, 27]. Acute exposures to radiation at these levels are not expected to result in adverse health effects. The average lifetime cancer risk for a worker from a whole-body dose of 250 mSv will be 1–2 %, depending on the dose rate [27], which is quite low compared with a background lifetime risk of 20–25 % [38]. As of March 2012, 408 workers received doses above the established annual limit of 50 mSv. Among them, 6 workers received doses greater than 250 mSv and 2 other workers received doses above 600 mSv [38, 39]. In addition, two workers received significant skin doses of ~2–3 Sv. Yet, no acute radiation sickness or acute radiation effects have been reported thus far. Nonetheless, these workers are continuously monitored [14, 38–40].

In its 2012 report, the WHO committee stated that observable increases in cancer risk above natural variation in baseline rate are unlikely in the Fukushima prefecture and the geographical areas most affected by radiation. For the residents in the most affected location of the Fukushima prefecture, the estimated relative increases in lifetime risks over baseline rates for specific cancers are [3]:

- Leukemia— ~7 % in males exposed as infants
- breast cancer— ~6 % in females exposed as infants
- all solid cancers— ~4 % in females exposed as infants
- thyroid cancer—up to ~70 % in females exposed as infants (the lifetime absolute baseline risk of thyroid cancer in females is 0.75 %, which is increased to 1.25 %)

For residents in the second most contaminated location, the radiation dose for the first year is estimated to be ~12 mSv. The additional lifetime cancer risk for these residents is estimated to be approximately half of that in the highest dose location. It should be kept in mind that these estimates were calculated based on some assumptions. For example, it was assumed that all people in the Fukushima prefecture consumed food in only the Fukushima prefecture. The estimate also assumed that people in the most affected areas outside the 20-km radius continued to live there for 4 months after the accident. Therefore, these risk estimates are more likely to be overestimates than underestimates [3].

So far, no one has died as a direct result of radiation exposure from the Fukushima Daiichi NPP, while some 18,500 fatalities have resulted from the earthquake and the subsequent tsunami. Cancer-related deaths as the consequence of the Fukushima accident are estimated to be statistically insignificant. In comparison, 0.1 % of the 111,000 emergency workers at Chernobyl have so far developed leukemia, which cannot be ascribed entirely to the accident itself [41].

Estimating the biological effects of low doses is complex, and lifetime cancer risk varies according to several factors, mainly radiation dose, duration of exposure, age at the time of exposure, sex, general health, and cancer site. These factors can influence the uncertainty in projecting radiation risks, in particular risk assessment at low doses [3]. Biological functions do not have a uniform response, especially to low levels of radiation [32]. These factors were taken into consideration in data analysis for the Fukushima accident, and experts concluded that there is an increased cancer risk for certain subsets of the population in the most contaminated areas of the Fukushima Prefecture. However, no observable increases in cancer incidence are expected in other populations within the Fukushima prefecture [3]. Nonetheless, the health of these individuals will be monitored for an extended period of time. Delayed cancers due to chronic low dose radiation exposure will be challenging to isolate because of various environmental factors and personal lifestyles. In many areas of Japan, individual risk of cancer from natural background radiation will likely be greater than the risk from the Fukushima accident [42].

13.5.2 Radionuclides Released from the Fukushima Daiichi Nuclear Power Plant

Radionuclides released into the environment as a result of the nuclear accident were: iodine-131 (^{131}I), iodine-133 (^{133}I), cesium-134 (^{134}Cs), cesium-137 (^{137}Cs), and tellurium-132 (^{132}Te) [43]. Other radionuclides of concern included strontium (^{90}Sr), yttrium (^{90}Y), lanthanide fission products, and actinides, but none of these have been measured in any detectable quantities within or beyond the established evacuation zone [10]. Most releases of noble gases (i.e. ^{133}Xe) would have occurred in the early days after the accident [3]. It is estimated that 160, 88, 18, and 15 PBq of ^{131}I, ^{132}Te, ^{134}Cs, and ^{137}Cs, respectively, were discharged from the Fukushima Daiichi NPP into the environment [43].

A primary health concern for internal exposure to ^{131}I is the potential development of thyroid cancer, since the thyroid gland is most sensitive to ^{131}I [44]. Examples of deterministic health effects induced by inhalation of β-emitting ^{131}I include bone marrow depression (1–10 Gy), hypothyroidism (10–100 Gy), and ablation of the thyroid gland (100–100 Gy). Increased stochastic effects induced by the inhalation of ^{131}I are estimated to be observed at an exposure 10–100 Sv [4]. Children are more susceptible than adults to risks of cancer from radiation [11]. For example, children receiving a 100 mSv thyroid dose have a 0.3 % increased risk of developing thyroid cancer [45]. ^{131}I has a half-life of only 8 days, meaning human exposure to an external source of this radionuclide is relatively short [41]. It is volatile and can be inhaled. It can also be ingested because it readily enters the food chain (^{131}I deposits on the ground). Similar to stable iodine, ^{131}I is actively taken up by the thyroid gland. Once ^{131}I is taken up by the thyroid gland, a constant bombardment of surrounding tissue can overwhelm the repair mechanisms of cells and trigger cancer [3]. Tokonamii et al. calculated the median thyroid equivalent dose to 4.2 and 3.5 mSv for children and adults, respectively [44].

Stable iodine tablets were distributed to Fukushima accident evacuees within a week after the accident. An oral dose of stable iodine blocks the uptake of ^{131}I by the thyroid, although the timing of the intake of stable iodine relative to exposure is important to optimize the effect of this protective measure [38]. Nagataki reviewed the results of thyroid equivalent doses in the initial phase of the accident in the most affected areas of Fukushima prefecture and concluded that 96 % of the children received <10 mSv, with a maximum of 35 mSv, which is lower than the IAEA intervention level (50 mSv) [46, 47]. It should be noted, however, that any increase in thyroid cancer cases may not be evident until several years following the incident (as was the case in the children and adolescent age groups in the Chernobyl region) [41].

^{134}Cs and ^{137}Cs, with a half-life of 2.1 and 30.2 years, respectively, pose a long-term threat since they remain on the ground [48]. Examples of deterministic health effects induced by inhalation of β-γ emitting ^{137}Cs include mild bone marrow depression and erythema (1–10 Gy), bone marrow failure, pneumonitis, and GI failure (10–1,000 Gy), with a very high risk of death above 100 Gy. Increased stochastic effects induced by inhalation of ^{137}Cs is estimated to occur at a dose of 1 Sv [4].

Current recommended decorporation therapy in the event of cesium intake is oral administration of Prussian Blue. Overall, solubility of particles affects the biokinetics in the body. Soluble forms would be better absorbed into the blood and result in higher content in tissues. The system biokinetics of Cs is similar to that of K, although Cs does not cross cell membranes as readily as K does. Inhaled or ingested, Cs is readily absorbed either from the GI tract or the lungs and is subsequently taken up by most tissues [10]. Upon reaching the systemic circulation, Cs distributes uniformly in the body, with a higher concentration in skeletal muscle than in most other tissues [4]. According to the Japanese Ministry of Health, Labor and Welfare, radioactive cesium in foods is less than 1 % of 1 mSv/year as of April 2014, and that radiation levels in public water supplies are below allowable limits [49].

The third largest source of radioactivity released from the Fukushima Daiichi NPP is ^{132}Te. This radionuclide has a half-life of 3.2 days and decays to ^{132}I, which has a half-life of 2.3 h, and then becomes ^{132}Xe, which is a stable isotope. Hence, ^{132}Te is biologically relevant during the first few days after a nuclear accident [43].

13.5.3 Health Effects and Consequences

Taking into account uncertainties associated with the LNT model of human exposure at low doses, Ten Hoeve and Jacobson used the model to quantify long term health effects. They factored in ingestion exposure, inhalation exposure, and external exposure pathways of radioactive ^{131}I, ^{137}Cs, and ^{134}Cs released from Fukushima. They estimated 130 mortalities and 180 morbidities related to cancer, chiefly in the most affected areas of Fukushima. These estimates do not account for the increased radiation risk for roughly 20,000 workers at the plant in the months following the accident [39].

Because most people were exposed to radiation doses that were just slightly above background, attributing carcinogenic effects to radiation exposure from the Fukushima accident is difficult [32, 50]. This challenge is mainly due to the multitude of variables that should be taken into consideration, such as smoking, diet, geographical location, etc. Furthermore, cellular damage incurred by irradiation may not manifest until many years after exposure. Some researchers assert that even a well-implemented study will not yield statistically significant data on stochastic effects, such as cancer. It should also be noted that 40 % of all Japanese develop cancer [32].

It is also important to consider the short- and long-term psychological effects following a devastating accident. The intangible nature of radiation exposure heightens the public's feelings of fear and vulnerability [51]. The Chernobyl disaster has illustrated that long-term psychological effects, including post-traumatic stress disorder, depression, anxiety, fear, and unexplained physical symptoms, may increase following a nuclear accident [12, 39, 51].

13.6 Conclusions

In the wake of the Fukushima Daiichi accident, safety concerns regarding nuclear energy have re-emerged into the limelight. All energy technologies, however, carry a certain level of risk [11] and the world is increasingly relying on nuclear power for energy [39]. As of May 2014, 435 nuclear reactors are operating throughout the world and 72 new nuclear plants are under constructions [52]. One study shows that using nuclear power to generate electricity is a safe alternative to technologies such as burning coal [11].

While currently available data suggest that the health consequences in those outside the epicenter of the Fukushima accident may be minimal, it is too early to know what the long term health consequences of the Fukushima Daiichi accident will be [14]. As science continues to evolve and more data become available, researchers face unanticipated observations that may result in paradigm changes. It is essential that scientists make comprehensive use of data to effectively and accurately communicate to the public and policy makers so that the perception of radiation hazards and risks associated with exposure to low doses of radiation is accurately captured [11]. This will help alleviate mass confusion as well as help public health officials and emergency responders better prepare and implement logistics should another event such as the Fukushima Daiichi accident take place. Furthermore, such practice will aid in the advancement of nuclear safety.

Our understanding of the biological mechanisms of action of radiation at low doses has greatly improved. Health risks at very low doses can only be estimated by extrapolating the data of individuals exposed at much higher doses. Therein lie inherent uncertainties and challenges. It is possible that the current radiation risk for internally deposited radioactive material is underestimated or overestimated [23].

Three years after the Fukushima disaster, the situation has improved and many local residents have returned to their homes. Despite relatively low dose exposures and reassurance from public health experts and government officials, public perception may be that cancer cases in or around Fukushima are caused by the NPP accident. Questions will continue to linger about chronic effects of exposure to low levels of radiation, and this event will likely be the subject of many scientific and governmental reviews and debates for many years to come.

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Appendix A: Glossary of Useful Terms

Absorbed dose	The mean quantity of radiation energy deposited per mass of tissue or organ, expressed in grays (Gy)
Acute effects	Adverse health effects that arise as a result of exposure to high doses of radiation over a short time (minutes to a few days)
Acute exposure	Exposure to a low dose of ionizing radiation for a short period of time (<24 h)
Acute radiation syndrome	Radiation sickness as a result of whole-body exposure to very high levels of radiation, usually over a short period of time
Alpha particle	A positively charged helium nucleus characterized by short range and low penetrating capability
Becquerel	The SI unit of radioactivity, equal to one disintegration per second
Beta particle	A charged particle (electron or positron) emitted from a nucleus during radioactive decay
Chronic effects	Adverse health effects as a result of exposure to low doses of radiation over an extended period of time (years)
Decorporation agent	The therapeutic processes by which radioactive materials are mobilized from tissues and organs and caused to be excreted from the body
Deterministic (or stochastic) effects	Health effects in which the severity varies with dose

Direct effect	Ionization energy resulting in damage to essential cellular components
Dose	The quantity of radiation absorbed in a target
Effective (or biological) dose	Absorbed dose to each organ, taking into account the relative biological effectiveness of different types of ionizing radiation
Gamma ray	Uncharged, electromagnetic radiation emitted from a nucleus during radioactive decay
Half-life	The time required for one-half of the atoms of a particular radioactive substance to decay to some other substance
Health effects	Changes in the health status of an individual or population, identifiable by diagnostic or epidemiological methods
Health risk	The probability of a health effect to occur in the event of an exposure to a hazard (e.g. radiation)
Hormesis	A hypothesis that receiving low ionizing radiation doses may induce beneficial biological responses
Indirect effect	Ionization energy resulting in radiolytic decomposition of water in a cell
Ionizing radiation	Radiation capable of removing electrons from an atom
Linear no-threshold model	A risk model that assumes that the effect of ionizing radiation is directly proportional to the dose, without any threshold
Neutron	Uncharged, indirectly ionizing radiation
Radioactivity	The process by which radioactive atoms spontaneously releases energy in the form of alpha or beta particles or gamma rays
Radionuclide	Radioactive species of an atom, characterized by an unstable nucleus
Relative biological effectiveness (RBE)	The ratio of the absorbed dose of ionizing reference radiation to the absorbed dose of a specified radiation
Sievert	The SI unit of effective dose, equal to 1 J/kg
Source	Anything that may cause radiation exposure
Stochastic effect	Probabilistic adverse health effects of ionizing radiation that increases with increasing dose, without a threshold

Appendix B: Suggested Literature for In-Depth Reading of Topics Discussed in This Chapter

15 July 2005 letter to The Honorable Dale E. Klein, Chairman, U.S. Nuclear Regulatory Commission titled "Report of the French Academy of Sciences, "The dose-effect relationship and estimating the carcinogenic effects of low doses of ionizing radiation." Washington, DC

Barcellos-Hoff, MH, Ravani SA (2000) Irradiated mammary gland stroma promotes the expression of tumorigenic potential by unirradiated epithelial cells. Cancer Res 60:1254–1260

Brenner, DJ, Sachs, RK (2006) Estimating radiation-induced cancer risks at very low doses: rationale for using a linear no-threshold approach, Radiat Environ Biophys, 44:253–256.

Burklakova, EB (2000) Low doses of radiation: are they dangerous? Nova Science Pub Inc, Huntington

Burklakova, EB (2013) The effects of low dose radiation: new aspects of radiobiological research prompted by the Chernobyl nuclear disaster. VSP, Leiden

Calabrese, EJ (1994) Biological effects of low level exposures dose-response relationships. CRC Press, Boca Raton

Cantone, MC, Hoeschen, C (2011) Radiation physics for nuclear medicine. Springer, Berlin

Choppin, G, Liljenzin, J-O, Rydbergy, J, Ekberg, C (2013) Radiochemistry and nuclear chemistry, Elsevier, Oxford

Eidus, LK (2002) Biological action of low doses of radiation: a novel view on the problem. Nova Science Pub, Ann Arbor

Klaunig, JE, Kamendulis, LM (2004) The role of oxidative stress in carcinogenesis, Annual review of pharmacology and toxicology, 44:239–267

Luckey, TD (1991) Radiation Hormesis. CRC Press, Boca Raton

Nygaard, OF, Sinclair, WK, Lett, JT (1992) Effects of low doses and low dose rate radiation Academic Press, San Diego, CA

Standton, R, Stinson, D (2009) Applied physics for radiation oncology, revised edition. Medical Physics Publishing, Madison

Wilson, 3rd, DM, Bohr, VA (2007) The mechanics of base excision repair, and its relationship to aging and disease, DNA repair, 6:544–559

Yamada, T, Mothersill, C, Michael, BD, Potten, CS (2000) Biological effects of low dose radiation: Proceedings of the international meeting on biological effects of low dose radiation. Cork, Ireland, 25–26 July 1999

References

1. Valentin J (1994) Radiation: levels and doses in everyday life. Radioprotection 29(3, Suppl.):45-58
2. Raabe OG (2012) Ionizing radiation carcinogenesis. Current Topics in Ionizing Radiation Research. Nenoi M (ed) InTech Rijeka, Croatia
3. World Health Organization (2013) Health risk assessment from the nuclear accident after the 2011 Great East Japan Earthquake and Tsunami based on preliminary dose estimation. Switzerland
4. National Council on Radiation Protection and Measurements (2008) Management of persons contaminated with radionuclides. NCRP draft SC 4-1 report
5. International Atomic Energy Agency (2010) Radiation biology: a handbook for teachers and students
6. International Commission on Radiation Units and Measurements (2011) Report 86. Quantification and reporting of low-dose and other heterogeneous exposures
7. Bethe H, Ashkin J (1953) Experimental Nuclear Physics. Segré J (ed) Wiley, New York
8. International Commission on Radiation Units and Measurements (1970) Linear energy transfer. ICRU Report 16. Washington D.C. Accessed 03 Jul 2014
9. Food and Drug Administration (2009) Radiation quantities and units. http://www.fda.gov/Radiation-EmittingProducts/RadiationEmittingProductsandProcedures/MedicalImaging/MedicalX-Rays/ucm115335.htm Accessed 03 Jul 2014
10. Harrison JD, Stather JW (1996) The assessment of doses and effects from intakes of radioactive particles. J Anat 189 (Pt 3):521-530
11. Brooks AL (2013) Thirty-sixth Lauriston S. Taylor lecture on radiation protection and measurements-from the field to the laboratory and back: the what ifs, wows, and who cares of radiation biology. Health Phys 105(5):407-421
12. United Nations Scientific Committee on the Effects of Atomic Radiation (2006) Effects of ionizing radiation. UNSCEAR 2006 report to the general assembly with scientific annexes, Vol. 1
13. Watson SJ, Jones AL, Oatway WB, Hughes JS (2005) Ionising radiation exposure of the UK populations. HPA-RPD-001, HPA, Chilton
14. American Nuclear Society (2012) Fukushima Daiichi: ANS committee report
15. USNRC (2012) Biological effects of radiation. USNRC technical training center reactor concepts manual
16. Preston RJ, Ron E, Tokuoka S, Funamoto S, Nishi N, Soda M, Mabuchi K, Kodama K (2007) Solid cancer incidence in atomic bomb survivors: 1958-1998. Radiat Res 168:1-64
17. Gori T, Münzel T (2012) Biological effects of low-dose radiation: of harm and hormesis. Eur Heart J 33(3):292-295
18. International Commission on Radiological Protection (1991) The biological basis for dose limitation in the skin. ICRP Publication 59. Oxford: Pergamom Press
19. Brooks AL, Retherford JC, McClellan RO (1974) Effect of 239PuO2 particle number and size on the frequency and distribution of chromosome aberrations in the liver of the Chinese hamster. Radiat Res 59(3):693-709
20. Morgan WF, Bair WJ (2013) Issues in low dose radiation biology: the controversy continues. A perspective. Radiat Res 179(5):501-510
21. Mitchel REJ, River C (2002) Radiation biology of low doses. ATW Internationale Zeitschrift für Kernenergie 47:28-30
22. Neumaier T, Swenson J, Pham C, Polyzos A, Lo AT, Yang P, Dyball J, Asaithamby A, Chen DJ, Bissell MJ, et al. (2012) Evidence for formation of DNA repair centers and dose-response nonlinearity in human cells. Proc Natl Acad Sci U S A 109(2):443-448
23. Mobbs SF, Muirhead CR, Harrison JD (2010) Risks from ionising radiation. Health Protection Agency, Radiation Protection Division HPA-RPD
24. Dauer LT, Brooks AL, Hoel DG, Morgan WF, Stram D, Tran P (2010) Review and evaluation of updated research on the health effects associated with low-dose ionising radiation. Radiat Prot Dosimetry 140(2):103-136

25. National Academy of Sciences (2006) Health risks from exposure to low levels of ionizing radiation: BEIR VII, Phase 2. Committee to assess health risks from exposure to low levels of ionizing radiation, board of radiation effects, Research division on earth and life studies, National Research Council of the National Academies
26. United Nations Scientific Committee on the Effects of Atomic Radiation (2012) Biological mechanisms of radiation actions at low doses
27. International Commission on Radiological Protection (2007) The 2007 recommendations of the international commission on radiological protection. ICRP Publication 103. Ann. ICRP 37. Oxford: Pergamom Press
28. Tubiana M, Feinendegen LE, Yang C, Kaminski JM (2009) The linear no-threshold relationship is inconsistent with radiation biologic and experimental data. Radiology 251(1):13-22
29. Tubiana M (2005) Dose-effect relationship and estimation of the carcinogenic effects of low doses of ionizing radiation: the joint report of the Academie des Sciences (Paris) and of the Academie Nationale de Medecine. Int J Radiat Oncol Biol Phys 63(2):317-319
30. Tubiana M, Aurengo A, Averbeck D, Masse R (2006) Recent reports on the effect of low doses of ionizing radiation and its dose-effect relationship. Radiat Environ Biophys 44(4):245-251
31. Kaiser J (2003) Hormesis. Sipping from a poisoned chalice. Science 302(5644):376-379
32. Normile D (2011) Tohoku-Oki earthquake. Fukushima revives the low-dose debate. Science 332(6032):908-910
33. Normile D (2013) Japan disaster. Cooling a hot zone. Science 339(6123):1028-1029
34. United Nations Scientific Committee on the Effects of Atomic Radiation (2013) Sources, effects and risks of ionizing radiation USCEAR 2013 report to the general assembly, scientific annex A. New York: United Nations
35. Harada KH, Niisoe T, Imanaka M, Takahashi T, Amako K, Fujii Y, Kanameishi M, Ohse K, Nakai Y, Nishikawa T, et al. (2014) Radiation dose rates now and in the future for residents neighboring restricted areas of the Fukushima Daiichi nuclear power plant. Proc Natl Acad Sci U S A 111(10):E914-923
36. Tsushima Y, Taketomi-Takahashi A, Takei H, Otake H, Endo K (2010) Radiation exposure from CT examinations in Japan. BMC Med Imaging 10:24
37. Brumfiel G (2013) Fukushima: Fallout of fear. Nature 493(7432):290-293
38. Wakeford R (2011) And now, Fukushima. J Radiol Prot 31(2):167-176
39. Ten Hoeve JE, Jacobson MZ (2012) Worldwide health effects of the Fukushima Daiichi nuclear accident. Energy Environ Sci doi:101039/c2ee22019a
40. Gonzalez AJ, Akashi M, Boice JD, Jr., Chino M, Homma T, Ishigure N, Kai M, Kusumi S, Lee JK, Menzel HG, et al. (2013) Radiological protection issues arising during and after the Fukushima nuclear reactor accident. J Radiol Prot 33(3):497-571
41. Rhodes CJ (2014) The Fukushima Daiichi nuclear accident. Science Progress 97(Pt 1):72-86
42. Beyea J, Lyman E, von Hippel F (2013) Accounting for long-term doses in "worldwide health effects of the Fukushima Daiichi nuclear accident". Energy Environ Sci 6:1042-1045
43. Tagami K, Uchida S, Ishii N, Zheng J (2013) Estimation of Te-132 distribution in Fukushima prefecture at the early stage of the Fukushima Daiichi nuclear power plant reactor failures. Environ Sci Technol 47(10):5007-5012
44. Tokonami S, Hosoda M, Akiba S, Sorimachi A, Kashiwakura I, Balonov M (2012) Thyroid doses for evacuees from the Fukushima nuclear accident. Sci Rep 2:507
45. von Hippel FN (2011) The radiological and psychological consequences of the Fukushima Daiichi accident. Bulletin of the Atomic Scientists 67:27-36
46. Nagataki S, Takamura N, Kamiya K, Akashi M (2013) Measurements of individual radiation doses in residents living around the Fukushima nuclear power plant. Radiat Res 180(5):439-447
47. International Atomic Energy Agency (2011) Report of Japanese government to IAEA ministerial conference on nuclear safety - accident at TEPCO's Fukushima nuclear power station. http://www.iaea.org/newscenter/focus/fukushima/japan-report Accessed 03 Jul 2014

48. Tanaka S (2012) Accident at the Fukushima Dai-ichi nuclear power stations of TEPCO—outline & lessons learned. Proc Jpn Acad Ser B Phys Biol Sci 88(9):471-484
49. Japanese Ministry of Health, Labor and Welfare (2011) Information on the Great East Japan Earthquake. http://www.mhlw.go.jp/english/topics/2011eq/index_food.html Accessed 24 July 2014
50. Cuttler JM (2013) Commentary on Fukushima and beneficial effects of low radiation. Dose Response 11:432-443
51. Bromet EJ (2014) Emotional consequences of nuclear power plant disasters. Health Phys 106(2):206-210
52. European Nuclear Society (2014) http://www.euronuclear.org/info/encylcopedia/n/nuclear-power-plant-world-wide.htm Accessed 03 Jul 2014

Chapter 14
Nuclear Safety Regulation in Japan and Impacts of the Fukushima Daiichi Accident

Hideaki Shiroyama

Abstract Historical progress of nuclear safety regulations and nuclear safety regulatory organizations in Japan in response to the Mutsu nuclear ship accident and JCO criticality accident are reviewed. Then the lessons we can learn from the "regulatory failures" on nuclear safety uncovered by the Fukushima Daiichi accident in 2011 are discussed focusing on the "failure" of interdisciplinary communication for setting up seismic and tsunami standards and the "failure" of voluntary safety efforts relating to the scope of sever accident management. After analyzing the policy process leading to the institutional reform after the accident aiming for independence and integrative capabilities under the newly set up organizational framework of Nuclear Regulatory Authority, remaining issues of current nuclear safety regulation in Japan, such as interdisciplinary sensitivity, capability of regulatory staff in government nuclear safety regulatory organization, independent source of expertise relating to nuclear technology in the context of Japan, and careers pattern for risk managers are also analyzed.

Keywords Safety regulation · Sever accident management · Independence · Integrative capabilities · Interdisciplinary sensitivity · Nuclear reactor regulation law · Nuclear Safety Commission · Nuclear and industrial safety agency · Nuclear Regulatory Authority

14.1 Introduction

After the Fukushima Daiichi Nuclear Power Plant accident caused by the Great East Japan Earthquake of March 11, 2011, various arguments for the reform of nuclear safety regulation were proffered. The government, in addition to setting up the Accident Investigation Committee, undertook a parallel process for regulatory

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reform. As a result, the “Basic Concept of Structural Reform of Nuclear Safety Regulations” was adopted at the Cabinet Meeting of August 15, 2011.

It advocated the launch of a new safety regulatory body, on the basis of the principle of “separating regulation from utilization.” The nuclear safety regulatory divisions of the Nuclear and Industrial Safety Agency (NISA) were to be separated from the Ministry of Economy, Trade and Industry; and a “Nuclear Safety and Security Agency” would be established by April 2012 as an external agency of the Ministry of Environment by integrating into it the functions of the Nuclear Safety Commission (NSC). After the negotiation with the opposition party at the time, it was agreed to establish Nuclear Regulatory Authority as an independent commission with decision making power in June 2012, which was finally set up in September 2012.

In the history of nuclear safety regulations in Japan, major reforms were undertaken after two accidents: the Mutsu nuclear ship accident of 1974 and the JCO criticality accident of 1999. It is important to have a historical perspective to understand what will happen this time. To that end, this chapter will review the historical progress of nuclear safety regulation in Japan in response to these two accidents. This chapter then discusses the lessons we can learn from the “regulatory failures” on nuclear safety uncovered by the Fukushima Daiichi accident in 2011, and about the institutional reform and remaining issues of nuclear safety regulation in Japan.

14.2 Historical Progress of Nuclear Safety Regulation in Japan

14.2.1 The First Period (1957–1978)

We can classify as the first period the two decades from 1957, when Japan established the Law for the Regulation of Nuclear Source Material, Nuclear Fuel Material and Reactors (the Nuclear Reactors Regulation Law), to 1978, when this Law was revised.

During this period, the Prime Minister had authority to approve licenses for nuclear businesses. Actually, the Director-General of the Science and Technology Agency, who was a cabinet member, had regulatory authority through assistance to the Prime Minister. As for commercial nuclear power reactors and commercial marine reactors, however, administrative measures, including construction permits issued by the Prime Minister, required the consent of the competent ministers (Article 71 of the Nuclear Reactors Regulation Law). In this case these were the Minister of International Trade and Industry (MITI) and the Minister of Transport, because these reactors had already been regulated by the old Electricity Business Act and the Ship Safety Act. In addition, some regulatory approvals and inspections of these two types of reactors, including approvals of design and construction plan, inspections of facilities and their performance, pre-service inspections, and periodic inspections, were exempted from the application of the Nuclear Reactors Regulation Law and were left to be covered by existing regulations (Article 73).

Meanwhile, the Nuclear Reactors Regulation Law also stipulated that the Prime Minister should listen to and respect the opinion of the Atomic Energy Commission of Japan (JAEC), which was established under the Prime Minister's Office based on Article 8 of the National Government Organization Act, including matters concerning safety regulation (Paragraph 2, Article 4). The Director-General of the Science and Technology Agency took on the position of chair person of the JAEC and this agency dealt with the staff work of the Commission. There had been controversy as to whether the JAEC should be set up as an organization prescribed in Article 3 or Article 8 of the National Government Organization Act, as the former is a decision-making organ and the latter is an advisory one. In the end, the JAEC was established as a de facto decision-making organ despite its legal nature as a very strong advisory council [1].

In this first period, one administrative agency—legally the Prime Minister, but actually the Science and Technology Agency—had nearly exclusively implemented nuclear safety regulation, even though some approvals were required by relevant ministries. Additionally, the JAEC had been established as a highly independent advisory council whose members were appointed upon confirmation from both Houses of the Diet. It was thought that the reason the JAEC had been granted a great deal of independence was so that it could ensure peaceful use of nuclear energy, as the purpose of its establishment was to provide "democratic administration of public affairs" (Article 4 of the Atomic Energy Basic Law and Article 1 of the Act for Establishment of the Atomic Energy Commission).

14.2.2 The Second Period (1978–1999)

The 1974 radiation leakage accident of Mutsu, the first and the only nuclear-powered ship in Japan, aroused public mistrust in the Japanese nuclear administration as a whole. The Japanese government established the Advisory Committee on Atomic Energy Administration under the Prime Minister in February 1975, whose chairman was Hiromi Arisawa, Emeritus Professor of the University of Tokyo, to reexamine the institution of nuclear-related organizations. Based on the Committee's report, the Nuclear Reactors Regulation Law was revised in 1978. We can regard as the second period the twenty years from that time to 1999 when the JCO criticality accident occurred, and the nuclear regulatory institution was reformed as a result of the reorganization of the central government.

The Arisawa Advisory Committee submitted its report in July 1976 detailing its recommendations on the reform and enhancement of nuclear administration in Japan. Three assertions closely linked with nuclear safety regulation were pointed out in this report as follows:

- To separate the functions related to nuclear safety from those of the JAEC, and to establish a new committee which shall deal with nuclear safety and double-check the safety reviews by the administrative agencies for enhancing the institutional framework of securing nuclear safety;

- To implement safety regulations consistently according to the types of reactors to clarify the responsibility of administrative agencies for ensuring the safety of nuclear reactors—the Minister of MITI be responsible for the regulation of commercial nuclear power reactors, the Minister of Transport for those of commercial marine reactors, and the Prime Minister for those of research and test reactors and those in the stage of research and development; and
- To implement some government measures such as holding public hearings and symposia to dispel the public's concerns over nuclear safety and obtain the public's understanding and cooperation on nuclear energy development [2].

Based on these recommendations, the Nuclear Reactors Regulation Law was revised in 1978 as described below. First, this revision assured consistency of safety regulations with respect to each type of reactor for ensuring their safety as follows: commercial nuclear power reactors would be regulated by the Minister of MITI, commercial marine reactors by the Minister of Transport, and research and test reactors and those in the stage of research and development by the Prime Minister. Next, the functions relevant to safety were separated from the JAEC and the Nuclear Safety Commission of Japan (NSC) was newly established to exercise jurisdiction over nuclear safety issues. Still, the legal position of the NSC fell under the category of "Councils, etc." prescribed in Article 8 of the National Administrative Organization Act as did that of the JAEC. As a result of this reform, the competent ministers were required to listen to and respect the opinions of the NSC about safety-related issues when they designated activities and issued permits; and the NSC stated its opinion in the form of double-checking safety reviews of the competent ministers on nuclear regulation. Meanwhile, neither the NSC nor the JAEC had its own secretariat, so the Science and Technology Agency dealt with the staff work of both Commissions.

With regard to the institutional form of the NSC and that of the JAEC whose reform was also re-examined at that time, the controversy as to whether an Article 3 organ or an Article 8 organ was adequate was rekindled. The Arisawa Committee concluded that the NSC and the JAEC should be "advisory committees" although the Socialist Party of Japan, the Japanese Communist Party, and the Federation of Electric Power Related Industry Workers' Unions of Japan proposed changing these institutional forms to "administrative committees" which have executive authority, such as the Japan Fair Trade Commission. The Arisawa Committee provided two reasons to support its conclusion as follows:

- Under the form of administrative committee, the JAEC and the NSC could not sufficiently perform their role as "the guardian of the Atomic Energy Basic Law" and would lose their ability to monitor the government because to become administrative committees meant being part of the government.
- The primary need was to secure the autonomy of both committees from the government from the viewpoint of ensuring the peaceful use of nuclear energy which was the starting point for Japan's nuclear energy development [3].

In addition to these considerations, the problem of the scope of authority was taken into account. That is, administrative committees could not deal with any issues other than their own administrative affairs authorized clearly by law. That meant there was the possibility that they would not be able to cover all the safety-related issues unless the laws prescribed the scope of authority very broadly; and that making a broad stipulation could overlap with the authority of other governmental agencies [4].

Furthermore, two public hearings would need to be held during the siting process of nuclear power plants (NPPs). Primary public hearings were held by MITI concerning various issues related to construction of NPPs before the Electric Power Development Coordination Council (so-called "Den-Chō-Shin") decided the Electric Power Development Master Plan for building new commercial nuclear power reactors. And secondary public hearings would be held by the NSC on the occasion of double-checking safety review documents submitted by MITI [2].

In this second period, the regulatory authorities were decentralized. What is more, several governmental agencies, including the ministries which had held jurisdiction over the development and promotion of nuclear businesses, also regulated nuclear safety according to the types of business. This was because the centralized regime of safety regulation in the first period had been judged not to work adequately. However, it can be said that these changes strengthened the integration inside each type of business, which meant the level of integration between the promotion side and the regulation side was enhanced. In addition, the highly independent advisory committee became responsible for the preliminary review of regulation by the regulatory agencies.

14.2.3 The Third Period (Since 1999)

The JCO (a nuclear fuel production company) criticality accident of September 1999 killed two workers, the first victims in the history of nuclear energy development in Japan, and caused radiation release which forced the evacuation of nearby residents. The report of the "Investigation Committee on the Criticality Accident at Uranium Processing Plant" proposed some measures related to regulatory issues as follows:

- Strengthening and enhancement of the capacities of regulatory agencies;
- Strengthening the independence of the NSC and the capacities of the NSC secretariat and ensuring input from expert groups in a variety of fields;
- Improving regulatory guides and making the multi-layered and mutually complementary regime of safety regulation function more effectively; and
- Enhancing the regulatory agency's and the NSC's responses to demands from society and the requirements of the present age, and improving their self-inspection.

The NSC in response to this report formulated its directions for ensuring nuclear safety in the Basic Policies for the Near-Term Initiatives of the NSC (NSC Decision in November 1999) as follows:

- To devote more attention to the viewpoint of operation management in the safety review of basic designs by adding experts in this field; and

- To verify the conditions in the operation stage as to whether the operators are maintaining their technical capabilities and taking appropriate safety measures. To assure that safety concepts are being followed at the time of the safety review, by receiving reports from the regulatory agencies on the compliance status of operational safety programs on the implementation status of periodic inspections and by conducting on-site inspections by the NSC itself.

The secretariat of the NSC was transferred from the Nuclear Safety Bureau of the Science and Technology Agency to the Prime Minister's Office in April 2000. This change brought about enhancement of human resources and improvement of the secretariat's capability to conduct expert investigations through such means as assigning experts from a wide range of areas as technical advisors, although it was a transitional institution until it was shifted to the Cabinet Office in 2001. In addition, the NSC institutionalized "the subsequent regulation review" of post-license regulations, which meant those regulations covering post-approval installation for nuclear facilities, including verification by on-site inspection for confirming the status of implementation of safety measures at construction and operation stages. The NSC published "The Basic Policies for the Near-Term Initiative of the NSC" (NSC Decision of June 2000) based on some trial implementations. Since then, the NSC began to implement fully the subsequent regulation review.

At the beginning of November 1999, there was a movement by the Administrative Reform Task Force of the Liberal Democratic Party to strengthen the NSC as an organization prescribed in Article 3 of the National Government Organization Act [5], but this was not put into action.

Furthermore, due to the reorganization of central government ministries, the regulation of commercial power reactors, reactors at the stage of research and development, and nuclear fuel facilities, etc. had come under the jurisdiction of the Minister of the Ministry of Economy, Trade and Industry (METI). However, the regulation of commercial marine reactors was placed under the jurisdiction of the Minister of Land, Infrastructure and Transportation from the Minister of Transport, and that of test and research reactors under the jurisdiction of the Minister of Education, Culture, Sports, Science and Technology (MEXT) from the Prime Minister (substantially from the Director-General of the Science and Technology Agency). In accordance with the abolishment of the Prime Minister's Office and the establishment of the Cabinet Office, the JAEC and the NSC had come under the Cabinet Office, and the NSC had come to have its independent secretariat in the Cabinet Office.

Also, organizations inside METI were restructured at that time. The Nuclear and Industrial Safety Agency (NISA) was newly established as an organization under METI—its legal position is a "Special Organ" attached to the Agency for Natural Resources and Energy. The purpose of this reform was to clarify the mission and responsibility of the agency in charge of nuclear safety administration, while ensuring independence to some extent, although it was still under METI [6].

It can be said that this government reorganization gave NSC greater independence because it was transferred to the Cabinet Office which has a higher position than the other Ministries, whereas previously it had been under the Prime Minister's

Office which was at the same level as the other Ministries, and the NSC had come to have its own secretariat. However, the original stipulation of "respect for decisions" prescribed in Article 3 of the Act for Establishment of the Atomic Energy Commission and the Nuclear Safety Commission was deleted in the revision in 1999, although the same sentence had been transferred to Article 23 in the revision in 1978 at the beginning of the second period. It would seem that the administrative reform had got rid of the provision of respecting the decisions of advisory councils without exception.

The NSC's involvement in post-license regulations was institutionalized as "the Subsequent Regulation Reviews (SRR)" in the third period in response to the JCO criticality accident, after its embryonic stage in the second period. Since then, the SSR has been implemented and advanced in response to various incidents. On October 29, 2002, for the first time since its establishment in 1978, the NSC submitted to the Minister of METI through the Prime Minister, "Recommendations for Restoring the Confidence of Nuclear Safety" based on Article 24 of the Act for Establishment of the Atomic Energy Commission and the Nuclear Safety Commission in response to Tokyo Electric Power Company's misconduct in concealing and falsifying inspection records. In addition, the regulatory agencies were required periodically to inform the NSC of the status of implementation of subsequent regulations since the amendment of the Nuclear Reactors Regulation Law in 2002 (Paragraph 3, Article 72). Moreover, this law amendment required the nuclear operators and their maintenance and inspection subcontractors to cooperate with the NSC's inspection in response to reports from the regulatory agencies.

On March 3, 2003 the NSC established new "Subsequent Regulation Review Implementation Guidelines" reflecting a stronger monitoring and oversight function for the subsequent regulations. This guideline set the performance goal of the SSR as "to clarify the responsibility of government and operators" for prompting the regulatory bodies to develop the continuous upgrading of quality, effectiveness, and transparency of post-license regulation activities [7].

14.3 Two Regulatory "Failures"—Systemic Causes of the Fukushima Daiichi Accident

The Fukushima nuclear accident reveals two "failures" of nuclear safety regulation in Japan.

14.3.1 "Failure" of Interdisciplinary Communication

First is the "failure" of interdisciplinary communication. The Fukushima Daiichi accident has made it clear that there was a severe delay in implementing tsunami counter measures. Why, then, could Japan not succeed in applying necessary measures against tsunamis?

In Japan, there had been a delay in taking actions to deal not only with tsunamis but also with seismic risks. However, the first decade of this century saw some progress in earthquake countermeasures. In September 2006, the Nuclear Safety Commission in Japan (NSC) revised the Regulatory Guide for Reviewing Seismic Design of Nuclear Power Reactor Facilities in accordance with the results of the 5 year study by the Subcommittee for the Regulatory Guide for Reviewing Seismic Design, which was established under the NSC in July 2001. With this revision, the Nuclear and Industrial Safety Agency (NISA) instructed nuclear operators to evaluate the seismic safety of existing nuclear facilities (so-called "back-checks") and reviewed its findings. In addition, the Chūetsu-oki Earthquake of July 2007, which shook the Kashiwazaki-Kariwa nuclear power plant with maximum seismic accelerations exceeding the levels assumed in the design, had made such efforts more imperative.

These processes, however, had not gone smoothly. In particular, there was a communication gap between the expert community on nuclear reactor safety, which consisted mainly of those in the engineering field, and that of earthquake resistance, which was made up of those in the scientific field.

As to the tsunami measures, Japan has responded in incremental ways. For example, the Tsunami Evaluation Subcommittee of the Japan Society of Civil Engineers (JSCE) published its "Tsunami Assessment Method for Nuclear Power Plants in Japan" in February 2002. The basic concept of this assessment method was to evaluate the design water level based on analysis of records of historical tsunamis and on some calculations with parameter variations. All the power companies which had nuclear power plants in Japan devised voluntary countermeasures against tsunamis based on this assessment method.

However, the Japanese nuclear community was unable to incorporate the rapid scientific progress in understanding tsunamis. For instance, in August 2002, the Earthquake Research Committee of the Headquarters for Earthquake Research Promotion, led mainly by scientific researchers, pointed out the possibility of earthquakes centered in plate boundary ocean areas which can be stronger than historical earthquakes. In addition, new simulation methods combined with sedimentological studies brought some new findings on the Jōgan earthquake of 869 mentioned in reliable historical records. Based on these findings, some tsunami experts estimated possible tsunami levels in the Fukushima coastal area higher than earlier predictions. Such advances in tsunami research have made the uncertainty of tsunami prediction more evident among the tsunami experts' community. Nevertheless, their recognition of this uncertainty was not transmitted to the nuclear safety community.

Moreover, in the Revised Regulatory Guide for Reviewing Seismic Design of Nuclear Power Reactor Facilities mentioned above, tsunamis are treated as part of the "accompanying phenomena" of earthquakes despite some subcommittee members' claim that tsunamis required particular attention in the revision process. The revised guide has only ambiguous stipulations about tsunamis as follows: "Safety functions of the Facilities shall not be significantly impaired by tsunami which could be reasonably postulated to hit in a very low probability in the service period of the Facilities."

Having taken some measures to counter seismic risks, the nuclear safety community was placing importance on tsunami risks as well. To cite a case, the Japanese Nuclear Energy Safety Organization (JNES), one of the technical support organizations in Japan, released study results of a tsunami probabilistic safety assessment (PSA) in December 2010 just before the Fukushima Daiichi accident. This study shows that tsunami levels above a certain height cause a high incidence of reactor core melt. However, these study results were not relayed to the regulatory body, NISA.

We can see from the above that insufficient interdisciplinary communication is one of the background factors in the delay in taking actions against tsunami risks. When utilizing a complex technology system such as nuclear technology, we are required to develop awareness of trends in a broad range of fields of knowledge. Nevertheless, we would have to say that institutions in Japan lacks a refined "antenna" which can constantly detect recent findings in different expert communities. It can be said that this is one of the fundamental functions expected of the regulatory body.

14.3.2 "Failure" of Voluntary Safety Efforts

Second is the "failure" of voluntary safety efforts by private nuclear utilities. Nuclear safety regulation in Japan has had a tendency toward relying heavily on operators' voluntary safety efforts. The current institutional design, where NISA is located under the Ministry of Economy, Trade and Industry (METI), has been well adapted to such attributes of regulation.

Though belatedly, Japan introduced its system for severe accident management in 1992. However, under the regulatory scheme of voluntary safety efforts, accident management measures were basically regarded as voluntary efforts to be made by operators, not legal requirements. Moreover, in Japan, it was decided in keeping with the intention of operators that the PSA(Probability Safety Assessment), which provides the basis for accident management, limit its scope to internal events, and exclude external events including earthquakes. These reflected operators' concerns on gaining public acceptance in siting areas as well as technical challenges involved in evaluations of external events.

Voluntary measures for severe accident management, however, became subject to informal evaluation by the regulatory body in the periodic safety review (PSR), which is one of the quality assurance activities taken up by operators voluntarily every 10 years. Through this informal evaluation, severe accident management had gradually expanded its scope to include external events such as fires. We might say that such voluntary safety efforts were effective to a certain extent.

However, when NISA made the PSR obligatory as a requirement of operational safety regulations after some scandals involving TEPCO's cover-ups of cracks in shrouds in 2002, NISA left the PSA-related matters as voluntary requirements because of insufficient technical expertise to conduct PSAs. As a result, NISA no longer evaluated severe accident management informally, and the expansion of the scope of the PSA was halted. This can be regarded as an adverse effect of institutionalizing voluntary safety efforts.

Operators had taken voluntary measures against tsunami risks as well. It was the electricity industry that supported a series of studies by JSCE on tsunami assessment technologies as mentioned above. Power companies also showed their concern about the new simulation studies on the Jōgan tsunami, and tried to seek countermeasures by making contact with researchers on this project.

In the end, such voluntary efforts were too slow to prevent this accident caused by the earthquake and tsunami. In addition, the delay in accident responses is assumed to be due also to the circumstance that it was hard for the operator to vent voluntarily without the government's involvement. Considering these points, we must conclude that there have been some real limitations in the conventional methods of voluntary safety efforts.

This does not necessarily mean, however, that the official regulation system by the regulatory body would be completely effective. As for the responses to tsunami risks, it was not the electricity industry but the regulatory body that should have commissioned the studies on tsunami assessment technologies by JSCE. The regulatory body has given less attention to recent findings in related fields than operators have.

14.4 Requirements for New Regulatory System

Based on the lessons from these "failures," what lesson we can learn to reform nuclear safety regulation?

14.4.1 Strengthening Independence

First, many argued the necessity of strengthening the independence of the nuclear regulatory authority body. If one of the causes of this accident was the regulatory authority's attitude of leaving voluntary safety efforts up to industry, this argument stands to reason. In addition, as long as this accident and the responses to it have undermined confidence in the regulatory bodies, to secure their independence is a necessary requirement for rebuilding public confidence.

In the past, when the radiation leakage incident of the atomic-powered ship Mutsu in September 1974 increased the public's mistrust, the institutional design of the atomic energy administration was put on review. As a result, the NSC was established in 1978 and the so-called "double-check" system was institutionalized in Japan: direct regulation of nuclear operators by the government regulatory agencies (the former Ministry of International Trade and Industry, etc.), and supervision/auditing of those agencies by the NSC for ensuring highly credible nuclear safety. In January 2001, NISA was newly established under METI as a "Special Organ" attached to the Agency for Natural Resources and Energy in response to the JCO criticality accident of September 1999. With this reform, the primary regulatory agency for nuclear safety secured "some" degree of independence from the Agency for Natural Recouces and Energy, which is also charged with promoting peaceful utilization of nuclear power.

These attempts at securing the independence of nuclear safety regulatory bodies, however, have coexisted with tendencies to depend on operators' voluntary safety efforts and to enhance collaboration and coordination with operators. These established ways had some merits, such as flexibility and regulatory cost savings. Still, in the case of crisis management of severe accidents like the Fukushima Daiichi accident, such institutions for nuclear safety regulation clearly caused delays in taking actions due to the unclear division of roles between operators and regulatory bodies.

Nuclear Regulatory Authority established as an independent commission with decision making power in 2012 at least satisfied this requirement of independence.

14.4.2 Ensuring Integrative Capabilities

Second, some claim that it is essential for the regulatory body to ensure integrative capabilities around nuclear safety. They state that although independence is important for the regulatory body, what is required is not only institutional independence but also integrative expertise to ensure substantive autonomy. In fact, we can say that the U.S. Nuclear Regulatory Commission (NRC) has integrative expertise which exercises jurisdiction comprehensively over nuclear safety, security, and safeguards for non-proliferation and has a staff of some 3,000. Similarly in France, L'Autorité de Sûreté Nucléaire (ASN) keeps those three areas under control in a comprehensive manner.

Of course, ensuring capabilities in nuclear safety regulation has been consistently an important issue in Japan too. Actually, after the JCO criticality accident and the reorganization of government ministries under the Hashimoto administrative reforms, NISA had been reinforced and JNES was established under NISA in 2003 with several functions transferred from some public-interest corporations. These regulatory agencies have been conducting mid-career recruitment from manufacturers in order to acquire technical expertise. Furthermore, NSC strengthened its secretariat functions after the JCO accident.

Despite these efforts, NISA, JNES and NSC have been facing the common challenge of human resource development. The mid-career staffs from manufacturers were certainly experts of parts of nuclear technology, but they could not always succeed in regulating in a comprehensive way, nor could they acquire enough skills as regulatory professionals to deal with operators.

In addition to these issues, there is also a problem with the adequacy of distribution of regulatory resources, that is, whether it is truly effective to establish two sets of regulatory bodies with the limited resources available after the series of administrative reforms: NISA and JNES primarily in charge of safety regulation; and NSC which conducts "double-checks." Moreover, the radiation dose regulation and the safeguard, the former which sets the overall goal of nuclear safety regulation and the latter which is essential for non-proliferation, are both under the Ministry of Education, Culture, Sports, Science and Technology (MEXT). This means that the authorities related to nuclear safety in its broad sense have

Table 14.1 Dispersion of regulatory agencies/institutions

	Organization	Number	
1	NSC	100	*2
2	NISA	330	*3
3	JNES	450	*2
4	AIST	35	*1
5	Nuclear Safety Association	80	*2
6	MEXT Policy Bureau	75	*1
7	MEXT R&D Bureau—safeguard	40	*1
8	JAEA	200	*1
9	Nuclear Safety Tech Center	150	*3
10	Sec of Radiation Council	5	*2
11	Japan Radioisotope Association	20	*1
12	National Inst of Radiological Sciences	50	*1
13	Nuclear Material Management Center	165	*2
	Total	1700	

Note *1: Direct employee; *2: Including indirect employee/management; *3: Unclear

been widely dispersed (refer to the Table 14.1 for the numbers in each organization). The dispersion of regulatory agencies led to the situation in which the chief Cabinet secretary had no choice but to constantly be the point person explaining the changing circumstances right after the outbreak of the Fukushima Daiichi accident even though he was not an expert in any nuclear field.

Under these circumstances, it is considered necessary to establish a consolidated regulatory authority for nuclear safety and to utilize human resources in an integrated manner for the efficient development of regulatory capabilities and for nurturing experts' careers.

Nuclear Regulatory Authority having jurisdiction over security and safeguard in addition to safety, and absorbing JNES, basically satisfied the requirement of integration.

14.5 Future Challenges

The requirements of institutional reform mentioned above are consistent with basically with the design idea of NRA, which was finally established in 2012. However, there are still some doubts about whether this institutional reform can be solutions to the "failures."

First, we can point to the problem of whether the integration of regulatory bodies can develop an interdisciplinary sensitivity. It is certainly significant to integrate nuclear safety, security, and radiation regulations into a comprehensive regulatory system. In addition, this can be a prerequisite for legislating severe accident management to make radiation regulation a goal of the overall safety regulations and to change the legislative purpose of safety regulations from "(to ensure public safety by) preventing hazards" to "preventing radiation damage to the public." Moreover, some measures for nuclear safety and nuclear security can overlap considerably, particularly in the thermal management of spent fuels and in the distributed arrangement of emergency diesel generators. Furthermore, broad experience in various aspects of nuclear safety fields can be useful in order for regulatory officials to develop interdisciplinary communication skills.

However, as noted earlier, one of the "failures" revealed by the Fukushima Daiichi accident is the lack of awareness of seismic and tsunami risks. Those risks and volcano risks, which seem to be among the future challenges of nuclear safety, are risks dealt with under different jurisdictions. Thus, attention must be focused on how to develop awareness of issues beyond the jurisdiction of the integrated regulatory authority and how to ensure interdisciplinary communication among such segmented fields.

The second problem, as made clear by the Fukushima Daiichi accident, is the limitation of voluntary safety efforts, and whether it is truly possible for the integrated regulatory body to strengthen the capability of regulatory staff in government nuclear safety regulatory organization. That entails the need for ensuring its capabilities independent of operators.

In the case of the United States, the Navy, which has many nuclear submarines, has played an important role as an excellent source of nuclear professionals other than power companies. In fact, many nuclear experts from the Navy have been employed by the NRC and the secretariat of the Institute of Nuclear Power Operations (INPO), which is a self-regulating organization of nuclear operators. In Japan, it can be said that some research institutes under the former Science and Technology Agency, such as the former Japan Atomic Energy Research Institute (JAERI), have played a role somewhat similar to the U.S. Navy. However, these institutes have had a tendency to downsize their operations as Japanese science and technology policy places more emphasis on research studies that have high possibilities to be applied to meet societal needs.

In Japan, assuring the careers of risk managers who have an interdisciplinary orientation based on various experiences of risk management in different fields, could be the key to ensuring continuous availability of human resources with capabilities in nuclear safety regulation but with sufficient independence from operators in nuclear fields.

References

1. Ito M (2003) Formation of Japanese model of administrative committee system: Administrative history of organization and institution. The University of Tokyo Press, Tokyo, pp 244-249 [in Japanese]
2. The Nuclear Safety Commission of Japan (1981) Annual report on nuclear safety 1981 [in Japanese]
3. Forum of Nuclear Energy Journalists (1981) Testimonies of journalists: Trajectory of nuclear energy for 25 years. Denryoku Shimpōsha, p 133 [in Japanese]
4. Arisawa H (1977) Revision of the basic law and future nuclear energy administration. p 5 [in Japanese]
5. Kitayama T (2008) Reform of supervisory framework of nuclear energy. In: Mabuchi M, Kitayama T (eds) Policy process at the time of political realignment. Jigaku-sha Shuppan, p 132 [in Japanese]
6. Suzuki T, Shiroyama H, and Takei S (2006) "Independence" and social trust in safety regulation: the Case of nuclear regulatory commission and its implication. Sociotechnica, 4:166 [in Japanese]
7. The Nuclear Safety Commission of Japan (2002) White Paper on Nuclear Safety 2002 [in Japanese]

Chapter 15
Radioactive Waste Management After Fukushima Daiichi Accident

Shinya Nagasaki

Abstract The categories of radioactive wastes have markedly changed due to the Fukushima Daiichi Nuclear Power Station accident. In addition to the conventional radioactive wastes such as high-level radioactive waste, the designated wastes, the wastes generated by decontamination work such as contaminated soil, the wastes contaminated with radionuclides or nuclear fuel which were generated within the on-site area of the nuclear power station, the spent nuclear fuel and debris, and the contaminated water are now critically required to be taken into account. The technological and legal schemes, by which these radioactive wastes will be appropriately processed and disposed of, must be established as soon as possible. These schemes also have to be widely supported by the public and society. This chapter gives an overview of the concept of radioactive waste management and discusses the problems and challenges to be solved for the management of all types of radioactive wastes and for the sustainable use of nuclear energy in the 21st century.

Keywords Radioactive waste management · Temporary storage · Intermediate storage · Disposal · Contaminated water · Debris · Spent fuel

15.1 Introduction

The Fukushima Daiichi Nuclear Power Station accident of Tokyo Electric Power Company (hereafter, "Fukushima accident") brought about a significant impact and change on the policy of nuclear energy development and use in Japan. Simultaneously, a challenge which has not been assumed scientifically, technologically, and legally before March 11, 2011, namely the processing and disposal

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of radioactive wastes generated by the Fukushima accident, is now becoming evident. All members of the nuclear community in Japan have a responsibility to clearly and concretely illustrate a roadmap of how the processing and disposal of the wastes contaminated with radioactive materials and nuclear fuels, generated by the Fukushima accident, can proceed as a function of time. This is the most critical subject that cannot be bypassed for the restoration and revival of communities and residents who were obliged to evacuate due to the Fukushima accident. Furthermore, this is a primal premise for advancing the safe and steady decommissioning of Units 1–4 of Fukushima Daiichi. Consequently, what we learnt, what we are learning, and what we will learn from the Fukushima accident will be able to be made to be the common property of all human beings in the world.

From now on, it is considered that the concrete plans for processing and disposal will be proposed by the relevant ministries and agencies, and these will be put into action. The purpose of this chapter is to summarize the current legal system for radioactive waste management in Japan after the Fukushima accident and to discuss the practical challenges to be overcome for safe and secure radioactive waste management in the future.

15.2 Legislation for Radioactive Waste Management after Fukushima Daiichi Accident

The waste produced by the use of nuclear fuels such as uranium and plutonium *in* nuclear reactors is regulated by the Law for the Regulations of Nuclear Source Material, Nuclear Fuel Material and Reactors, and the waste generated by the use of radioisotopes, radiation rays, accelerators, and so on are controlled by the Law Concerning Prevention of Radiation Injury due to Radioisotopes, etc. This is the established legal structure, and the competent authorities have been designated. These laws presume that radioactive waste is generated in a controlled area, and is managed and stored there appropriately.

After the Fukushima accident, in addition to such conventional wastes, waste has been generated that is contaminated with radioactive materials and nuclear fuels produced outside of a controlled area, i.e., nuclear reactors or the nuclear power station of Tokyo Electric Power Company. Consequently, in order to manage the waste generated outside the nuclear power station, the Law on Special Measures Concerning the Handling of Environmental Pollution by Radioactive Materials by the NPS Accident Associated with the Tohoku District—Off the Pacific Ocean Earthquake that occurred on March 11, 2011 (hereafter, "the Law on Special Measures") came into force, over which the Ministry of Environment has jurisdiction. Decontamination and processing and disposal of wastes are being conducted under this legal system.

Figure 15.1 shows the flow of processing of waste generated in Fukushima Prefecture by the Fukushima accident, determined by Cabinet decision, based on the Law on Special Measures. Disaster waste is treated by the Law on Special

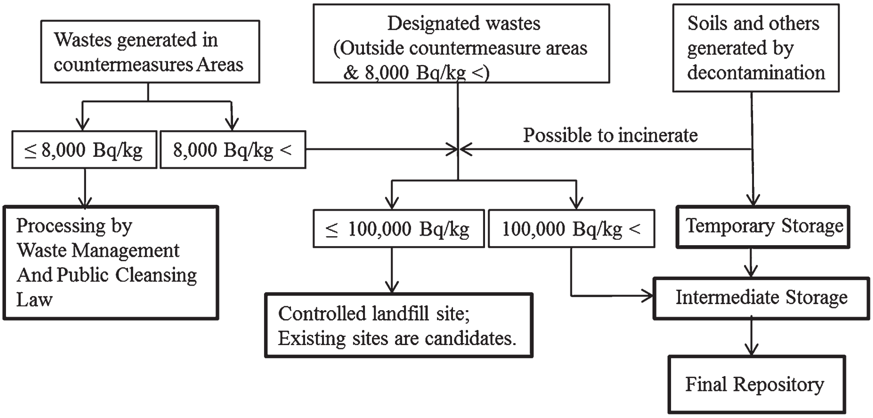


Fig. 15.1 Flow of processing of wastes generated in Fukushima Prefecture by Fukushima accident. Radioactivity level is sum of ^{134}Cs and ^{137}Cs

Measures Concerning Disaster Waste Management after the Great East Japan Earthquake, but the waste of radiation levels higher than 8,000 Bq/kg (sum of ^{134}Cs and ^{137}Cs; hereinafter the same meaning shall apply) is treated in the Law of Special Measures, and hence, it will enter the flow of Fig. 15.1.

The criteria of 8,000 and 100,000 Bq/kg, illustrated in Fig. 15.1, were decided for the following three reasons [1]. First, when waste of 100,000 Bq/kg or less is disposed of in the landfill site which will not be used for residence and will be managed appropriately for a long period, the annual radiation dose rate of the residents around the site after the completion of landfill is estimated to be less than 10 μSv/y. Second, during the operation of controlled landfill sites for waste of 100,000 Bq/kg or less, the annual radiation dose rate of the residents around the site is evaluated to be less than 1 mSv/y, if their residence area is sufficiently far from the boundary of the site. Third, when waste of 8,000 Bq/kg or less is directly transferred to the landfill site, the annual radiation dose rate of workers is expected to be less than 1 mSv/y and the safety of workers is assured.

The waste generated in the countermeasure areas (areas where evacuation orders are ready to be lifted, areas where residents are not permitted to live, and areas where it is expected that the residents will have difficulties in returning for a long time) [2] is classified into two classes: waste of 8,000 Bq/kg or less and waste of over 8,000 Bq/kg. The former will be processed by local municipalities or waste disposers in accordance with the Waste Management and Public Cleansing Law. The latter will be treated as waste equivalent to the designated waste. The waste which is generated outside the countermeasure areas and for which radiation level exceeds 8,000 Bq/kg is labelled as designated waste by the Minister of Environment.

In Fukushima Prefecture, not only a large amount of waste accompanied with decontamination but also highly contaminated waste of over 100,000 Bq/kg is expected to be generated. The contaminated soil and other waste generated from decontamination will be stored in the temporary storage site, and then be transferred to the intermediate storage facility where those will be stored together with waste of over 100,000 Bq/kg. The waste generated outside Fukushima Prefecture is not transferred to the intermediate storage facility. Because waste of over 100,000 Bq/kg is not considered to be generated in prefectures other than Fukushima, the flows which go to the intermediate storage facility in Fig. 15.1 are not assumed for the waste outside Fukushima Prefecture.

Irrespective of location, waste of over 8,000–100,000 Bq/kg or less will be disposed of in a controlled repository/disposal site located in each prefecture. The existing landfill site is considered to be a candidate for this site. When a new controlled repository/disposal site needs to be built, the Japanese Government will select two or more proposed sites within the national lands in each prefecture, and will decide on a site. In addition, the volume of waste will be reduced through incineration, dryness, fusion, and so on, until a controlled repository/disposal site starts operation. A temporary facility will also be built for incinerating the by-products (straw from rice and pastures, etc.) from agriculture or forestry which cannot be incinerated in the existing incineration facility.

The flow through the intermediate storage facility is particular to the waste generated in Fukushima Prefecture. The roadmap of the flow is planned as follows. The waste will be stored in the temporary storage site for approximately 3 years. Each city, town, or village is required to secure its own site within its boundary. In countermeasure areas, the Ministry of Environment will secure the sites in cooperation with local municipalities. By approximately 3 years after starting the formal temporary storage process, transport to the intermediate storage facility will be scheduled to start. The waste stored in the intermediate storage facility will be disposed of in a final repository, which will be constructed and operated outside Fukushima Prefecture. The transport from the intermediate storage facility to the final repository will be scheduled to start within 30 years after the intermediate storage starts.

However, under the current situation, many problems about specific processing and disposal still remain, as mentioned below, and the challenge of site selection for the intermediate storage facility and for controlled landfill has yet to be overcome. As can be seen in opposition movements and protests by the residents of Yaita City, Tochigi Prefecture, and Takahagi City, Ibaraki Prefecture, which were selected as the final landfill site by the Japanese Government, issues such as transparency of the selection procedure, communication with stakeholders, and equity in liability and onus are quite important. Furthermore, the Law on Special Measures decides only the framework on processing, decontamination, and budget. Most procedures and schedules are planned according to the basic policy by Cabinet decision, and specific methodology of landfill is illustrated in the notification from the Ministry of Environment. For the management of waste of over 100,000 Bq/kg, only the abstract requirements for safety of disposal are decided in Enforcement Regulations for the Law on Special Measures.

Management of radioactive waste generated within the Fukushima Daiichi nuclear power station by the accident must be performed primarily by Tokyo

Electric Power Company in accordance with the Law for the Regulations of Nuclear Source Material, Nuclear Fuel Material and Reactors, but in actuality nothing is decided about processing, reprocessing, storage, and disposal of the waste. Damaged fuel, such as melted fuel, the debris and waste contaminated with radioactive materials, and nuclear fuel generated by the Fukushima accident, are not assumed in the Law for the Regulations of Nuclear Source Material, Nuclear Fuel Material and Reactors. Thus, revision of the law and/or the preparation of new legal system for the management of these radioactive wastes are critical and essential, and regulation for safety of radioactive waste management is inevitable. At present, solid wastes, such as debris and rubble, are planned to be stored in storage facilities in which the radiation shield and prevention of waste scattering are appropriately implemented. Furthermore, the volume of waste will be reduced and the materials with low radioactivity will be recycled within the Fukushima Daiichi Nuclear Power Station.

In the following three sections, the kinds of waste generated within Fukushima Daiichi Nuclear Power Station and the problems to be solved for safety and security of radioactive waste management are discussed.

15.3 Management of Contaminated Water

To cool fuel debris stably, cooling water is continuously recirculated inside the primary containment vessel. Nevertheless, approximately 400 m^3 of groundwater flows into power station buildings per day, and hence the amount of contaminated water increases daily.

In order to manage the contaminated water, three measures have been implemented [3, 4]: (i) “Remove” sources of contamination, (ii) “Isolate” water from contamination, and (iii) “Prevent leakage” of contaminated water. In order to reduce the risk from contaminated water, some measures have been implemented. For example, the contaminated water has been treated with a multi-nuclide removal equipment (ALPS), the groundwater has been pumped up from sub-drains near nuclear power station buildings, land-side frozen soil impermeable walls have been installed, and the soil has been improved with sodium silicate. Furthermore, some additional measures have been decided. For example, more multi-nuclide removal equipment will be installed, measures to prevent water leakage from tanks will be taken, broader area pavement (surface waterproofing) at the site will be implemented, and the length of contaminated water transfer piping will be reduced. Further detailed measures are illustrated in the Refs. [3, 4].

Also being addressed are the necessity and importance of accelerating the installation of further tanks to the extent possible with combined efforts of the public- and private-sectors, developing measures with high technical difficulties, such as methods to clean up the sea water in the harbor and to remove radioactive materials in the soil, and of making a comprehensive evaluation of all options for tritiated water containing residual risks as soon as possible and consider appropriate measures.

15.4 Management of Radioactive Wastes Generated Within Nuclear Power Station

Figure 15.2 illustrates the kinds of waste contaminated with radioactive materials and nuclear fuels emitted from the damaged nuclear reactors to the atmosphere, groundwater, and soil by the Fukushima accident, and an example of the flow of processing and disposal processes of the radioactive waste. Figure 15.2 roughly consists of three streams of wastes. The two upper streams show the management of wastes generated within Fukushima Daiichi Nuclear Power Station, and the bottom stream represents that generated outside of the Station.

The radioactive waste consists of liquid waste and solid waste. The liquid waste includes the liquid which was initially stored in Mega-Float and the barges and whose radioactivity level is not high, the waste fluid which will be generated from the decontamination processes in future, the zeolite containing waste liquid with high radioactivity level, the sludge with high radioactivity level, and sea water near a sluice gate which the silt fence prevents from diffusing to the open sea, and so on. The radioactive liquid waste will be separated into freshwater components, sea water origin components such as sodium chloride, and solid components through evaporation and condensation, and then the freshwater and sea water origin components will be released into the environment such as the ocean after confirming its safety to discharge into the environment. The radioactive solid waste generated will be classified into waste of which the disposal is judged to be appropriate and waste deemed unsuitable from the viewpoint of current available technologies or existing legal system.

The solid waste includes soil, rubble, and forest in the on-site areas of Fukushima Daiichi Nuclear Power Station. In addition to these, the solid waste also includes the dredged sludge, the soil and rubble on the sea floor, the filters of cesium adsorption facility, and so on. According to its radioactivity level, form, and characteristic, radioactive solid waste is considered to be decontaminated by, for example, washing, blasting, or exfoliation, if necessary. Consequently, waste which does not need to be managed as radioactive waste will be dealt with as industrial waste and suitably processed and disposed of, and waste, of which the safety is confirmed and which is able to be reused, will be recycled. The waste which needs to be managed as radioactive waste will be classified into the waste of which the disposal is judged to be appropriate and the waste to be unsuitable, as described above in the solid waste generated from the liquid waste. The former waste will be reduced in its volume, stored, solidified by appropriate methods and then disposed of. The latter waste, which is judged to be unsuitable for disposal by the current available technologies or in the existing legal system, will be reduced in its volume and stored until the technology development and the new legal system are in place. The adsorption material (ferrosyanide) used in ALPS and the slurry generated in the pre-processing stage of ALPS are examples of such. Hence, it is necessary to develop the technology and prepare the legal system, which include the concept of disposal, the concept of waste form, and the criteria

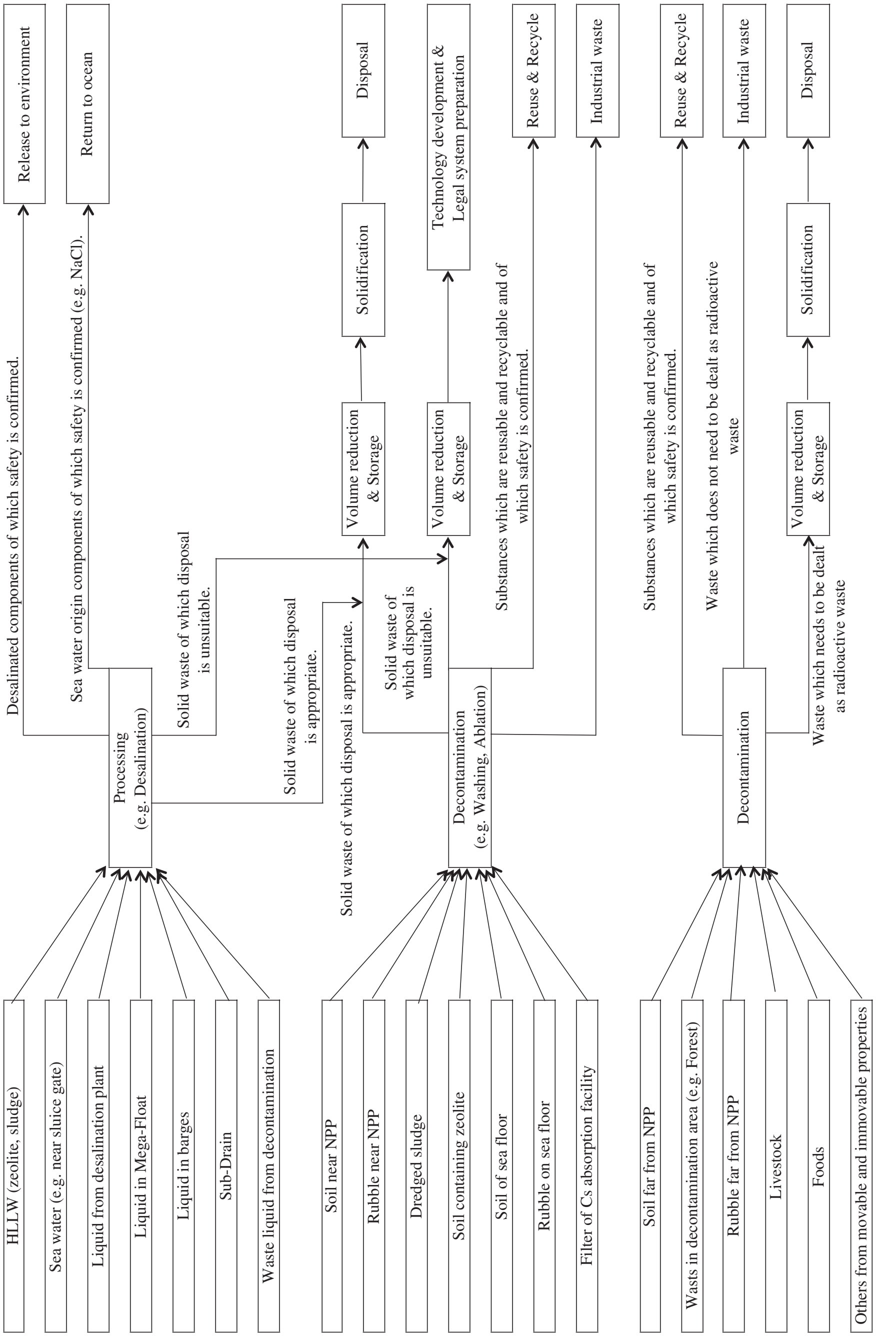


Fig. 15.2 Kinds of waste generated by Fukushima accident and an example of the flow of processing and disposal processes of radioactive waste

of release from the legal control on land use of the repository site and so on, to enable future disposal of this waste through social consensus and agreement.

Furthermore, the kinds and radioactivity levels of waste are widely distributed. For example, incombustible, flame-resistant, and combustible wastes intermingle and most are difficult to separate out from each other. There are wastes containing not only plutonium and/or an anti-scattering agent but also oil and sea water components, and lead, PCB, and asbestos which require special consideration in processing and disposal. It is also necessary to measure their contents in the waste. It is well known that it is difficult to elucidate the physicochemical characteristics of radionuclides in sludge.

In addition to these, there is the problem of the huge quantity of the waste. The processing for efficient reduction of the volume of intermingled waste is indispensable even for temporary storage. The quantity of the sea water components such as sodium chloride is also huge, and these components have to be separated. For example, the sea water components have to be separated from the sludge which is produced in the processing facility of high-level liquid waste, and simultaneously the radionuclides have to be separated from the sea water components. It is also essential and critical to solve the problem of how to reserve the many skilled workers for long-term restoration, considering their radiation exposure management, and so on.

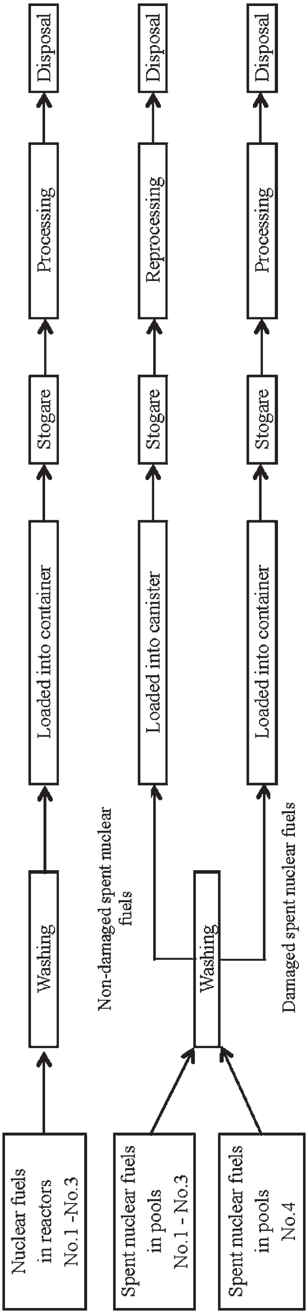
15.5 Management of Nuclear Fuels in Nuclear Reactors and Spent Fuel Pool

Figure 15.3 illustrates an example of management of nuclear fuels in the reactors of Units No.1–3 of Fukushima Daiichi Nuclear Power Station and of spent nuclear fuels in the pools of Units Nos. 1–4.

The spent nuclear fuel in the pools will be classified into non-damaged spent nuclear fuel and damaged fuel. The former will be washed, loaded into canisters, and stored. (The policy on the nuclear fuel cycle in Japan after the Fukushima accident is not discussed in this chapter.) It is not yet clear how to manage the damaged spent fuel concretely and whether the non-damaged spent fuel will be reprocessed. In order to reduce the risk of spent fuel in the pools, the transfer of spent nuclear fuel in the pools to the common pool has started. In Unit No. 4, 726 fuel assemblies (704 spent and 22 new fuels) have been transferred to the common pool as of April 23, 2014, and the transfer of 1,533 fuel assemblies (1,331 spent and 202 new fuels) will be completed around the end of 2014. In Unit No. 3, the removal of large pieces of rubble from the pool is underway. In Unit No. 2, after progress is made in decontamination and shielding within the reactor building, formulation of a concrete plan will be discussed. In Unit No. 1, the construction of a yard to operate large and heavy machines is scheduled, and the demolition of the reactor building cover commenced in the first half of 2014.

Investigation has been performed on the amounts of fuel that were melted down and where the debris is distributed, and the decontamination and the fixation of

Fig. 15.3 Example of management of nuclear fuel in reactors No. 1–3 and spent nuclear fuel in the pools of No. 1–4



the pressure boundary of the primary containment vessel, as well as examination of physical and chemical characteristics of the debris. Furthermore, management of these nuclear fuels includes resolving the problems of where the nuclear fuels removed from the nuclear reactors are to be stored, who is to implement the final disposal, what the repository site selection procedure is, what the concept of disposal including the nuclear fuel cycle is, and how the legal system is prepared. This will entail the development of the method for processing and disposal of debris/melted nuclear fuel and development of technologies consistent with this method, the development of a specific container, and the development of remote-controlled technologies to locate the leaks of water in reactors and to repair those, as the work of removing the nuclear fuel from the reactors is carried out under the condition in which the reactors are filled with water. In addition to these, it is critical to confirm the soundness of the pressure vessels and containment vessels for a long time (at shortest, until completion of removing all nuclear fuels) because sea water containing salt was boiled in the vessels.

Although some of these steps cannot be taken until the conditions of nuclear fuels are known, we must take steady and appropriate actions one by one.

15.6 Concept of Radioactive Waste Disposal

All nations that have been using nuclear energy have adopted the method of disposal into the underground environments where the radioactive waste is generated. This is because it is most appropriate that the radioactive waste generated in a country is disposed of in its own territory; because currently available technologies, knowledge, and skills can be used in disposal; because the long-term safety assessment of disposal is expected to be performed reasonably; and because the retrievability of radioactive wastes is not technically impossible if it is required.

In Japan, very low-level radioactive waste has been disposed of at approximately 5 m below the ground surface ("landfill disposal" or excavation disposal), and relatively low-level radioactive waste, which is generated in operation and maintenance of nuclear reactors, has been disposed of at approximately 10 m depth from the ground surface ("vault disposal"). For low-level radioactive waste whose level of radioactivity is relatively high, the disposal at depths of 50–100 m ("subsurface disposal") has been considered and will be planned. High-level radioactive wastes are legally mandated to be disposed of at 300 m or more below the ground surface ("geological disposal"). This concept of disposal in Japan is illustrated in Fig. 15.4 [5, 6]. In vault disposal or subsurface disposal, radioactive waste is solidified using cementitious or other materials within a drum or a container specific to the solidification, and the drum or the container is covered by cement or concrete and further covered with material such as clay or mixture of clay and sand through which the groundwater is hard to penetrate and by which cations are easy to be trapped. The barrier of these artifacts is called an artificial barrier, and the safety of disposal is secured by the multi-barrier system which consists of the artificial barrier and the natural barrier which functions in the geosphere and the biosphere. In geological disposal, high-level radioactive liquid waste is mixed with borosilicate glass material and solidified in a stainless steel

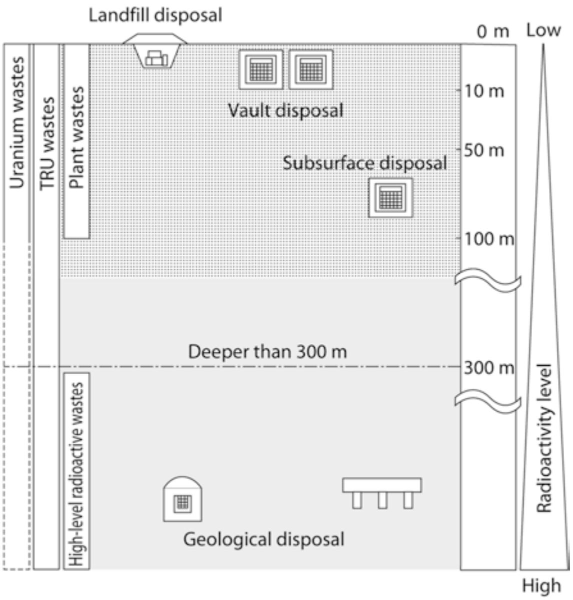


Fig. 15.4 Four types of disposal in Japan [5, 6]

canister (vitrified waste), and inserted into an overpack (e.g., carbon steel). The overpack containing the vitrified waste is transferred to the underground repository, placed in the tunnel and covered with compacted clay materials.

What is described above was the fundamental concept of radioactive waste disposal in Japan before the Fukushima accident. This concept is natural, scientifically reasonable, and technically sound. We mine, for example, iron, copper, or uranium ore, and refine it to use as iron, copper, or uranium. This fact clearly indicates that the deep underground environment has the capability to retain and contain metals over a long period of time in a geological sense (some 10 million years to some 100 million years).

To be accommodated in the disposal system mentioned above, it is expected that the waste contaminated with radioactive materials and the damaged nuclear fuel generated by the Fukushima accident will also be adequately processed, sealed in suitable containers, stored for a certain period, and then disposed of in the repository built in the relevant geological environmental conditions, according to their radioactivity levels. The plan, design, and implementation of the processing of radioactive waste must be optimized for achieving the safety in the final disposal, because the processing may influence the feasibility of disposal options.

Not only the technical and regulatory compatibility with the current system, but also broad support from the public for final disposal of radioactive waste generated by the Fukushima accident must be achieved. It is imperative that the Japanese people share their opinions on this issue with each other. The discussion will inevitably extend to Japan's nuclear future, i.e., whether Japan continues to exploit nuclear energy or phases it out.

15.7 Summary

Many countries, not only Japan, which have been using nuclear energy and have plans to use nuclear energy were forced to rethink the ethical value of use of nuclear energy by Fukushima Daiichi Nuclear Power Plant accident. Considering the final disposal of all nuclear fuels generated by the Fukushima accident, we fully recognize that radioactive waste management is an enterprise which will not be completed within the 21st century. Simultaneously, it goes without saying that the safe and steady management of radioactive waste is the premise for the restoration and revival of communities and residents of Fukushima. In such a situation, the management of various radioactive wastes generated by the Fukushima accident will be expected to proceed steadily and safely under greater coordination among science and technology, politics, and the public and society.

References

1. Ministry of the Environment, Japan (2012) Management of off-site waste contaminated with radioactive materials due to the accident at Fukushima Nuclear Power Stations. Available at: https://www.env.go.jp/en/focus/docs/files/20121128-58.pdf. Accessed 18 July 2014
2. Ministry of Economy, Trade and Industry (2013) Areas to which evacuation orders have been issued (August 7, 2013). Available at: http://www.meti.go.jp/english/earthquake/nuclear/roadmap/pdf/20130807_01.pdf. Accessed 18 July 2014
3. Ministry of Economy, Trade and Industry (2013) Basic policy for the contaminated water issue at the TEPCO's Fukushima Daiichi Nuclear Power Station. In: Mid-and-long-term roadmap towards the decommissioning of TEPCO's Fukushima Daiichi Nuclear Power Station Units 1-4. http://www.meti.go.jp/english/earthquake/nuclear/decommissioning/pdf/20130904_01a.pdf. Accessed 18 July 2014
4. Ministry of Economy, Trade and Industry (2013) Preventive and multi-layered measures for decommissioning and contaminated water management. In: Mid-and-long-term roadmap towards the decommissioning of TEPCO's Fukushima Daiichi Nuclear Power Station Units 1-4. Accessed 18 July 2014.
5. Niibori Y (2014) Radioactive waste disposal. In: Nagasaki S, Nakayama S (eds) Radioactive waste engineering and management. Springer, Japan (in press)
6. Web Archiving Project of National Diet Library (2009) Houshaseihaikibutsu no homupeji (Homepage of radioactive wastes). http://warp.da.ndl.go.jp/info:ndljp/pid/282070/www.enecho.meti.go.jp/rw/gaiyo/gaiyo03.html. Accessed 18 July 2014

Chapter 16
From Fukushima to the World

How to Learn from the Experience in Japan

Tatsujiro Suzuki

Abstract This is the text for the after-dinner speech given by Prof. Tatsujiro Suzuki, then Vice Chair of Japan Atomic Energy Commission, on August 4, 2011 in Berkeley for the 2011 PAGES Summer School, “Reflections on the Fukushima Daiichi Nuclear Accident: Toward Social-Scientific Literacy and Engineering Resilience.”

Keywords Vice chair • Japan Atomic Energy Commission • Speech • 2011 PAGES Summer School at Berkeley

Thank you very much for your kind introduction. It is my great honor to speak as a dinner speaker at the 2011 Advanced Summer School of Nuclear Engineering and Management with Social-Scientific Literacy. The given title of my speech is; “From Fukushima to the World: How to learn from the Japan’s experiences.” This is a great title and I wish to make personal remarks tonight, so please note that this is not necessarily representing the views of Japan Atomic Energy Commission (JAEC) or the government of Japan. Before I start my speech, I would like to make a few remarks on my personal feelings on this issue.

First is “sympathy.” I would like to express my deepest sympathy and condolences for victims of the Earthquake and Tsunami, and their families. In particular, my personal sympathy goes to people who have been forced to evacuate from their own homes and land. Even after several months they are not sure when they will be able to go back to their own homes and some fear that they may not be able to ever return. It is heartbreaking to watch the site and hear people’s anger, frustration, and anxiety over the accident and their future.

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Second is "regret." As a researcher working on nuclear energy policy for over 30 years and as a government official, I am truly regretful for what happened at Fukushima. How could this have happened? Why could we not prevent the accident? How can we prevent such nuclear disasters in the future? These are the questions that I have been asking myself every day since March 11. It is our responsibility to answer these questions with complete transparency and sincerity. This is the only way, I believe, to restore the trust lost by this accident.

Third is "thank you." I would like to express my sincere thanks for all the assistance and heartwarming support given to us by the U.S. and many other countries after the Earthquake and the accident. I also thank you for this great opportunity to give a talk in front of distinguished experts and outstanding students who are pondering the future of nuclear energy. To be honest, I do not have any good answer regarding the future of nuclear power. I am sure that not only experts but general citizens are also concerned about the future of nuclear power. In this context, I am convinced that it is my (and Japan's) responsibility to share information and experiences about the accident to the greatest extent possible so that you can make better decisions. That is why I have been accepting as many invitations as possible to speak on Fukushima since May 2011.

Today, though, it may take too much time to give you speech I prepared for other international conferences which consists of more than 60 slides. Instead, I will summarize four major points which are: the seriousness of the accident, securing safety of the public and the environment, energy and nuclear energy policy, and implications for international society.

First, how serious is this accident? It is clear to everyone that the Fukushima Dai-ichi accident is one of the worst in global nuclear history. It is unique in the sense that it was triggered by a massive earthquake and tsunami, which resulted in three core meltdowns and four explosions at one site. A large amount of radioactive release occurred which forced more than 80,000 people to evacuate, and it is not yet completely under control, more than four months after the accident. In terms of the quantitative impact of the accident, the International Nuclear Events Scale (INES) scale is now rated as Level 7, but I believe the social consequences of this accident cannot be expressed by this single number. The most serious social consequence of this accident is "loss of public trust in Japan's governance over nuclear safety." JAEC issued statements on this point as follows:

> We are gravely concerned about this accident which can fundamentally undermine public trust in safety measures, not only in Japan but also in other countries [1].
>
> [t]he people's confidence in the adequacy of the risk management activities has been lost due to the occurrence of this accident [2].

While it is technically possible to take measures to enhance nuclear safety responding to this accident, it will be extremely difficult to restore public trust in the near future. This is the biggest challenge, I believe, for Japan's nuclear energy policy.

Second, we must secure public safety and restore the environment. This is the top priority of the government, but so far the results of its efforts are not completely satisfactory. There are many challenges that we must face. Managing a large amount of highly contaminated water is one big challenge on site. Continuous monitoring and drawing a more detailed "contamination map" is another. Huge efforts may be required to decontaminate the land/water and to assure that people can return without fear of radiation. And it will probably take decades to remove spent fuel from the reactors and to completely decommission all four reactors. *This is a huge, very expensive, very complex, and unprecedented challenge which we have never faced before*. We may need new technologies to cope with these difficult tasks. I believe we need a systematic, strategic, and well-planned approach to complete this process. We probably need a new institutional scheme as we must deal with technological, economical, legal, and social issues. International cooperation on this matter is essential. JAEC also issued a statement on this issue:

> The government should develop an organizational framework to promptly and effectively carry out such emergency measures, … and if necessary, it should develop the legal framework required for each measure, and immediately start on such steps as implementing demonstration tests on effective technology [2].

Third, we must formulate an overall energy and nuclear energy policy. The top priority on this issue is how to secure the safety of existing nuclear power plants and gain public trust. This is a short-term energy policy issue, but critically important for long-term energy future, too. Unless we regain public trust in the safety of existing nuclear power plants, it is not possible to discuss a positive future for nuclear power in Japan. Unfortunately, public trust in nuclear safety regulation has been completely lost. The government plans to separate the Nuclear and Industry Safety Agency (NISA) from its parent body, the Ministry of Economy, Trade and Industry (METI); and the Nuclear Safety Commission (NSC) will probably be incorporated into a new safety regulatory agency. Restructuring the nuclear regulatory agency alone may not be enough to regain public trust.

In this context, the Government's report to the International Atomic Energy Agency (IAEA) issued in June states:

> it is necessary for Japan to conduct national discussions on the proper course for nuclear power generation while disclosing the actual costs of nuclear power generation, including the costs involved in ensuring safety [3].

I agree. We need an innovative policy making process, stimulating public debate and incorporating public input while still being based on scientific evidence. Do we have such a forum? One possible social function that we need is an institution dedicated to Technology Assessment (TA) which can provide objective and unbiased assessment of societal implications of science and technology. Information disclosure with proper assessment is critically important for informed public debate.

For a longer term energy policy, the newly created "Energy and Environment Council" released its interim report on July 29, 2011, outlining a basic new energy policy. There are three basic philosophies: (1) Three principles toward a new best energy mix (reducing dependency on nuclear power, strategic approach for energy security, complete reevaluation of nuclear energy policy); (2) Three principles toward a new energy system (realization of a distributed energy system, international contribution, multi-perspective approach); (3) Three principles toward national consensus (national debate in order to overcome "pro-" "anti-" conflict, strategy based on objective data, dialogue with various sectors of the public). The Council also suggests that it will re-evaluate costs of nuclear power considering the impact of the accident. Given public opinion polls (more than 60 % of the public are now in favor of "phasing out" nuclear power), "reducing dependency on nuclear power" is probably the likely outcome of the new energy policy. But it is not yet certain how soon, how much, and what other energy sources will fill the gap.

Fourth, we must address implications for international society. This accident is not just a Japanese accident, and has already had significant impacts on the global nuclear energy picture. There are more than 400 nuclear power plants worldwide and it is critically important to assure the safety of those plants. In this context, it is Japan's responsibility to share our information and experiences as much as possible. One concern is that the world is now clearly divided into two groups, "pro-nuclear" and "anti-(including phasing out) nuclear." This trend, which existed before but was much more subtle, is now clearly changing the global politics of nuclear power. It is getting more difficult to reach a consensus on nuclear energy policy, although there is a growing consensus on enhancing nuclear safety in general.

At the recent UN Conference on Nuclear Disarmament held in Matsumoto City, Japan, July 27–29, 2011, there was an interesting discussion on civilian nuclear power. Under the Non-proliferation Treaty (NPT), Article IV guarantees the "inalienable right" of the peaceful use of nuclear power by member countries. But Ms. Yoriko Kawaguchi, former co-chairperson of International Commission on Nuclear Non-proliferation and Disarmament (ICNND), suggested that there should be "responsibility" concerning use of nuclear power. However, there was a strong statement by Dr. Yukiya Amano, Director General of the International Atomic Energy Agency (IAEA), that "global use of nuclear power will continue to grow in the coming decades and it will remain an important option for many countries." There was still another important issue emerging from the Fukushima accident. That is the common characteristic of "nuclear safety" and "nuclear security," especially the safety and security issue associated with spent fuel storage which has become a major policy issue for the international community.

I would like to conclude my talks with the following remarks.

First, we should be able to overcome this tragic accident with our wisdom. Never give up. Yes, this is an unprecedented crisis, but crisis can be an opportunity. We will draw lessons and come up with innovative ideas to improve the safety of nuclear power plants and to clean up the site. If we cannot control nuclear energy, how can we control nuclear weapons? We should overcome this man-made disaster with a humble attitude towards nature and science/technologies. I truly believe that the international community can work together with Japan to overcome this crisis.

Second, let's make Fukushima a symbol of "recovery." Hiroshima and Nagasaki were victims of nuclear destruction, but became symbols of "peace."

Fukushima is now victim of one of the most serious nuclear accidents in human history. But, I sincerely believe that Fukushima can become a symbol of "recovery." This should be the goal of the Japanese government, and I personally will do my best to achieve this goal as a government official and as an individual.

Finally, in order to achieve the above two goals, I believe that the role of scientists, like yourselves, can be extremely significant. One of the important lessons we learned from the Fukushima accident is that closer collaboration between nuclear engineers/scientists and scientists in other fields, especially social scientists, is definitely needed to improve the "safety culture" of the nuclear community. I believe this summer school has already played a very important role in achieving this important goal. I appreciate and congratulate you on all of the efforts you have made, and I hope my talk today has contributed to a better understanding of the implications of the Fukushima nuclear accident.

Thank you very much for your attention.

References

1. Japan Atomic Energy Commission (5 Apr 2011) Statement on measures responding to the Tokyo Electric Power Fukushima Daiichi and Daini nuclear accident caused by the Great East Japan Earthquake. Available at: http://www.aec.go.jp/jicst/NC/about/kettei/seimei/110405_e.pdf. Accessed 21 July 2014
2. Japan Atomic Energy Commission (10 May 2011) Measures to be taken for the accident at the Fukushima Dai-ichi Nuclear Power Plant of Tokyo Electric Power Company (Statement) Available at http://www.aec.go.jp/jicst/NC/about/kettei/seimei/110510_e.pdf. Accessed 21 July 2014
3. Nuclear Emergency Response Headquarters, Government of Japan (Jun 2011) Report of Japanese Government to the IAEA ministerial conference on nuclear safety: The accident at TEPCO's Fukushima Nuclear Power Stations. Available at: http://www.kantei.go.jp/foreign/kan/topics/201106/iaea_houkokusho_e.html. Accessed 21 July 2014

Part IV
Reflections by Students and Mentors

Chapter 17
Students' Reflections

Beth Cary

Abstract Sixteen essays written by the students who participated in the PAGES 2011 Summer School are presented. They were written stimulated by the lectures and students' discussions during the Summer School. Their essays focus on issues observed at the interface between technology and society, such as risk/cost versus benefit, rationality and irrationality, communication, and the role of nuclear engineers.

Keywords Students' essays · PAGES 2011 summer school · GoNERI · Interface between technology and society · Roles of engineers

17.1 Format for Students' Discussion at the Summer School

When the 2011 PAGES Summer School was organized, the central consideration was providing students with sufficient time and guidance for discussions. It was deemed crucial to make students' discussions integrative and free of stereotypical perceptions from their own fields.

Morning discussions spanned 30 min, and afternoon sessions included a 90-min "reflection and discussion" slot. In these latter sessions, discussants were designated to lead the discussion; three postdoctoral researchers, Dr. Mary Sunderland, Dr. Robert A. Borrelli, and Dr. Takuji Oda, took on this role, as well as contributing chapters to this book. They encouraged interaction among participants by proposing points to be explored and steering discussion as needed. Table 17.1 is the list of lectures and lecturers. Stemming from these lectures, students were encouraged to join in discussion with their fellow students and lecturers.

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Table 17.1 List of lecture(r)s at PAGES 2011 Summer School and questions provided by lecturers

8/1 Mon.	Scientific analysis of radiation contamination at the area around the Fukushima-Daiichi Nuclear Power Station, Prof. Satoru Tanaka (Univ. of Tokyo) 1. How can we improve the transmission of information? 2. How can we accelerate decontamination outside of the reactors site and people's returning home?
	Physics of Fukushima damaged reactors and its preliminary lessons, Prof. Naoyuki Takaki (Tokai Univ., Japan) 1. How serious is the consequence of Fukushima accident? Consider from various views, such as the number of deaths; health risk for current and future generations; fears and inconvenience imposed on the public; impact on economy, etc. Is it unacceptable even if benefit (energy) derived from it is considered? 2. If society allows continuous use of nuclear, what attributes should a nuclear system in the new era have? Give a concrete image/concept of such a new nuclear system (e.g., reactor plant and its fuel cycle)
	Radiation safety regulation under emergency condition, Prof. Toshiso Kosako (Univ. of Tokyo) 1. What do we think about the emergency workers dose limit? (Cf. Japanese regulation: 100 mSv, changed to 250 mSv in this period) What happened to the remediators' working conditions when dose limits are exceeded while working on emergency tasks? 2. What do you think about evacuation for the general public under a nuclear emergency situation? (Cf. Japanese regulation: 10 km as a typical evacuation zone) What kind of arrangement is possible after using SPEEDI code? The arranged area should be circle or fan-shape? 3. What is the main reason for administration of iodine pills to children? (Japanese regulation: about 40 mg for children) 4. What kind of arrangement is effective for making surface contamination maps? Use only radiation monitoring? 5. What do you think about the radiation level for school playgrounds? What is your idea for a dose rate guideline? 6. Is it possible to remove contaminated soil by slicing off 5 cm for the decontamination of radionuclide in all areas of Fukushima prefecture? 7. What method exists for the control of foodstuffs after the accident? Please explain your idea
8/2 Tue.	Impact of Fukushima for reactor design practice, Prof. Per Peterson (UC Berkeley) 1. Discuss "backfitting" policy (10 CFR50.109 in the U.S.) which establishes the types of changes that a national regulatory authority can require for existing nuclear facilities. Consider analogies to policies for when existing buildings must be upgraded to meet new building code requirements, and requirements for when automobiles and consumer products must be recalled for repair or replacement. Discuss the societal tradeoffs in requiring backfitting (balance of the cost of backfitting against the benefit of improved safety). Discuss how backfitting policy might affect decisions to introduce improvements in new reactor designs 2. Considering the vertical axis of the Farmers chart for the frequency of internal initiating events, discuss the commercial risks associated with introducing different fuels and materials in new reactor designs, and how such risks can be reduced

Table 17.1 (continued)

	Ethics, risk and uncertainty: reflections on Fukushima and beyond, Prof. William E. Kastenberg (UC Berkeley) 1. Are risk analysis methodologies robust enough to assess and manage the risk of core-melt accidents, such as at Fukushima, i.e. could the accident have been predicted or mitigated? 2. Was emergency planning and emergency response adequate enough to protect public health and safety both before and after the Fukushima accident? 3. Was there an adequate "safety culture" in place prior to and following the accident? 4. What would it take to improve the quality of risk analysis and emergency planning so that the loss of public confidence could have been avoided?
8/3 Wed.	"Failure" of regulation and issues in public policy studies, Prof. Hideaki Shiroyama (Univ. of Tokyo) 1. Who and what mechanism should play roles for searching and integrating diverse knowledge that is necessary for managing complex system? 2. What is the way for strengthening regulatory capacity? Or how to keep civilian nuclear regulatory power without military use (which provide fund and personnel)? Or is it possible to restructure voluntary safety capability? 3. Is it possible and effective to organize and implement nuclear safety research separated from nuclear research and development in general?
	The structural failure of the science-technology-society interface: a hidden accident long before Fukushima, Prof. Miwao Matsumoto (Univ. of Tokyo) 1. How was the mutual relationship between success and failure in the little known but serious accident happened during wartime mobilization? 2. How do you think is the mutual relationship between success and failure in the Fukushima accident? 3. What are the similarity and the difference between the accident during wartime mobilization and the Fukushima accident in terms of the mutual relationship between success and failure in the science-technology-society interface? 4. What do you think about possibility of detecting the cause of structural failure in advance and incorporate structural remedies, if there are, in your design practice?
	Three mile Island and Fukushima: some reflections on the history of nuclear power, Dr. J. Samuel Walker (Former USNRC Historian) 1. What are the most important lessons of Three Mile Island? 2. To what extent would a good understanding of the lessons of Three Mile Island have been helpful in the response to Fukushima? Would they have been useful in reacting promptly and as effectively as possible to the technical failures caused by the earthquake and tsunami? Would they have been helpful in responding to media questions and public fears about the effects, real and potential, of the accident? 3. Is it ever appropriate to intentionally provide information to the public about a nuclear accident that is incomplete, overly optimistic, or misleading? If so, under what conditions? 4. How do authorities deal with the problem of providing accurate and up-to-date information when their own knowledge of the situation after a nuclear plant accident is fragmentary? 5. Are the benefits of nuclear power worth the risks?

Table 17.1 (continued)

8/4 Thu.	Engineers in organization, in industry and in society: ethical considerations, Prof. Jun Fudano (Kanazawa Institute of Tech., Japan) 1. Compare and contrast the Code of Ethics of the American Nuclear Society (http://www.new.ans.org/about/coe/) and its counterpart in Japan, namely, the Code of Ethics of the Atomic Energy Society of Japan (http://www.aesj-ethics.org/02_/02_03_/). Also make a list of values, in order of priority, which are stipulated in each code. 2. Which ethical principles have been violated in the case of the Fukushima Nuclear Accident? 3. Reflecting on the Fukushima Accident and referring to the above codes and any appropriate ones, write your own code of ethics (Cite all codes you used.) 4. Explain, to laypeople, why engineers, especially, nuclear engineers, have special responsibility
	Long-Term Energy and Environmental Strategy, Prof. Yasumasa Fujii (Univ. of Tokyo) 1. When should we use Uranium resource in the long-term perspective of human civilization? 2. To what extent can we depend on intermittent renewable energy?
	[After-dinner Talk] From Fukushima To the World: How to Learn from the Experience in Japan, Dr. Tatsujiro Suzuki (Atomic Energy Commission of Japan)

Note affiliations are as of August 2011

Students formed small groups (about 4–6 people) during the group discussion/work sessions. This grouping was undertaken by the students themselves, and was based on shared interests. Students repeatedly held discussions within the groups and formulated tentative answers to some of the questions posed by lecturers, as well as other questions they found important in the larger group discussions.

To accelerate interactions among student participants, "student session" slots were scheduled for the evenings of August 2 and 3. In these sessions, the students gave oral presentations that introduced their own, often quite intensive, activities after the Fukushima accident, described their thoughts regarding the event, and sought feedback from other students and lecturers.

The four days of lectures and discussions then culminated in student presentations on Friday, August 5. The self-organized student groups gave presentations about their questions and answers and received feedback from lecturers and other participants. The summer school closed with a session of reflections by the lecturers and organizers and a general discussion with the student participants.

All students were required after completing the school to submit individual essays that described their own answers to the questions they chose to focus on, based on all of the discussions they participated in, including the concluding sessions.

The rest of this chapter consists of essays written by the participating students. Note that some of these essays may seem ambiguous and confusing, which results from two reasons. One obvious reason is that some students were not native English speakers. The Editor has tried to reduce this kind of ambiguity. The second and more fundamental reason is because of the complexity and ambiguity inherent in the topics themselves. The Editor intentionally left this type of ambiguity. Actually, these two kinds of ambiguity are not so clearly separable. The Editor hopes to have accomplished this complex task, and to successfully convey to the reader the students' struggles to seek their answers.

17.2 Students' Essays

17.2.1 Thoughts on Emergency Workers' Dose Limit, by Toshiyuki Aratani, the University of Tokyo

I was able to think about various things as I participated in the PAGES 2011 Summer School. While reflecting on the discussions at the summer school, I selected for my response the first question by Prof. Kosako: "What do we think about the emergency workers dose limit? (Cf. Japanese regulation: 100 mSv, changed to 250 mSv during this period) What happened to the remediators' working conditions when dose limits are exceeded while working on emergency tasks?".

The optimization of workers' radiation dose should be considered. It is unfortunate that while doing emergency work, workers are exposed to large doses. The emergency worker will not be able to work longer in the place when he has exceeded the dose limit. Because the accident has been protracted, skilled workers who were initially on the scene were forced to leave because they exceeded the dose limit. Therefore, further recovery work was in the hands of less skilled workers. It is expected that the accident's impact will result in a prolonged situation in which the public would have a greater amount of exposure. In addition, later work is also problematic for workers who exceed the dose limit. So, an emergency dose limit should not be set at too low a value, and policy decisions should be made on the optimization premise.

100 mSv was changed to 250 mSv in this period, in line with the ICRP2007 recommendation written as follows: ~100 mSv—a dose for those engaged in emergency rescue; 500 mSv or 1000 mSv—doses to avoid deterministic effects may occur, as the dose of those engaged in emergency rescue; nothing—indicating that the lifesaving benefits outweigh the risks to life of others.

Evidence shows that there is not a clear current value. First of all, if we have adopted the recommendations of the ICRP value for other regulations, the amount of exposure in an emergency should also be adopted.

I have heard that nuclear power is earth-friendly, low cost. This may be right from one side, but from another side this might not be so. While the world is still actively using coal power generation, nuclear power is better to deal with global warming. With the end of the depreciation on a nuclear plant such as Fukushima Daiichi, the fixed costs become significantly less, which means more inexpensive power unmatched by any other means. However, an old power plant like a Fukushima Daiichi can be a defense against disasters. I think it is probably safe even if more disasters occur. Even then, we must consider the mind-boggling issue of the destination for radioactive waste. And we must be prepared for ruin of the land and its enormous cost. Each technology has advantages and disadvantages. Though inexpensive, fears about nuclear power have called for stopping its use from a simplistic point of view. But there is the risk that we will not find any other alternative energy. Thus, gridding and distributed energy development firms feel it necessary to increase research and development budgets.

17.2.2 The Role of Engineers in Democratic Societies, by Christian Di Sanzo, University of California, Berkeley

After the Fukushima accident, the governments of Germany and Switzerland have planned a phase-out of nuclear energy, while France and U.S. have decided to have little or no debate on the public's concerns about nuclear energy. Other countries, such as Italy, have chosen the way of a national referendum on energy policy which led to halt of the nuclear program.

What should be the role of engineers and what are its limitations in the decision making process?

In simple terms, we could say that engineers should honestly evaluate the technological performance, technological costs, and the risks associated with the use of energy technologies. This information should be conveyed to policy makers who should use their judgment to evaluate the social/economic benefits and then choose a solution for the benefit of the public. However, in this process it is of crucial importance to understand the information that is conveyed by the engineers. An energy analysis always has some uncertainties, e.g., in the numerical data available and in the expected cost of technologies. Consequently, all analysis should be conveyed to the policy makers with the related uncertainties. However, since policy makers often do not have a complete (all energy) background, it is hard for them to understand the real meaning of uncertainties, and they could often, even unconsciously, use them to fuel their own personal hopes for renewable energy or personal passions favoring oil companies. During this process the engineers could step in as advisors to policy makers as it is often done. However, the experts could often be tempted to hide some uncertainties in some results and overstate the importance of uncertainties in other results during the advising process. In fact, each engineer is often specialized in his/her own field and consequently he/she will be more passionate regarding his/her own specialization, such as nuclear engineering. The creation of expert figures with broad backgrounds could help in this regard. However, the final decision is in the hands of policy makers who are limited in their understanding of uncertainties. We could ask what would happen if the decision is in the hands of engineers as in a technocratic form of society. The risk of this approach would be that engineers would downplay the social consequences and have overconfidence in technologies, which is the opposite effect (and potentially even more dangerous) of decision makers who overstate the social consequences and put confidence in technologies with low performance (such as renewables).

A simple solution to this dilemma, whether energy policy decisions should be taken by scientific experts alone or by policy makers who often come with little scientific background, does not exist.

Engineers should limit their work to convey all possible data in an honest way, with the expectation that other engineers will do the same in their respective fields and that the public or policy makers will listen to experts' analysis. However, these expectations are often unfulfilled.

The creation of mixed figures such as policy makers with technological backgrounds could be a possible improvement. However, a division of roles in the decision making process between policy makers and engineers must be preserved to clearly identify who should have an unbiased scientific opinion and who should consider socio-political aspects during decision making.

17.2.3 Greater Public Good and Rationality, by Denia Djokic, University of California, Berkeley

In a society comprising many stakeholders, there is no consensus on the definition of the "greater public good." For the case of each stakeholder, this utilitarian construct is based on a certain combination of: information, misinformation, different ways of interpreting the same information, lack of information, and most of all, different value systems, some of which do not always fit into the neat frame of a traditional cost-benefit analysis.

In student discussions at this summer school, we tried to delve deeper into the meaning and function of the cost-benefit analysis. We asked questions such as whether seemingly "irrational decisions" were merely a different framing of the same cost-benefit analysis, where different stakeholders (e.g., nuclear engineers in contrast to the public) simply weigh the risks and the benefits differently. There is no simple answer, and furthermore I have no doubt that the solution depends on much more than just "communication" between the stakeholders. A good first step, however, is to encourage this kind of thought among the population that has traditionally been a major influence in top-down decisions: the nuclear engineering community.

All these insightful and fruitful discussions at the summer school made me wonder: why is it that we nuclear engineering students are not usually challenged to think this way? We seem to be well trained in our field, and yet there seems to be a very large gap in our education.

Undoubtedly, nuclear engineering students from UC Berkeley and the University of Tokyo are well educated in the breadth and depth of the discipline. However, in my nuclear engineering graduate school training to date, I have found that we are groomed to be inside-the-box thinkers without the necessary training to understand nuclear issues holistically. To solve technical problems, we are taught to draw clear boundaries around a limited problem, because without a clear definition, you cannot find a solution. Despite the fact that this method of solving problems often breaks down when scaling up to societal levels, the rhetoric among nuclear engineers as a community seems to remain along the lines of either "do what we say, we are the experts," or "if only we could make our data and methods clear enough, the public would understand and accept nuclear power." Any discussion as to whether our assumptions about society could be wrong seems rarely encouraged in a traditional educational setting for nuclear engineers. As a result, students easily adopt this overbearing rhetoric from our role models, and then from each other, feeding the "hubris of the engineer" (as mentioned in Prof. Kastenberg's lecture). It has only been in this summer school that I have been formally (i.e., in an academic framework) asked to think about how to break this cycle.

Many senior figures in the nuclear industry or academia seem to try to groom students to become advocates of nuclear power, rather than educating us to be holistic thinkers on top of being experts in our field. Unfortunately, too often in the greater nuclear engineering community, the issues surrounding the implementation of nuclear energy, from siting power plants to waste disposal sites, are brushed off as "a social issue." Statements like that usually have the flavor of an afterthought. Such a paradigm has bred a nuclear engineering community, in Japan and elsewhere, which was unprepared to meaningfully interact with the public and understand its views and fears.

Our traditional engineering training tells us there is one "right" way to view a problem, and that we engineers are the only ones who understand the "true" way to come up with a solution. I think we need to continue to challenge the traditions as we have done in this summer school, students, organizers, and lecturers alike. Specifically in the nuclear engineering field, academic research and thought is still intimately tied to the rigid nuclear industry (to varying degrees in different countries). After a major shakeup of our discipline's foundations at Fukushima, both literally and figuratively, the necessity of introspective, "blue-sky" discussions has never been more obvious to me. Something is flawed in our discipline, and we need to start by opening new avenues within our community's academic and educational philosophy. This summer school has been an invaluable step in the right direction.

17.2.4 Role of Nuclear Professionals After Fukushima, by Kenta Horio, the University of Tokyo

The Fukushima nuclear accident caused a significant impact on Japan. Many people were forced to evacuate from their homes, energy shortage deeply affected the economy, and people's distrust of nuclear energy has become tremendous. Also, there are a lot of difficult tasks to be done by nuclear professionals, such as stabilization of the accident, clean-up of contaminated areas, ensuring and improving safety of existing nuclear power plants, recovering melted fuels, and decommissioning damaged reactors.

Whether we will continue to use nuclear energy in the future or not, rebuilding confidence in the general public is essential for us nuclear professionals, since we already have hundreds of reactors all over the world. In order to rebuild confidence in the general public, we have to reconsider our role in society. The conventional role of nuclear professionals in society was to provide technical information about nuclear energy, such as risk analysis, cost-benefit analysis, etc. How did we conduct this role? Was it sufficient? Or are there any other roles which we should perform for society? These are questions which we have to think about and find some answers.

I'm still convinced that the conventional role of nuclear professionals, providing information, is essential, since people need reliable, technical information to make decisions on nuclear policy and energy policy. But I also consider we have to be much more sensitive in our attitude towards the general public. Most technical information, such as simulations, calculations, or forecasts, contains some sort of uncertainties and assumptions which do not appear clearly when the outcomes are shown as numbers. Though some people are not accustomed to dealing with uncertainties or assumptions, we have to explain technical information, including uncertainties and assumptions, in a sincere and honest manner. Otherwise, information won't be truly meaningful and we won't be trusted in a real sense.

In addition to the above conventional role, I'm wondering if there are other roles which we should play. Since the culture of engineering is utilitarianism, our strongest assets and tools are based on a utilitarian way of thinking. But utilitarianism is not the only philosophy of modern society, especially in current Japan, and there are other major social values. Though I'm not sure whether it is possible to justify use of nuclear energy without utilitarianism, it might be our role to facilitate discussions among people with different sets of values and to help them to bridge the gaps. At least, we have to understand various social values and gaps among them.

The above are my thoughts on our role in society after Fukushima and I haven't yet reached any concrete conclusion. But at least, I have no doubt that we have to play a certain role in society and I consider we have to keep thinking about what our role is, not only with engineering methods but also with social scientific literacy.

17.2.5 Risk Analysis and Public Confidence, by Naomi Kaida, the University of Tokyo

In this summer school, lecturers and students proposed various arguments. In this essay, however, I would like to focus on two points: one is an answer to the question posed by Professor Kastenberg, and the other is an extension of the discussion among the students. The construction of this essay is as follows. Firstly, a response to the question is proposed. The question is about improvement of risk analysis and avoiding loss of public confidence. Secondly, further thoughts about the discussion are suggested. The main point of the argument is the relationship between social decision-making and nuclear engineers. One of the students said that it was society that would make a decision about whether to stop using nuclear power, and he would obey the social determination as an engineer. However, this essay suggests that the social/technical dichotomy is meaningless. Finally, an integrated idea of the whole is demonstrated: to construct or reconstruct public confidence, arguments in more detail among nuclear engineers are needed.

Professor Kastenberg posed some interesting questions, and one of them is, "What would it take to improve the quality of risk analysis and emergency planning so that the loss of public confidence could have been avoided?" Regrettably, risk analysis on nuclear power plants and emergency planning has not been sufficient in Japan. Emergency planning has been especially weak because power utilities had stressed that there was almost no danger that severe accidents at nuclear power plants would occur in Japan. Moreover, conducting emergency planning had been regarded as acknowledging the possibility of severe accidents at nuclear power plants. This caused weakness in emergency planning in Japan. Therefore, in order to avoid the loss of public confidence, or to reconstruct public confidence, information about risk and what will be done in case of emergency must be released to the public. Although it is too late to gain public confidence after the Fukushima accident occurred, disclosure is still needed not only by Japanese, but also by people all around the world.

Disclosure is an important keyword when people think about public confidence in nuclear power, but I would like to point out one more significant way of thinking. It is about the relationship between society and technology. In the discussion among students, one student said that it was society that would make the decision whether to stop using nuclear power in Japan, and if the public decided to withdraw from using all of the nuclear power plants, he would abide by the decision. However, I felt somewhat puzzled by his words, because he seems to assume that withdrawing from using nuclear power is not a technical but a social issue. Is it a purely social problem or a purely technical problem regarding the Fukushima accident and nuclear power policy in Japan? For instance, the emergency workers' dose limit, transmission of information, the radiation level for school playgrounds, etc.: every problem revealed has aspects of both social and technical problems. Why is only the withdrawal issue regarded as a purely social problem? When people think about the Fukushima accident and the future of nuclear power in Japan, the social/technical dichotomy is useless. Therefore, not only the public but also nuclear engineers have to discuss whether to stop using nuclear power and how to realize a safe phasing out of nuclear power.

As shown above, I think disclosure and in-depth discussion among nuclear engineers are necessary to achieve public confidence on nuclear power. While doing so, engineers should not think of society and nuclear technology separately. Public suspicion about nuclear power is becoming worse. People suspect that engineers, utilities, and the government suppress the facts about radioactive substances. In order to rebuild public confidence, unprecedented discussions and suggestions have to be proposed by nuclear engineers. For example, how to stop using nuclear power safely, how to renew or do away with nuclear power plants.

17.2.6 Benefits Versus Risk, by Keisuke Kawahara, the University of Tokyo

I was wondering whether nuclear power can be acceptable to the public. So I chose the question from Dr. Samuel Walker: "Are the benefits of nuclear power worth the risks?" The answer is "yes" from engineers, but "no" from the public side.

Engineers have been making efforts to assess costs quantitatively using risk benefit analysis. This analysis, which can be applied at probability from 10^{-4} to 10^{-6}, is regarded as the most effective and persuasive method to justify nuclear power so far. However, the public seems to be unable to accept using the analysis and cutting off the risk below 10^{-6} considering that there still exists a possibility for accidents to occur. This kind of discrepancy can be found between engineers and the public, though it is not realistic to take into account something that would hardly ever occur. There are three points which generate this discrepancy.

First, cut-off risks below the probability of 10^{-6} are decided by engineers, regarding such a probability equal to a natural disaster that should be socially acceptable. However, the cut-off line may not be acceptable to the public, because the outcome of the accident is related to human activities, even if its initial cause was due to a natural disaster. In addition, from the Fukushima accident, the public realized again that the damage from the nuclear plant was so huge that they might get less and less tolerant of accepting such a way of thinking.

Second, the difference in accidents between nuclear power and other risks is that the damage from nuclear power is concentrated in space and time. This character of nuclear power accidents increases the risk which the public feels from the perspective of fairness and makes people more emotional. In that case, the public cannot calculate the risk as "probability times damage" and risk overwhelms the benefit.

Finally, it is difficult for the public to judge results of quantitative analysis. The public reacts sensitively to risks and makes irrational choices while we engineers ask them to accept quantitative judgments. But making irrational choices is human and making rational choices is inhuman, which hinders accepting decisions based on quantitative cost-benefit analysis.

I could not come up with a clear solution to such a discrepancy from attending this summer school but can only recognize what lies between them. Widening the territory of risk benefit analysis is not meaningful, and it would be hard for the public to completely accept the analysis. However, it must be meaningful to be aware of the discrepancy and, by understanding this condition, both engineers and the public can walk together through the tough path of risk communication. If the benefits of nuclear power exceed the risk from the public side, that is not from conventional risk communication based on risk benefit analysis but from communication taking into account such a discrepancy.

17.2.7 Was Mr. Yoshida Ethical?

by Lukis MacKie, University of Tennessee, Knoxville

During his lecture, Dr. Jun Fudano of the Kanazawa Institute of Technology posed a rather deep question to the students: "Was Mr. Masao Yoshida ethical?" The answer is yes.

Mr. Yoshida is the plant manager of the Fukushima Daiichi Nuclear Power Plant and was on site in the time immediately following the March 11 tsunami. When the ability to cool the reactor's nuclear core with fresh, clean water was lost, the plant workers began pumping salt water through. While salt contacting the fuel rods would accelerate their deterioration, this solution was preferable to not cooling the nuclear material at all.

This action was reported to the highest levels of the Japanese government and began to trickle down the Tokyo Electric Power Company's (TEPCO) senior management. Aware that the central government was concerned with some possible negative ramifications of this endeavor, TEPCO's executives leaned forward and directed salt water cooling activities to cease. Mr. Yoshida received this order and not only decided to ignore it, but misled his corporate leadership by telling them that salt water was no longer being pumped onto the reactor cores.

According to the Josephson Institute of Ethics: "Ethics refers to principles that define behavior as right, good and proper. Such principles do not always dictate a single 'moral' course of action, but provide a means of evaluating and deciding among competing options." (Josephson Institute of Ethics. "Making Ethical Decisions". Web. 2011).

Some are questioning Yoshida-san's ethical fortitude because he disobeyed an order from his leaders while at the same time actively deceiving them. It is reasonable to believe that if he disobeyed the order and informed those up his chain of command that he planned to continue cooling the reactors with salt water, he might have been given more external "assistance" than he desired. It is not unreasonable to believe that, if he had informed them of his actions, TEPCO's upper management might have removed him from his post and replaced him with a "yes man."

If Mr. Yoshida had followed orders and ceased using salt water cooling, it is almost impossible to conclude that the outcome would have improved. If no coolant had been used, the meltdown would have accelerated drastically. This would likely have caused considerably more damage to the surrounding area, and quickly raised radiation levels in the plant too high for personnel to continue working. While contaminated seawater was released back into the ocean, this should be seen as the lesser of two evils and the more desired result given the seemingly only other alternative.

During a crisis, particularly one that is evolving and growing more dangerous by the hour, it is often ill-advised to remove/replace essential personnel and increase bureaucracy. Micro-management from personnel more concerned with politics and less knowledgeable about the full spectrum of events on location can slow down time-critical decisions drastically.

Removing the on-site commander can be just as devastating—but sometimes it is necessary. A new commander most probably lacks the history and important details of how the situation reached its current point in time, and back-briefing him or her will cause delays. However, if the person currently in charge has proved incapable of handling the situation properly, a replacement (hopefully an early replacement) is needed.

If Yoshida had informed upper management of his plans to continue using sea water as the coolant, they might have decided a replacement capable of following orders was necessary and the best solution for the emergency at hand.

Masao Yoshida was the right person for the job. While it is probable that other TEPCO employees with thirty-plus years of experience could have managed the situation properly, none would have known the plant as well as he, nor would they have been there from day zero. By continuing to pump sea water through the reactor core, Mr. Yoshida controlled the radiation leakage as best he could. By lying to his superiors, Yoshida-san controlled the entire situation as best as he could.

Some members of the public, and certainly some members of TEPCO, are questioning Yoshida's ethics because he did not follow instruction and he lied to his leadership about it. Just as the Josephson study stated, the plant manager was left to decide "… among competing options."

Based on his experience and on-site knowledge of the situation, Yoshida-san made the call to continue using salt water to cool the reactor and deceive his leadership. Those judging his principles could see this as two ethical failures.

However, anyone questioning him must be asked one thing: If Yoshida had stopped using salt water to cool the reactor—or continued using the salt water but been truthful with his leadership, which might have resulted in his swift removal—the radiation contamination would have been much worse. If this had occurred, would you be questioning his ethics then?

Mr. Yoshida acted ethically. He had an understanding of the ground zero situation better than any member of his senior leadership, and better than any member of Japan's central government.

Given all the factors, he made the decision that he believed would result in the lowest possible radiation dose to his employees and his countrymen. He disobeyed and misled those above him; he shepherded the plant workers below him and the civilians who had no say in the matter but needed him to keep them as safe as possible.

Question Mr. Masao Yoshida's loyalty to TEPCO. Question his faith in the company's senior executives. And, if you choose, question his ethical fortitude. And when you are done second guessing his ability to determine right from wrong, thank him for the decisions he made.

17.2.8 Safety Culture and the Accident, by Hiroshi Madokoro, the University of Tokyo

My essay is a response to the question raised by Prof. William E. Kastenberg: Was there an adequate "safety culture" in place prior to and following the accident?

I think a "safety culture" existed before the Fukushima disaster, but not an adequate one. Most of us believed without doubt that we had done enough preparation for accidents. Some people argued that there is a certain probability for an accident to occur, but preparation was not sufficient. I wonder why people didn't do anything to prepare for a future accident. I think this has something to do with Japanese people's behavior.

Through discussions in this summer school, I found out there is something in common in Japanese people's minds. Japanese people tend to pursue comfort more than people in other countries do. We don't like to think about tiresome things. That is our usual behavior, but what was bad was that we also took such an attitude even toward safety management. This is one of the causes that worsened this accident. We avoided discussing "accidents," because we don't like to hear words like "accidents" or "risks" and because we assumed that a terrible event never occurs.

What is important is that we have to think about normal culture and "safety culture" separately. I heard that, even in the U.S., safety culture is different from normal culture. As I wrote above, Japanese people always want to be in a comfort state and avoid thinking about troublesome matters. However, because the Fukushima accident has occurred, we'd better change our attitude. We should no longer take this attitude toward nuclear safety. People involved in safety management need to know this culture and our behavior, and take pains to think about safety management and regulations as much as they can. I insist that "safety culture" cannot be a universal law, but the idea of "safety culture" can be generalized throughout the world. When we think about "safety culture" in Japan, we should not just import the safety culture of the U.S. or other countries. It is better that we import the concept of "safety culture" from the U.S., and then adjust it to Japanese culture, as we consider our culture. Also I conceive that each culture cannot be altered. Neither can the way people at large think and act. It is the particular people who take part in nuclear programs who should change.

People engaged in safety management or regulation need to take pains for the safety of nuclear energy, even though the probability of a terrible event is very low. It is hard for them to do so because of our culture. However, it is our responsibility to make nuclear energy safer and safer.

I believe that Japan can be an exemplar of safety to developing countries that do not yet have the idea of "safety culture." Each of the developing countries that introduce nuclear power within a few decades need to adjust the concept of "safety culture" to their country. In that process they can refer to the Japanese case.

17.2.9 Information Sharing at the Accident, by Haruyuki Ogino, the University of Tokyo

My essay responds to the lecture by Prof. Satoru Tanaka. I would like to describe how to improve the transmission of information by giving two illustrations of crisis communication implemented after the Fukushima nuclear accident. One is the press conference and the other is the distribution of information through the web.

With regard to the press conference, first of all, the spokesman should be trusted by the public and should be a person who can take responsibility. In this context, he or she should be a politician. Furthermore, the information should be given not only by the spokesman but also by experts in order to deliver precise information to the public and to meet the demand of reporters. Misunderstanding due to ambiguous explanations by a non-professional can lead to harmful rumor and panic. Taking these aspects into account, the press conference after the Fukushima nuclear accident should have been given in cooperation with both the chief cabinet secretary and experts from such agencies as the Nuclear Safety Commission of Japan, at the same time and place. We discussed the above useful and transparent communication in an emergency situation, and the American students also agreed on this point in the summer school.

The next illustration is the distribution of information through the web. After the accident, a huge amount of information was distributed day by day through the web about the reactor conditions (e.g., temperature, pressure, water level) and environmental conditions (e.g., radioactivity concentration in air, dose rate, surface contamination density). In other words, the public with access to the web was exposed to this huge amount of information without explanations of how to understand and act on it. Of course it is very important to disclose all information, but the sender should always pay attention to the recipient when information is sent out. In this context, the sender should have added the essence or intelligence that summarized the huge amount of information. We should also pay attention to the problems of how to deliver the information to the public without access to the web, such as evacuees. One solution may be a newsletter to the evacuees that summarizes the current situation on reactor and environmental conditions. This information should be delivered to those who really need it for their lives near the site.

Finally, what is needed when the information can be transmitted smoothly is "public trust" over nuclear safety. The loss of public trust was widely discussed in the summer school and we know that it will be extremely difficult to restore it in a short period of time. Thus it is our responsibility as the younger generation to keep going to achieve the long-term goal.

17.2.10 Risk Perception and Communication, by Petrus, Tokai University

After the Fukushima accident caused by the tsunami on March 11, the public had lost their trust in the safety of nuclear power plants. But, as we have seen in many disasters, people will not protect themselves if they don't believe their lives are at risk. Changing the way people perceive danger is an important way to save lives. To change the way people think, we must have specific plans for communicating the risks of dangers they could probably face.

"Sharing" is one of the ways to know how the public thinks about nuclear power plants before and after the accident. The public is not monolithic. Some people will be directly affected by the risk and some will be indirectly affected. We have to share all of the information transparently, not only information about safety but also about the risk of nuclear power plants that might result when the nuclear power plants operate. It's difficult to make people perceive this risk, because the public has realized that it is not true that "NPP is absolutely safe" or "safety first" is the foundation of nuclear plants. In this condition, engineers can take a role to improve the safety and design to make plants as safe as possible.

Understanding a public risk typically involves the range of benefits and costs associated with nuclear power plants. All aspects of the risk need to be thought through and explained, or the dialogue about the risk may become dominated by one part of the analysis. This risk-benefit analysis can be used as our tool to help us demonstrate the limit of the public risk. However, transparency of the information is better than "hiding" the information from the public. Lack of information may cause one to have exaggerated fears regarding the possible risk of a certain situation. Without factual information, we make uninformed decisions.

If the risk is considered to be the government's or the local government's responsibility, then our role as engineers may be more to coordinate and to support rather than to take responsibility. In this case, public trust in the government also plays a major role. When the government and engineers are not highly trusted, for example after the accident, we can only share accurate information, whether or not the public can take it in. Deliberative processes can provide an inclusive way of involving the public in seeking their views but these also need to be fair.

17.2.11 Radiation Risk Communication, by Kazumasa Shimada, the University of Tokyo

My essay is to respond to questions raised by Prof. Kosako related to the issue of radiation risk communication and estimated number of cancer deaths based on the collective dose.

Calculating the number of cancer deaths based on the collective effective dose caused by very small exposure to a large population has a very huge uncertainty because, statistically and biologically, it is incorrect usage of the amount of protection (ICRP, Pub.103, paragraph 161).

On the other hand, the Chernobyl Forum (performed in several international organizations; IAEA, WHO) reported that targeting about 600,000 people [decontamination personnel (average. dose is 100 mSv), evacuees (10 mSv), most contaminated local residents (50 mSv)], the number of deaths is expected to be 4,000 people and targeting about 6,800,000 people [public and workers (average dose is 7 mSv)], the number of deaths is expected to be 9,000 people (Chernobyl Forum, Chernobyl's Legacy: Health, Environmental and Socio-economic Impacts and Recommendations to the Governments of Belarus, the Russian Federation and Ukraine. IAEA, 2005). In addition, in the report of Cardis in 2006, it is said that the number of deaths is expected to be 16,000 people (CRIEPI, health effects of Chernobyl Research Center for Radiation Safety Accident http://criepi.denken.or.jp/jp/ldrc/study/topics/20060904.html).

The Fukushima nuclear accident was evaluated to be INES level 7. Therefore, calculation of the number of cancer deaths based on collective dose is unavoidable. If someone calculates the number of deaths based on radiation by this accident as a few hundred people, how is this to be explained to the public, especially the people of Fukushima? At this time, we have no answer to the question: "How do I know if my child will be one of the few hundred victims?".

Nowadays, we cannot identify whether this cancer is due to radiation. In the future, some cancer patients will likely go to court about the Fukushima nuclear accident. If the court decides to accept a causal connection between low dose and cancer, I am concerned that all cancer will be viewed as radiation. This situation is like the atomic bomb case.

In my opinion, it is against humanism to calculate the number of deaths. We should rethink the meaning of low dose radiation risk.

I propose to develop two things. One is a total health risk evaluation. The other is a minus-dose evaluation. The total health risk evaluation is to be considered with radiation, ultra-violet ray, chemical material, mental stress, etc., to evaluate human health risk. Nowadays, only the radiation risk is evaluated quantitatively and gives some cause for anxiety. Therefore, it is important to know that radiation is not a special cancer risk compared with other risks even if this evaluation has a huge uncertainty. Moreover, minus-dose evaluation is more important. Today, Linear Non-Threshold model (LNT model) can evaluate the cumulative radiation risk forever. Therefore, people have no way to escape radiation to reduce risk. On the other hand, we can find protection functions in our body, for example DNA repair, apoptosis, radioadaptive response, and immunity. This means radiation damage in our body is continually being repaired by these functions. To make quantity evaluations of these functions we can calculate that the dose was canceled by these minus-doses. For example, to increase our immunity function to reduce cancer risks quantitatively, we use methods of ordinary health promotion (for example, spas) so that our radiation risk will be canceled and our health will actually become better.

17.2.12 Benefits Versus Risks, by Kampanart Silva, the University of Tokyo

Are the benefits of nuclear power worth the risks? The question raised by Dr. J. Samuel Walker stimulated me to write this essay. There are some questions which needed to be and *could be* answered in order to specify the scope of the decision making and finally move toward the progress of answering the question.

Where is this question asked?

If it is asked in developed countries, such as the U.S. or Japan, with the money and resources that those countries have, and the high level of education of the population, there are a number of choices for electric power supply and the population has the ability to correctly select them. Therefore, we can easily move to the next question. However, if it is asked in developing countries, where rapid energy growth is a requisite condition, and the population does not even know what would be the consequences of their choices, there comes another question very difficult to answer: is it ethically preferable to ensure their rights to select the energy sources?

To whom is this question is asked?

If it is asked of an individual, and if that individual is an expert, he (or she) might try to quantitatively analyze the risk and the benefit based on the data he has, include some of his personal perceptions, and finally give you the answer. (Perhaps this is also what I am going to do.) If not an expert, he might emotionally give you the answer based on the information he has. But when it comes to a decision of a country or a society, apart from achieving the utility (by quantifying the risks and the benefits and make sure that the benefits are worth the risks), the fairness among the society members must also be taken into account by some means or other.

When is the answer needed?

In the case of decision on the energy policy of a country, when it has money and resources, which means it has the chance to choose its preferred energy resources, the answer to the question "are the benefits of nuclear power worth the risks?" might not be needed until the next decade or even the next century because its energy production potential is several times the demand. On the other hand, for a country with small potential, it might need the answer within several years or even several months. In that case, the only thing it can do is to try to improve and make use of the tool (risk-benefit analysis) it has, and set up some system to obtain as much as possible the perceptions of its public.

Under this circumstance, regarding the results of risk-benefit analysis being done by developed countries, even after including the social impacts (public anxiety or opposition movements) or ethical issues (which came up in the answer to the first question) to be observed, I still personally think that the benefits of nuclear power in Thailand are worth the risks, for the time being. However, this is based on the present information I have. If in the future, the possibility of severe accidents is to become tens or hundreds of times what we see now, and the social and economic impacts are proved to be much larger than what they are now, this evaluation may change. In my personal view, the most important thing is to be able to judge the risks and benefits under the present circumstance with limited information, and take responsibility for the judgment, no matter whether you are an individual, an expert, or a decision maker.

17.2.13 Benefits of Nuclear Power, by Christina Novila Soewono, Tokai University

The nuclear accident that occurred at Fukushima, Japan, has brought people's attention to the risks of nuclear power. While there had not been direct human cost in deaths because of the nuclear accident itself, people once again are faced with the question whether nuclear power benefit is worth the risks. It is natural to fear what you cannot see and many people do not find enough reassurance in being told that they are not at risk from the radiation that had been released.

With the rate of increasing demand of our current energy needs and the ineffectiveness of current methods, I will say that nuclear power is worth the risk. By agreeing that nuclear power is worth the risk, I am not saying that nuclear is completely safe nor that there are no alternatives, but I agree that nuclear is the better alternative and therefore worth it.

So far there have been no confirmed casualties of deaths directly attributed to the Fukushima nuclear accident. This showed us that despite the old age of Fukushima Daiichi nuclear reactor, nuclear power plant safety has been greatly improved since the Chernobyl accident. There were 64 confirmed deaths from radiation and a prediction of 60,000 cancer deaths as a result of fallout from Chernobyl. Though it is hard to predict the number of cancer deaths caused by radiation exposure, since precautionary action had been taken to protect the public, I believe that the predicted number of cancer deaths is going to be a lot fewer than Chernobyl.

The Fukushima nuclear accident has induced fear and inconvenience to the public, especially those who lived near the Fukushima site. The feelings of insecurity, unsafeness, inconvenience, and other effects are difficult to measure. The interesting part is that so far I think that coal power is far more dangerous to human life and long-term health issues than nuclear power. A coal powered plant releases more radioactivity than a well maintained nuclear power plant. In addition to that, a coal powered plant releases more pollutants, especially gases which contribute to global warming. Since coal is likely to be more hazardous than nuclear we should fear coal more than nuclear. And yet, people seem to be more comfortable with coal power plants than nuclear power plants.

Due to its effectiveness in producing energy on a large scale and ensuring energy security, I think that nuclear power plants are economically worth the risk. Japan did not have enough natural resources, which was the reason why Japan developed nuclear as an energy source during the postwar period in the first place. The energy availability in Japan supported industries which then led Japan to be the first Asian developed country that succeeded in catching up with Western countries.

Nowadays people have started to develop renewable energy that not only can be used to produce electricity but also is environmentally friendly. Unfortunately, if renewable energy sources such as wind and solar are used as energy with current technology, they are not only unreliable, but also not useful in some geographic areas due to weather patterns. Since not many people are familiar with the use of renewable energy, the cost of generating electricity is relatively high. I do believe that in the future we can overcome this problem faced by renewable energy and finally have a clean energy source. Until then, however, it is good to use nuclear power which I think is more reliable and cost effective.

17.2.14 Who Am I? What Is My Own Role on Earth? by Shin-etsu Sugawara, the University of Tokyo

This summer school has posed these challenges to me. During the last presentation of our group, a question from Dr. Juraku was of grave significance to me: what is *your* role?—not the role of "engineer" as a general noun.

This reflection shows my own reply to this.

Throughout the full program of this summer school, the "limitation" of cost-benefit analysis and the "irrationality" of social decision-making were major topics of discussion. In particular, our group focused on the issue of how nuclear engineers provide their expertise in society under conditions where the decision-making methods about energy policies look so "irrational" from their point of view in Japan and in some other countries.

Re-examining this discussion, however, I now think that our framing was too narrow and too ironical. That is because engineers' activities, which are said to be based on "rational" thoughts, failed to control nuclear technology, and as a result made society "irrational." In other words, it is engineers who want to "improve" society that drive society toward the opposite direction.

This is applied not only to the Fukushima accident but also to all the failures, misconducts, and "unexpected" accidents which are related to science and technology. And, this is not valid simply for each engineer but for all the persons and organizations who stand on the side of promoting science and technology.

These FACTS are, I think, the biggest "failures" of engineers and the points which should be considered to be the responsibility of everyone concerned with nuclear technology—of course including me—in the historical context.

Reflecting on these considerations, I will give an opinion of my own role.

I am not a nuclear engineer. I am a researcher tackling nuclear issues based on social-scientific methodologies. I now recognize my special role as a "boundary worker" as follows: to show available prescriptions—sometimes ideal ones—for dealing with risks associated with the social utilization of nuclear technology, including socially amplified risks; that is, to envisage and to publish the social systems where expertise is referenced appropriately in social decision-making processes; and to maintain the relationship between expertise and social decision in the face of extreme fluctuation.

Such roles have a substantial overlap with my own studies over 4 years. I can now be more confident on this point.

This is my principle in the profession of "boundary worker" between nuclear technology and society. Wherever I go after my graduation, I shall hold on to this principle.

17.2.15 The Role of Nuclear Engineers in Society, by Tatsuhiko Sugiyama, the University of Tokyo

Through the summer school, I became interested in the role of engineers in disclosing information, and I was particularly intrigued by Prof. Satoru Tanaka's question: How can we improve the transmission of information? I have reinforced my idea that this kind of topic involves some ethical issues and we cannot clearly decide what to do, especially in emergency situations. On the point of "transmission," however, I have found some problems and some ideas to improve the way information is transmitted.

In the Fukushima case, the major problem in transmitting information was that engineers or professionals were not trying to let citizens fully understand the meaning of the information they disclosed. They were mainly disclosing numerical data unfamiliar to citizens and the mass media were doing "interpretation" of these data. Moreover, press conferences were conducted without engineers or professionals. This led to multiple interpretations among citizens about "how serious is the accident?," "should we evacuate as soon as possible?," and so on.

In my opinion, engineers or professionals have to try to do what mass media are now doing and try to explain with or on behalf of politicians, especially in crisis communications. I agree they disclosed enough data in the Fukushima case. But this is not enough. In order to prevent panic or incorrect behavior, they themselves must try to let citizens understand without going through the media. They have to reconsider the role of engineers or professionals in emergency situations.

If our society allows the continued use of nuclear power, what are the attributes needed for a nuclear system in the new era? I will try to think about this question based on a concrete image/concept of the new nuclear system (reactor plant and its fuel cycle).

One factor that caused station blackout (SBO) was that the isolation condenser (IC) and reactor core isolation cooling (RCIC) batteries were not sufficient to survive for a long period. One advantage of IC and RCIC is that they can utilize vapor from the reactor to operate. But if they also need batteries to operate, I think this system is nonsense. Emergency core cooling systems should be isolated from such anxieties.

In my opinion, however robust a plant may be designed, some residual risks remain. Through the Fukushima case, we have gained some ideas on future reactor designs. But even if we adopt all these ideas, reactors will not be perfectly robust, and most of the people who are against the usage of NPPs often quote this problem. We have to clearly admit the existence of residual risk in the future design.

17.2.16 The Role of Nuclear Engineers in Society, by Eva Uribe, University of California, Berkeley

What is the role of nuclear engineers in society? As a scientist, and not an engineer, the summer school made me think about the relationship between science and engineering, and how both interact with society. During the conference, one of my colleagues, an engineer, made the observation that science is about discovery, while engineering is about *optimization.* Engineers make the knowledge of science useful to others through optimization of that knowledge to specific problems. The National Society of Professional Engineers' Code of Ethics makes engineers responsible first to society: "Engineering has a direct and vital impact on the quality of life for all people. Accordingly, the *services provided* by engineers require honesty, impartiality, fairness, and equity, and must be dedicated to the protection of the public health, safety, and welfare" (Preamble, emphasis added). The American Chemical Society also published a Chemical Professionals Code of Conduct, which establishes a primary responsibility to the public: "Chemical professionals have a responsibility to serve the public interest and safety and to further advance the knowledge of science."

While the engineering ethical code speaks of "services" to the public, the ACS code encourages scientists to "advance the knowledge of science." During the summer school, many asked the question how we could justify nuclear energy outside of the cost/benefit paradigm used by engineers to decide which problems to solve and how to solve them. My initial reaction was to justify nuclear energy based on the progress of science and the general advancement of knowledge. Very generally speaking, my opinion is that we should learn more about splitting the atom not only so that we may better control it, but also because this process is fundamental to how the universe works, and we as inquisitive beings should want to know how everything works. This kind of pursuit of knowledge allows scientists to justify research that others may consider unethical or immoral, such as embryonic stem cell research or even human cloning. During the conference, I began to understand that the engineering profession cannot be so easily isolated from public interests, even in the name of advancing knowledge, because its central creed is to *serve* the public.

The debate lies in the form that this service shall take, a dilemma not exclusive to engineering, but rather common to all professions. What happens when the experts and the public disagree about what is best for society? Who should decide?

The educated minority, or the majority? James Madison, one of the founders of the United States Constitution, wrote about this dilemma in Federalist Paper #10. Madison and many of his contemporaries believed that a strict democracy would be very dangerous, because it would allow the majority to suppress the rights of the minority simply by force of numbers. To combat such a tendency in government, they sought to found not a democracy, but a republic, in which elected *representatives* of the people govern the nation, rather than the people directly. His words, then spoken about political representatives, are also relevant to nuclear engineering professionals today when it comes to nuclear energy policy. He argues that representative government "refines and enlarges the public views by passing them through the medium of a chosen body of citizens, whose wisdom may best discern the true interest of their country and whose patriotism and love of justice will be least likely to sacrifice it to temporary or partial considerations … it may well happen that the public voice, pronounced by the representatives of the people, will be more consonant to the public good than if pronounced by the people themselves" (Federalist Paper #10). A representative must often look beyond local interests and seek to serve broader and deeper interests. But a representative is also directly responsible to the public. Engineers may be considered representatives of the public to the progress of technology. Scientists unveil what is known and what may be known, and engineers decide how this knowledge can be incorporated into people's daily lives. As representatives of the people, engineers are also directly responsible to them. But unlike politicians, who risk losing votes if they displease the public, engineers have much more at stake: the credibility of the profession, the usefulness of scientific progression, and the inquisitiveness of humankind. This is why their dedication to honesty, openness, and education is so important.

Chapter 18
Educating the Post-Fukushima Nuclear Engineer

Mary E. Sunderland

Abstract While the Fukushima Daiichi Nuclear Accident shook the community of nuclear engineers, it had a special significance for nuclear engineering students. What were they supposed do? How should they and could they answer questions about nuclear safety? What about their future opportunities? The incident caused many students to question their deepest convictions about all things nuclear and opened up new questions about their social responsibilities. This chapter looks to the history of nuclear engineering education to provide context for the discussions that took place during the summer school. Historically, students have seldom had opportunities to engage the socio-ethical dimensions of their work. The summer school offers evidence that today's students are actively seeking new analytical skills and different ways to conceptualize the socio-ethical complexity of nuclear engineering problems. Moreover, students are poised to play a key role in shaping much needed curricular reforms.

Keywords Education · Ethics · Collaboration · History · Interdisciplinary · Students · Societal role

18.1 Introduction

What is the role of the nuclear engineer and how is it learned? Motivated by the Fukushima Daiichi Nuclear Accident, the 2011 Advanced Summer School of Nuclear Engineering and Management with Social-Scientific Literacy provided an occasion to reexamine the role of nuclear engineers. By reflecting on the content and context of the Summer School, this chapter examines how the education

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of engineers has shaped their societal and professional roles and also their understanding of these roles. The Summer School raises questions about what kinds of educational changes are needed to ensure that nuclear engineers are better equipped to deal with the inherent challenges of the Post-Fukushima world. The events and outcomes of the Summer School provide evidence in favor of curriculum reform. Students don't just need the different approaches offered by the social sciences—they want to learn them. Historically, there has been very little space in the curriculum for students to think about nuclear engineering more broadly, little tolerance of positions that question the safety and necessity of nuclear power, and limited resources to facilitate an informed discussion about these topics. Despite these challenges, students are actively seeking alternative ways to address the multidimensional Post-Fukushima problems that are not amenable to engineering's traditional utilitarian reasoning and optimization studies.

The engineering community has a long-standing interest in educational improvement. In 1893 engineering was one of the first professions to institutionalize its commitment to education with the establishment of the Society for the Promotion of Engineering Education (SPEE). Founded as part of an effort to standardize an engineering curriculum that stressed fundamental concepts in science and math rather than practical know-how, the SPEE identified engineering colleges as the right place for engineers to receive their training [1]. Yet despite engineering's professional commitment to educational improvement, recent research demonstrates that engineering education is extremely resistant to change [2, 3]. Studies show that new pedagogical approaches are rarely implemented on a larger scale because of institutional barriers including financial constraints, class size, classroom space, technology, instructional staff time, and skepticism of whether student learning will really improve [4]. Compounding these hurdles are the hierarchy structures, reward systems, ideologies, and the general curricular organization of engineering education [3]. Historical analyses, for example, suggest that global-scale catastrophic events are needed to initiate educational reforms [5]. Although it is unfortunate that real change can only be justified and implemented in the aftermath of significant geopolitical events, this historical perspective helps us to make sense of how the nuclear community is responding to the Fukushima Daiichi accident; the time is finally right to transform the education of nuclear engineers.

Fortunately, there are many resources that are available to support this transformation. Today, engineering education is an emerging discipline in its own right, complete with PhD programs, journals, and conferences [6].[1] There is a growing community of scholars who are committed to advancing education through research, whose efforts are supported by a range of funding institutions, including the National Science Foundation, which invests millions of dollars into engineering education endeavors [7]. There is also a growing group of scholars who are committed to developing

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[1] For example, Virgina Tech, Purdue University, and Clemson all offer advanced degrees in engineering education. The Journal of Engineering Education, PRISM, Advances in Engineering Education, Science and Engineering Ethics, The Bridge, and the European Journal of Engineering Education are all dedicated to issues regarding engineering education.

strategies to overcome the hurdles that challenge the effective implementation of innovative educational initiatives (e.g. [6, 8]). So, while the Summer School is subject to many of the constraints that obstruct educational change, it can also draw on the resources of scholars who work at the intersection of engineering, education, and the social sciences. Building on this scholarship, this chapter emphasizes the importance of involving students as partners in envisioning and implementing curricular reforms [9, 10]. As the nuclear community imagines new societal roles for the next generation of nuclear engineers, it is essential to consider students as key community members who hold unique perspectives that should contribute to shaping future educational programs and opportunities.

This chapter offers a brief history of nuclear engineering education in the U.S. to contextualize the discussions that took place at the Summer School and to provide a better understanding of current curricular gaps.[2] One of the central challenges is to understand how the identification and articulation of these gaps differs between students and faculty members. A recent study of the engineering undergraduate community, for example, revealed the existence of important differences, especially regarding how students experience engineering ethics. Whereas faculty members think that they are presenting ethics in a nuanced and interesting manner, students describe learning ethics as a set of rules to be followed [11]. Recognizing that students' interpretation and experience of the curriculum matters, is an important step toward implementing effective educational changes. By drawing attention to student experiences, this chapter proposes that the nuclear curriculum would benefit from a pedagogical shift away from the formal lectures and quantitative reasoning style that usually dominate classroom instruction in order to make room for more discussion-based learning as a way to promote critical reflection through dialogue. In addition to learning through discussion, today's students are ready to take the socio-ethical dimensions of their work seriously. Doing this requires more than just exposure to the social sciences [12]. Students require opportunities and time to effectively engage with and practice new approaches and analytical techniques. Exposure to and practice with alternative research methods would help to lay the foundation for productive collaborative research opportunities with non-engineering scholars.

18.2 A Brief History of Nuclear Engineering Education

Engineering has a long history of educational change. Throughout the twentieth century educational reformers in the U.S. have sought ways to reach the right curricular balance between practical design and basic science and math, while also

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[2] Ideally, the chapter would present a comparative account of nuclear engineering education in both the U.S. and Japan. However, I had access to substantially more literature regarding the American context, particularly because my search was limited to material that was published in English. For this reason, I was unable to locate information about nuclear engineering education in Japan, with the exception of a paper by [11], which does not include historical information.

making room for the social sciences and humanities [13–15]. An overemphasis on engineering's scientific foundations became especially prominent in the U.S. after World War II alongside the emergence of nuclear engineering [14, p. 285]. New funding opportunities for academic engineering research were created by an influx of post-World War II funding. Massive, unprecedented amounts of federal money from the military and the Atomic Energy Commission (AEC) triggered educational and institutional reforms that emphasized science over practice while pushing the humanities and social sciences aside [14, p. 289]. Funding from the military and the AEC favored research on jet propulsion, rockets, computers, and nuclear power, and provided institutions with enough money to support entire graduate programs, including new facilities and equipment [14, p. 289]. The educational approach exemplified in these research-heavy fields, such as nuclear engineering, stood in sharp contrast to the apprenticeship programs that had provided the training for the majority of engineers throughout most of the nineteenth century [1].

In the 1950s, the AEC began sponsoring summer seminars on the new "glamour field" of nuclear engineering that was beginning to materialize in conjunction with the development of nuclear energy [1, 16]. Efforts to formalize nuclear engineering education in the U.S. followed. Physicists, chemists, and electrical engineers populated the first programs, reflecting the important role that these disciplines had played in the Manhattan Project. Early curricula emphasized nuclear physics, the analysis of neutron transport, and the materials needed for nuclear weapons. In step with the commercialization of nuclear power, the first undergraduate programs in nuclear engineering emerged in the 1960s and incorporated elements of reactor science [16, pp. 1, 16]. Strong national support of civilian nuclear power during the 1960s spurred the growth of the nuclear industry. New opportunities arose for nuclear engineering professionals as plants anticipated increased electricity demand. By 1975, the U.S. had eighty nuclear engineering departments. Growth was fueled by developments in the nuclear power industry and by the substantial quantity and quality of fellowships and funding that was available through the AEC. In addition to supporting students, the AEC paid for nuclear reactors that were dedicated for educational and research purposes—a contribution that reflected their commitment to promoting the development of civilian nuclear power.

The expansion of nuclear engineering did not slow until the late 1970s when concerns about the environment and radiation shaped a changing nuclear market that was characterized by plant cancellations and closures. The accidents at 3 Mile Island (1979) and Chernobyl (1986) fueled pubic concern about nuclear power [16, p. 16]. By the 1980s there was growing distress in the nuclear engineering community that downward trends in student enrollment, in both undergraduate and graduate programs, warranted a comprehensive assessment of the state of the field. Many institutions wanted to learn more about these negative trends with the aim of identifying possible solutions, including the American Nuclear Society (ANS), the Institute of Nuclear Power Operations (INPO), the Nuclear Engineering Department Heads Organization (NEDHO), and the U.S. Department of Energy

(DOE). In response, the Energy Engineering Board of the National Research Council conducted a study to analyze: the declining numbers of U.S. university nuclear engineering departments and programs; the problem of aging faculty; the mismatch between curriculum and the needs of industry and government; the availability of scholarships and research money; and the increasing ratio of foreign to U.S. graduate students [16, p. xi].

The report's investigation centered on addressing whether current educational programs were "appropriate for future industry and government needs" and asked "What skills and education may be required for the next generation of nuclear engineers?" The committee conducted interviews and surveys across academia, industry, and government to assess the "history, status, and future" of nuclear engineering education and concluded that the curriculum was "basically satisfactory" [16, pp. 2, 5]. Rather than exploring possible curricular reforms, the report focused on strategies for dealing with the field's research shift away from new reactor technologies and with its aging faculty members. The only suggested curriculum adjustments were modifications to improve students' communication skills, and to increase their general knowledge of reactors and of the biological effects of radiation [16, p. 5].

Satisfaction with the nuclear engineering curriculum in 1990 was short lived. By 1998 NEDHO issued the report *Nuclear Engineering in Transition*: *A Vision for the 21st Century* that recommended a number of more substantial curricular changes to aid the profession through "a period of transition" in which the focus was shifting away from nuclear power to embrace a broader range of nuclear science applications [17, p. 1]. Both reports assuredly concluded that maintaining nuclear engineering as a distinct discipline was vital to the future success of nuclear energy programs. The program's curriculum was described as uniquely preparing students to address the complexities of nuclear technologies [16, p. 3]. Nuclear power and nuclear engineering were portrayed as interdependent in both the past and the future. Considering the ongoing international impact that Fukushima is having on the future of nuclear power, it is prudent for nuclear engineers to reassess their roles and to build the skills that they will need to address the challenges ahead.

Driven by the concern that engineers were not prepared to meet the demands of the future, the National Academy of Engineering published a series of reports in 2004 and 2005 titled *The Engineer of 2020*: *Visions of Engineering in the New Century* that emphasized the need to refocus and reshape the engineering learning experience to meet societal goals. The report includes suggestions about how to restructure programs, reallocate resources, and refocus faculty and professional time and energy while emphasizing the need to keep the social sciences and humanities in the curriculum [18, p. xi]. The report foresaw the ideal engineer of 2020 as someone with an understanding and appreciation of the impact of engineering on "sociocultural systems" and also the value of non-engineering jobs. As a creative leader, the future engineer would remain knowledgeable in math and science, but their design visions would be grounded in the social sciences, humanities, and economics [19, pp. 48–49]. The report, however, was researched and published well before the events at Fukushima. Would this hypothetical engineer of 2020 have been equipped to deal with the challenges of post-Fukushima nuclear engineering? Looking more closely at some of the discussions that took place at the Summer School points to unanswered questions that signify the need for more radical reforms.

18.3 Post-Fukushima Questions and Answers

Engineers are celebrated for their role as superior problem-solvers who depend on math and science to make rational, accurate decisions, and ultimately to create new things [20]. Increasingly, scholars are raising questions that challenge the engineers' role, including: For whom do engineers work? How do engineers select the problems to solve? Which problems are not worth engineers' investment, and which are beyond the expertise of the engineer? Who benefits? [20, p. 26]. Since their role is traditionally in the problem-solving domain, engineers tend to stick to solvable problems, wherein a problem's solvability is directly related to the amount of *quantitative* information that can be gathered about it. Trained to approach problems with the tools of optimization studies, cost-benefit analysis, and risk analysis—engineers depend on manipulating numbers to obtain objective results. One of the core issues with the problems surrounding Fukushima is that the answers rely on more than numbers. This was a concern that was raised repeatedly throughout the Summer School. Much time was devoted to searching for ways that nuclear power could be justified without weighing its costs and benefits in numerical terms. In this sense, the problems are distinctly non-engineering. And yet, they involve a technology—nuclear power plants—that are beyond comprehension to the majority of those outside of the nuclear engineering community. What then, is a reasonable and desirable approach to take when weighing the analyses and recommendations of nuclear engineering experts alongside the views of the rest of the population? This question, in particular, seized the Summer School participants' attention.

Discussions about the challenges of communicating the safety of nuclear power persisted throughout the week. These discussions largely focused on public communication, safety, and trust, which were the most salient issues to the participants, perhaps because communication seems within the nuclear engineers' realm of responsibility. In contrast, it was more difficult to have "productive" discussions about issues that were more squarely located in the social sciences, including conflicts of interest, troubling institutional arrangements, and different ideas about the concepts of rationality, expertise, and risk. One of the professional norms that became evident during the Summer School was that engineers learn that it is irresponsible, and perhaps even impossible to make the "right" decision without adequate knowledge of the scientific facts. This prioritization of factual knowledge was evident in the organization of the summer school. For example, the first day of the program involved a series of content-heavy lectures that offered rigorous scientific analyses of radiation, reactors, and regulations. Starting off the program with these lectures implicitly communicated its priority to the students; it was important to know this information first. Throughout the day, the discussions considered how this kind of scientific information was and was not communicated to the public. Many engineers felt that it was their responsibility to do some of this public communicating and also to act as information gatekeepers. One student, for example, remarked that it was irresponsible to risk panic by releasing data to the public before professionals were able to act on it.[3] Students also expressed that their role was to model and measure the available data in order to bound problems, but also expressed concerns about how and what to measure.

The second day included lectures on the future of reactor design and on the ethics and "safety culture" of nuclear power plants, which fueled a discussion about engineering's reliance on utilitarian reasoning. The first presentations from social scientists began midweek, in which new ways of thinking about the Fukushima Daiichi Nuclear Accident were introduced. Students were asked to reconsider the challenges of building interdisciplinary awareness across engineering and the social sciences, but also across the more specialized fields within engineering and science (e.g., between nuclear engineers and climate scientists). The social scientists provided students with examples of how to study the institutional and organizational factors that are shaping the ongoing events at Fukushima, including the arrangements between regulatory bodies, industry, government, and academia. Instead of framing the accident in terms that are familiar to engineers, such as safety culture, students were encouraged to consider how social conditions and institutions had shaped the definition of safety. A historical perspective, for example, shows us that nuclear power is judged with great severity, in part because of the public fear of radiation. For this reason, analyses that compare the risks of nuclear power with those of motor vehicles or airplane crashes are not always meaningful. Looking back on the events surrounding 3 Mile Island reminds engineers that severe accidents will happen and that it is important to communicate about them openly and critically.

After a day of social science immersion, students had an opportunity to begin in depth discussions with one another. This provided an important space for students to identify issues beyond their professors' gaze. For engineering students, this is a necessary exercise to facilitate a pedagogical shift away from lecture-style learning, and to allow each student to develop a perspective and voice that is different than their professors'. A recent study of the undergraduate experience of engineers as compared to students in computer science, science, technology, math, arts and humanities, social sciences, business, and other majors determined that engineering students spend considerably more time preparing for class and have the highest number of credit hours, many of which are spent in lecture [21]. Engineering students quickly learn how to intake and apply the information from lectures wherein the focus is on finding the most efficient way to complete problem sets rather than critically engaging each professor's views.

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[3] To protect the privacy of the Summer School's participants, comments are not linked with individuals.

In contrast, students at the Summer School were expected to participate in a discussion that involved deep reflection about apparently unanswerable questions. Students were instructed that although discussion and reflection would likely feel unfamiliar to them, and perhaps even unproductive, it was something that they owed to the society that had funded their work. After hearing from the social scientists, students were asked to break off into smaller groups in order to further discuss the issues that most concerned them. The process of group formation was not obvious, and students spent much time brainstorming the issues that interested them before they cohered into groups. But even after this coherence, the students decided to remain in close proximity so that they could move from group to group. Many of the students shared common concerns and valued the opportunity to learn from their peers.

On the fourth day of the Summer School students had an opportunity to learn about how engineering ethics was largely imported to Japan from the U.S. in the late 1990s. Comparing the United States and Japanese codes of ethics reveals that Japan does not emphasize engineering as a profession. In Japan, most engineers' identities are linked to their place of employment rather than with the general engineering profession. Students were encouraged to think about how these differences might have shaped the Japanese response to Fukushima. In response, students began to discuss who belongs to the engineering profession. Who counts as a member of the engineering community? U.S. students also admitted that they had never read the U.S. engineering code of ethics. The discussion turned to explore the role of the code—is it for students, or advanced professionals? It was pointed out that mid-career engineers had little time or incentive to discuss ethics and furthermore, that the relationship between ethics and regulation were unclear. Students were asked to think about the role of nuclear power in long-term energy planning. Again, the discussion turned to questions about how to deal with "irrational" decision-making. Engineers felt strongly that it was their responsibility to keep public discussions about energy on "rational grounds" by providing important data about the costs and benefits of investing in different energy technologies. Increasingly it became clear just how uncertain the future of nuclear energy had become in the wake of Fukushima.

Throughout the week, students had been breaking off into smaller groups to discuss the problems and questions they found most concerning and interesting. On the final day, students were asked to present the findings of these discussions. Students felt that they were in a transitional moment. They knew that they wanted and needed something different, such as skills that could enable them to communicate with different audiences and contribute to different discussions. The nuclear engineering students were clearly open to new ways of thinking and recognized the importance of building these skills. Students were especially interested in developing skills that would enable them to move beyond focusing on cost-benefit analyses.

Although some students expressed frustration with the program's lack of clear answers, it was evident that their discussions had generated important new perspectives that moved the conversation in different directions. For example, students recognized that it would be unproductive to try to evaluate the Fukushima events without first learning more about the history of nuclear power in Japan. In addition, students suggested that important insights might be drawn from conducting a comparative analysis of the different assumptions regarding the safety of nuclear power that were held in the U.S., Europe, and in Japan.

Different international perceptions of nuclear safety inform the nuclear engineer's role in each country. Students were attracted to the Summer School for a variety of reasons. Some were generally committed to the importance of nuclear energy in the future and were interested to learn more about how and why the events at Fukushima had jeopardized nuclear energy's reputation. Others were not clearly advocates of nuclear energy, but wanted to make sure that it was used correctly in the future, especially in developing countries. Still others were drawn to nuclear engineering by the lack of good planning that they had witnessed in their home countries and hoped that attending the Summer School would provide them with important information to help their home countries incorporate nuclear energy responsibly. The diversity of interests and concerns that attracted students to the Summer School point to the wide-ranging role of today's nuclear engineer. Whereas nuclear engineers in the past were expected to be advocates of the nuclear power industry, students today are drawn to the field for a diversity of reasons and will undoubtedly play different roles. One clear role does not exist. Each nuclear engineer is responsible for shaping his or her own role.

As they tried to gain a better understanding of the engineer's problem solving approaches, students started to ask how others solve problems. They wondered if everyone was doing their own version of cost-benefit analysis, or if there were entirely different approaches available. The shortfalls of cost-benefit analyses became clear as the students wondered if there was any value in comparing things that were fundamentally incommensurable. Students pointed out that it was paternalistic to label an individual as irrational and noted the shared societal value of respecting a diversity of perspectives. The trouble with many discussions about benefiting the public is the inherent assumption that the public is homogeneous. Students want to find ways of identifying and communicating their assumptions. They are looking to social scientists for help with these problems.

18.4 Building Sustainable Interdisciplinary Bridges

Engineering education has received much scholarly attention from historians of technology, in part, because looking at education offers a window to how the societal roles of engineers have been communicated both explicitly and implicitly [22, p. 738, 23]. Engineers' understanding of this role is shaped by their assumptions about how science and technology work. This is because ideas about the relationship between science, technology, and society underlie the engineers' decision-making process. Since the turn of the twentieth century, these ideas have been informed by engineers' educational experience of reading texts about the inevitability of technological progress. [15, p. 754, 22, pp. 740–741]. Although the notion of inevitable technological progress is widely shared within the engineering community, it is deeply problematic to many social scientists. The fact that engineers' predominant understanding of technology is counter to that of social scientists raises questions about how engineers are exposed to the social sciences and points to a need to develop new learning opportunities.

Is there anything new to try? In the 1960s, there were substantial initiatives to incorporate the humanities and social sciences into the engineering curriculum. One pedagogical approach involved describing why technology's adverse affects on civilization required engineers to learn the humanities: the humanities would help engineers to avoid technologies' negative consequence. Another method gave social scientists the task of developing courses that could make engineers into expert policy-makers, without substantial curriculum reform. The third approach was to make engineers more introspective by assigning readings that would allow them to use the social sciences and humanities in the same way that they used mathematics and science. During these 1960s reforms, historians of technology became embedded in the engineering culture as they sought to make the humanities relevant to engineers in a way that made them effective managers of technological progress. Although the programs did not last, the impression that engineer's should manage technology's inevitable progress remains powerful today [15]. The Summer School seeks to offer something new: a collaborative opportunity that brings engineers and social scientists together. Collaborative learning and knowledge production, however, is not easy [10, 24].

Although the social sciences are continually recognized as an important aspect of the engineering curriculum, they are often interpreted by engineers as a way to learn how to "put yourself in another person's shoes," as one Summer School participant described. This understanding, however, misinterprets much of the social science scholarship, which develops concepts and analytical approaches to better understand science, technology, engineering, and society. For example, historians, sociologists, and philosophers all use different methods and theories to do their work. Some studies are highly empirical and descriptive and others are more conceptual. Some studies aim at explanation while others seek normative evaluation, or ethical analysis. Some focus on the theories and methods of science and engineering, while others pay closer attention to social forces [25, p. 5]. Instead of trying to "put oneself in the other's shoes" ethicists and philosophers of science, in particular, have emphasized the importance of trusting the authority, perspectives, and opinions of the people who are not in a position of power [26].

The social sciences and humanities are steadily described as a necessary part of the engineering curriculum, but are mostly viewed as a way to teach students communication skills. Students often perceive these sorts of courses as irrelevant requirements that must be fulfilled. Engineering faculty are hesitant to give too much time to such courses, and thus they usually remain a distinct add-on, non-critical, non-technical course in an otherwise integrated curriculum [15, p. 754, 27]. The Summer School is a distinct departure from this history, but also constrained by its legacy. While it does provide students with an intense social-science immersion opportunity, the course is not part of the core curriculum. The social sciences are relegated to the summer, in part, because there is little time to engage them during the regular semester. When students finally find themselves at the summer school, they struggle with the unfamiliarity of open-ended discussions even while they recognize the limitations of lecture-style instruction. The Summer School experience is a distinct outlier in their educational experience—a feature that magnifies its challenges and successes.

18.5 Conclusion

Histories of engineering education have examined how the training of engineers positioned them with respect to larger societal roles [22, p. 739]. In the post-Fukushima world, nuclear engineers are positioned to assume a new social role. In fact, this is what they are being instructed to do. Students are learning from their professors about the widespread severity of the Fukushima events on the future of the nuclear industry. Students were told that they were at the Summer School to learn how to communicate in a global society. They have been charged with rebuilding the trust of the nuclear engineering community; a task that they have inherited, like it, or not. They are being asked to think and act differently—to challenge their professors, to challenge all of their assumptions, to find their own answers. Students are hearing that it is time to expand the scope of nuclear engineering. Programs are being restructured. The Summer School provides those that are doing the restructuring with good evidence about: the value of discussion as a tool to facilitate critical reflection; the importance of collaboration for enabling engineers to inhabit new societal roles; and the necessity of incorporating student perspectives during curriculum reforms in a way that allows students to become active participants in shaping the future of nuclear engineering.

References

1. Reynolds TS, Seely BE (1993) Striving for balance: A hundred years of the American Society for Engineering Education. J Eng Educ 82:136–151
2. Wisnioski M (2012) Engineers for change: competing visions of technology in 1960s America. MIT Press, Cambridge
3. Lucena J (2013) The road ahead: questions and pathways for future teaching and research in ESJ. In: Lucena J (ed) Engineering education for social justice: Critical explorations and opportunities. Springer, Dordrecht, p 271– 286
4. Borrego M, Froyd JE, Simin Hall T (2010) Diffusion of engineering education innovations: a survey of awareness and adoption rates in U.S. engineering departments. *JEE* 99:185–207

5. Lucena J (2005) Defending the nation: US policymaking in science and engineering education from Sputnik to the war against terrorism. University Press of America, Lanham
6. Beddoes K (2013) Methodology discourses as boundary work in the construction of Engineering education. Soc Stud Sci, doi: 10.1177/0306312713510431
7. Baillie C, Ko E, Newstetter W, Radcliffe DF (2011) Advancing diverse and inclusive engineering education practices through interdisciplinary research and scholarship. J Eng Educ 100: 6–13
8. Lucena J (ed) (2013) Engineering education for social justice: Critical explorations and opportunities. Springer, Dordrecht
9. Sunderland ME (2013) Using student engagement to relocate ethics to the core of the engineering curriculum. Sci Eng Ethics, doi: 10.1007/s11948-013-9444-5
10. Sunderland ME, Taebi B, Kastenberg W, Carson C (2014) Teaching global perspectives: Engineering ethics across international and academic borders. Journal of Responsible Innovation, doi: 10.1080/23299460.2014.922337
11. Takashima Y (1993) Education in the nuclear sciences in Japanese universities. Journal of Radioanalytical and Nuclear Chemistry 171:83–93
12. Holsapple MA, Carpenter DD, Sutkus JA, Finelli CJ, Harding TS (2012) Framing faculty and student discrepancies in engineering ethics education delivery. J Eng Educ 101:169–186
13. Sørensen KH (2009) The role of social science in engineering. In: Meijers A (ed) Handbook of the philosophy of science, Vol 9: Philosophy of technology and engineering sciences. Elsevier, p 93–115
14. Seely BE (1995) SHOT, the History of technology, and engineering education. Technol Cult 36:739–772
15. Seely BE (1999) The other re-engineering of engineering education, 1900–1965. J Eng Educ 88:285–295
16. Wisnioski M (2009) "Liberal education has failed": Reading like and engineer in 1960s America. Technol Cult 50:753–782
17. Committee on Nuclear Engineering Education (1990) U.S. nuclear engineering education: Status and prospects. National Academy of Sciences, National Academies Press, Washington DC
18. Freidberg J, Kazimi M (eds) (1998) Nuclear engineering in transition: A vision of the 21st century
19. National Academy of Engineering (2005) The engineer of 2020: Visions of engineering in the new century. National Academy of Sciences, National Academies Press, Washington DC
20. National Academy of Engineering (2004) Innovations: A survey of awareness and adoption rates in U.S. engineering departments. J Eng Educ 99:185–207
21. Pawley A (2009) Universalized narratives: patterns in how faculty members define "engineering." J Eng Educ 82: 136–151
22. Lichtenstein G, McCormick AC, Sheppard SD, Puma J (2010) Comparing the undergraduate experience of engineers to all other majors: Significant differences are programmatic. J Eng Educ 99: 305–317
23. Brown JK, Downey GL, Diogo MP (2009) The normatives of engineers engineering education and the history of technology. Technol Cult 50:737-752
24. Harwood J (2006) Engineering education between science and practice: Rethinking the historiography. Hist Technol 22:53–79
25. Calvert J (2014) Collaboration as a research method? Navigating social scientific involvement in synthetic biology. In: Doorn N, Schuubiers D, van de Poel I, Gorman ME (eds) Early engagement and new technologies: Opening up the laboratory. Springer, Dordrecht, p 175–194
26. Meijers A (2009) General Introduction. In: Meijers A (ed) Handbook of the philosophy of science, Vol 9: Philosophy of technology and engineering sciences. Elsevier, p 1–19
27. Pantazidou M, Nair I (1999) Ethic of care: Guiding principles for engineering teaching and practice. J Eng Educ 88:205–12
28. Blewett P (1993) Introducing breadth and depth in the humanities and social sciences into an engineering student's general education curriculum. J Eng Educ 82:175–180

Chapter 19
Reflections on Developing an Identity for the Third Generation Nuclear Engineer in the Post-Fukushima Society

Robert Angelo Borrelli

Abstract The March 2011 nuclear reactor accidents at the Fukushima, Japan nuclear reactor complex catalyzed public discussion about nuclear technology and energy worldwide. As part of this, in August 2011, the Department of Nuclear Engineering at the University of California-Berkeley (UCBNE) hosted the 2011 Advanced Summer School of Nuclear Engineering and Management with Social-Scientific Literacy: Reflections on the Fukushima Nuclear Accident and Beyond (the Summer School). This unique program featured world leaders in nuclear engineering, social science, and history. The student body was comprised of post doctorate researchers and graduate students. This chapter will discuss the identity of the nuclear engineer within the context of the post-Fukushima society. Specifically, this is directed to what will be termed the ‘third generation’ engineer. In the upcoming decades, it is this third generation that will lead and shape perspectives on nuclear technology and develop new relationships with society. This chapter is intended to pose questions to the third generation to consider as part of their own, professional self-assessment. This chapter draws primarily from the experiences at the Summer School in an effort to direct meaningful discussions about the need to consider the identity of this third generation nuclear engineer in the post-Fukushima society.

Keywords Fukushima · Society · Engineering ethics · Nuclear energy · Historical inertia · Third generation

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19.1 Preface

The March 2011 nuclear reactor accidents at the Fukushima, Japan nuclear reactor complex triggered a scrutinous public discussion about nuclear technology on an unprecedented scale, much more so than from the accident at Chernobyl or Three Mile Island. As part of this, in early August 2011, the Department of Nuclear Engineering at the University of California-Berkeley (UCBNE) hosted the 2011 Advanced Summer School of Nuclear Engineering and Management with Social-Scientific Literacy: Reflections on the Fukushima Nuclear Accident and Beyond (the Summer School). This unique program, in its third year, featured world leaders in nuclear engineering, social science, and history. The student body was comprised of post doctorate researchers and graduate students.

One of the most important questions unanimously raised during this week by the students focused on the professional identity of the nuclear engineer in the post-Fukushima society. Students had difficulty with this, in terms of a real examination of themselves as nuclear engineers and future leaders in the field. This was primarily due to the increasingly complex relationship of nuclear technology with contemporary society. The Fukushima Daiichi accidents resulted in the students coming to realize this relationship in a very real and tangible way. To this end, this chapter will discuss the identity of the nuclear engineer. Specifically, this is directed to what will be termed the ‘third generation’ engineer; i.e., the student body at the Summer School. In the upcoming decades, it is this ‘third generation’ that will lead and shape perspectives on nuclear technology and develop new relationships with society. This chapter is intended to pose questions for the nuclear engineer to consider as part of their own, professional self-assessment. This chapter draws primarily from the experiences at the Summer School in an effort to direct meaningful discussions about the need to consider the identity of this third generation nuclear engineer in the post-Fukushima society.

19.2 Implications of the Fukushima Daiichi Accident to Nuclear Engineering

The severity of the accidents that occurred at the Fukushima nuclear reactor complex in central-eastern Japan in March 2011 was classified as Level 7 on the International Nuclear and Radiological Event Scale (INES)[1] by the Ministry of Economy, Trade,

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[1] The INES scale is an internationally accepted tool for communicating the severity of a radiological event. Levels 1–3 represent events that are classified as ‘incidents.’ Levels 4–7 are defined as ‘accidents.’ Level 7 specifically is classified as a ‘Major Accident.’ Three areas of impact are considered in this scale: (1) people and the environment, (2) radiological barriers and control, and (3) defense-in-depth. The scale is logarithmic (similar in concept to the comparative magnitude scale of earthquakes) in that each level represents an accident or incident ten times more severe than the previous level. There are 69 INES Member States.

and Industry[2] in April 2011 [1, 2]. The Chernobyl accident that occurred in Ukraine (1986) is the only other accident with a Level 7 classification [3].[3]

These accidents altered the social perceptions of nuclear technology on an unprecedented scale much more so than those at Chernobyl or Three Mile Island. Such strong public response resulted due to the instantaneous access to information and communication on social platforms, such as Twitter. This is an anecdotal judgment based on personal experience and dialogue with participants at the Summer School and many news reports at the time, and not supported by rigorous study. The premise proposed here is that the rapid exchange and availability of information allowed for discussions about the Fukushima Daiichi accidents while events were unfolding in real time, around the world. Based on this, public opinion regarding nuclear engineering issues is historically at its strongest, and this has continued to be the case in the three years following the accident. Contrasting this to the late 1970s–1980s; back then, sources of information were limited to newspapers and the three broadcast television news programs. Today, the 24-h news cycle allows for continuous access to news with a near-infinite amount of resources.[4]

Practical solutions to contemporary problems in the discipline of nuclear engineering are unique and require integration of technical and institutional issues. In this chapter, 'institutional' issues refer to political and societal considerations; those which are primarily in the purview of the social scientists and historians and are not traditionally part of the current nuclear engineering education or professional

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[2] The Japanese Ministry of Economy Trade and Industry (METI) classified the accident at the Fukushima Daiichi Nuclear Power Station (NPS) as Level 7 on 12 April 2011. METI houses the Nuclear and Industrial Safety Agency (NISA) and Japan Nuclear Energy Safety Organization (JNES). These agencies basically estimated the amount of radioactive materials discharged from the Fukushima Daiichi NPS with additional, separate calculations by Nuclear Safety Commission of Japan (NSC). Both NISA and NSC analyses corresponded to a Level 7 classification on the INES scale.

[3] The INES rating for any event is not assigned by a centralized body and therefore is subject to qualitative judgments that inevitably will cause some variation. While both the accidents at Fukushima Daiichi NPS and Chernobyl are classified as Level 7, they should be not considered equivalent. A Level 7 accident indicates implementation of countermeasures to protect the public from the health and environmental effects of radiation. However, this does not mean that these effects have occurred. Additionally, at Chernobyl, twenty-eight reactor staff and emergency workers died from radiation and thermal burns. These deaths are directly attributed to the reactor itself. There have been no deaths at Fukushima Daiichi NPS reported in this way presently. The amount of radioactivity released at Fukushima is only 10 % of the amount released from Chernobyl. Finally, the accident at Fukushima was initiated solely by natural disaster, but the Chernobyl accident resulted due to human factors. These are reported by experts who were in attendance at the Summer School. The severity of the Fukushima accident should not be downplayed by these statements. The ramifications of the accident are serious, both technically and socially. Comparisons between both accidents are expected and have been discussed in mainstream news sources. This technical note is provided for context.

[4] See also the uses of social media resulting in the 'Arab Spring,' in 2011, or the 'Green Party' protests in Iran in summer 2010 and 'Discussion on the Fukushima Dai-Ichi Nuclear Power Plant accident' http://www.facebook.com/groups/177355305643452/ as an example of social media in the public dialogue relating to Fukushima.

training. It is an objective of the Summer School to provide a forum for nuclear engineers to develop some facility with these institutional issues. Additionally, the discipline is also based on a very particular 'historical inertia.'[5] The discipline of nuclear engineering was essentially born during World War II in the form of weapons development. Challenges to nuclear engineering in the public sphere have continued to be affected by this historical inertia; i.e., derived from the legacy of weapons development. Following World War II, nearly a half-century was dedicated to the cold-war arms race against communism. Even with the fall of the Soviet Union, this historical inertia continues; i.e., proliferation risks associated with enrichment of uranium by Iran. When dealing with nuclear reactors, which were developed for peaceful purposes, there is still the risk of plutonium acquisition from used fuel. This historical inertia is always going to be a factor in nuclear engineering problems.

The Fukushima Daiichi accidents also affected current energy policy-making in other nations [4, 5].[6] This shows a connection of nuclear technology with the public sphere, through institutional issues, and there is little doubt that this will continue. At the Summer School, many questions emerged from the discussion regarding whether nuclear engineers should really operate solely within the technical sphere, separate from that of the institutional and perhaps this was beyond the professional concerns of the nuclear engineer.[7] In reality, however, a clear demarcation between the technical and institutional will never happen, and, while the nuclear engineer must be a technical expert, they also must develop a facility with institutional issues as well. Frankly, acknowledging this technical and institutional integration is crucial for all nuclear engineers in the post-Fukushima society, and, because of this, the nuclear engineer must be literate in the social sciences and aware of historical inertia. This chapter is focused on how the nuclear engineer can recognize these issues as part of their identity and their place in the discipline in the post-Fukushima society.

19.3 Goals for This Chapter

During the Summer School, many discussions involved questions about the identity of the nuclear engineer. In reflecting on the events shortly after the accidents, the student body expressed apprehension at being considered 'nuclear experts' by the public (friends, family, and neighbors). This seemed to be an issue of being perceived as an authority, rather than as just a student or researcher. Many of the

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[5] This 'historical inertia' term was used by Professor Cathryn Carson, UC-Berkeley, Department of History, Office for History of Science and Technology, during discussion on Friday, 05 August, 2011 in order to characterize the inception of nuclear engineering as a discipline.

[6] At the end of May 2011, the Swiss government decided that existing nuclear power plants will close at the end of operating lifetime (2019–2034). Additionally, the coalition German government announced a policy to phase out nuclear power entirely by 2022.

[7] This topic was largely the focus of the student discussion session on Wednesday, 03 August 2011.

participants expressed a lack of preparedness and surprise for this, which was not related to their ‘traditional engineering’ training. This may be because the prior accidents at Three Mile Island and Chernobyl happened long enough ago that most of the students, who were born in the 1980s, were too young to comprehend implications of the accidents or remember them personally. While learning from those who ‘lived through’ these accidents at the Summer School is instructive, there is a lack of a certain connection for the student body. The Fukushima Daiichi accidents, however, brought that reality to the forefront for the students. Nearly everyone remarked that this really changed their views on the perception of nuclear engineering in relation to the society.

The goal for this chapter then is to discuss these concerns from the point of view of the ‘third generation’[8] nuclear engineer. Each generation of nuclear engineer has dealt with many unique challenges and the reasoning in defining the generations proceeds in this way: The first generation of nuclear engineers is those who established the university programs and curricula, at UC-Berkeley, for example, during the 1950s–1960s. Clearly, the societal context was dominated by cold war politics in that nuclear engineering was primarily based on weapons development, the arms race with the Soviet Union, and power reactor development. The second generation, then, would be those currently leading and shaping nuclear engineering research and development who directly studied from the first generation, some of whom participated in the Summer School as lecturers and organizers. While influenced by the cold war, by 1990, this was over, and the arms race essentially ceased. Two major nuclear reactor accidents had essentially ground reactor development in the USA to a halt, and the nuclear engineering community finally began to seriously address the issue of waste disposal.

It follows that the third generation is comprised of the student body at the Summer School, who are those postdoctoral researchers and graduate students, well through their programs of study in nuclear engineering and those who have not yet established permanent careers. During this period of study for the third generation, the so-called nuclear renaissance promised a new era of reactor development. Energy policy has since become more of an energy security concern, as many of the emerging countries are pursuing nuclear power technology. The spread of nuclear technologies to non-weapons states is a societal risk as the potential to produce weapons becomes less technologically prohibitive. European countries have advanced back-end management strategies, while the USA is still trying to develop a repository siting policy, after about 2 decades of research and development at the Yucca Mountain site. Clearly, the challenges in nuclear engineering currently are quite varied and the third generation will be expected to deal with these as leaders in the field over the several decades.

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[8] Here, the ‘third generation’ nuclear engineer is not derived based on outside studies. This is an interpretation based on personal experience over about 2 decades of study as a student and researcher in nuclear engineering. There is clearly some overlap between the generations; a so-called ‘zeroth generation’ could be considered luminaries such as Drs. J. Robert Oppenheimer, Edward Teller, Enrico Fermi et al.

Therefore, this third generation will face challenges in nuclear engineering that are not strictly technically based, and, in the upcoming decades, will lead and shape perspectives, advancements, and education in nuclear engineering. To this end, lessons learned from the Summer School revealed an important question addressing the practical understanding of the nuclear engineering identity: How can the third generation understand that the nuclear engineer is a professional and how can the third generation develop a sense of responsibility related to being a professional? Fundamentally, nuclear engineers must be primarily technical experts. However, a better awareness of the larger context within which the third generation will comport themselves in relation to society requires examination and reflection. Because the topic is very expansive, this chapter will draw upon the experiences directly from the Summer School in an effort to pose a meaningful discussion.[9]

19.4 Motivation for This Chapter

The third generation nuclear engineer must recognize that nuclear engineering is a profession that carries certain responsibilities. This was not really recognized by the students during the Summer School. Many students in attendance were asked if they consider nuclear engineering a profession and themselves as professionals. More than half responded in the negative. Furthermore, none were able to recall any specific university studies that were directed to training the nuclear engineer as a professional, nor did contemporaries in the third generation indicate that such issues were routinely discussed. This requires a re-structuring of the engineering university educational system in these terms; clearly, the Summer School is a very worthwhile effort toward this goal, and those organizers who are also faculty members are beginning to make these changes.

The third generation nuclear engineer, though, will most likely enter into the workforce by the time these concepts could be integrated more formally into engineering education. This places a great challenge on them to develop a professional mentality without formal training prior to starting a career in nuclear engineering. There may not be sufficient time to really reflect and learn about nuclear engineering as a profession as there would be afforded in an academic setting. Learning and recognizing the professional role really should start early in the university curricula and not developed ad hoc or ‘on the fly.’

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[9] Clearly, the body of outside scholarship and research based on this topic is tremendous. A thorough investigation concerning the relationship to nuclear engineering to the post-Fukushima society will take several years of serious study, at the least, all of which is necessary and worthwhile. Therefore, fully addressing this in a single chapter is not really possible. By drawing upon the experiences at the Summer School, however, a meaningful dialogue can be initiated for the purposes of self-reflection and examination of the relationship of nuclear engineering to society. It is proposed that the issues addressed in this chapter may motivate the third generation to further consider, study, and reflect on their professional identity, each in different ways.

Observing that Three Mile Island occurred in 1979, Chernobyl in 1986, and Fukushima in 2011, could lead to a pessimistic conclusion that there is risk of a severe nuclear accident nearly every generation. Were another accident to occur in the future, it is the third generation that will be at the forefront of ensuing response. Technical communication with the public in terms of risk management would be an imperative then as it is now. A dialogue addressing the nuclear engineer as a professional, and responsibilities therein, beginning now, could, optimistically, avoid the public problems associated with accidents. Lacking an awareness of the professional concept is a disservice to the public-at-large, and this must be addressed.

19.5 What Is a Professional?

A professional is an individual that has experienced some form of rigorous training that involves specialized theory, knowledge, and skills. This is directed for improvement or protection of the society. This usually includes an advanced degree or further training in order to obtain a license to legally practice the given profession. Professional duties are promulgated formally in a code of ethics for the many professions: medicine,[10] law,[11] and the many disciplines of engineering, including nuclear.[12] Based on study of these codes of ethics, the professional, generally, is therefore expected to conduct themselves in a manner demonstrating a regard for the public good and an awareness of the societal context within which the profession exists.

Additionally, society itself is becoming increasingly technological, and therefore, the roles of technical experts in terms of protecting public safety are exceedingly crucial. Then, this third generation must recognize that their future role as professionals will include societal considerations. Clearly, this implies that nuclear engineers need significantly more collaboration with others who have professional expertise with institutional issues. This is fairly obvious and not particularly

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[10] The Preamble to the American Medical Association Code of Medical Ethics states (emphasis added): As a member of this profession, a physician must recognize *responsibility* to patients first and foremost, as well as *to society*, to other health professionals, and to self.

[11] The Preamble and Scope to the American Bar Association Model Rules of Professional Conduct states (emphasis added): Lawyers play a vital role in the *preservation of society*. The fulfillment of this role requires an understanding by lawyers of their relationship to our legal system. The Rules of Professional Conduct, when properly applied, serve to define that relationship.

[12] The Fundamental Principle of the American Nuclear Society states [emphasis added]: ANS members as professionals are dedicated to improving the understanding of nuclear science and technology, appropriate applications, and potential consequences of their use. To that end, ANS members uphold and advance the integrity and honor of their professions by using their knowledge and skill for the *enhancement of human welfare and the environment*; being honest and impartial; *serving with fidelity the public, their employers, and their clients*; and striving to continuously improve the competence and prestige of their various professions.

constructive. However, just realizing this is needed advances the profession itself. This includes recognizing that nuclear engineering contains equally important technical and institutional considerations and that these are intertwined. Maintaining more awareness of the context in which the nuclear engineer is working and that relationship to the society is a significant improvement and a realistic near-term goal to the development of the professional third generation nuclear engineer.

19.6 A Particular Challenge to Engineering as a Profession

In medicine or law, clients and the professional interact on a personal level. This is largely not the case in engineering because most engineers work for large corporations or national research institutes. Those in academics greatly impact the student body, as educators, mentors, and advisors; however, professional discussions, in and of themselves, in the academic setting are lacking. The engineer's 'client' really is the public-at-large. Nuclear engineers execute computer models that test new reactor designs, build reactor pressure vessels, fabricate nuclear fuel, and work with hazardous chemicals to treat fuels and waste. Nuclear reactor operators are essentially in control of distributing electricity to the nation. There is a lack of experience with direct interaction between the nuclear engineer and the public in all of these. This can contribute to degradation of the professional sense of responsibility. This will impact both present and future society.

This leads to an interesting consideration with respect to the time-scale of nuclear engineering within the concept of the profession. Much of the nuclear engineering profession involves solutions to problems that may not be realized for decades. Current light-water commercial reactors in the world have licenses to operate, initially for forty years, but have been or are in the process of extending lifetimes to 60 years and even greater. The performance assessment for the nuclear waste repository is based on rigorous mathematical modeling that includes nuclear engineering, but also chemistry, materials science, mechanical engineering, and civil engineering. Validation of the performance assessment results cannot be realized for thousands of years at the earliest. Therefore, the 'client' for the nuclear engineer also spans several generations.

Most of the third generation nuclear engineers who are beginning careers now or soon may not have had any opportunity to directly interact with the 'client', and engagement in issues related to the profession may be scant.[13] Unfortunately, nuclear engineers become severely aware of their clients when an accident like Fukushima occurs and tens of thousands of people are evacuated from their

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[13] Of course, there are those nuclear engineers who are involved in medicine, who will in fact interact with clients individually and directly. However, those nuclear engineers working at a power plant or corporation will affect far more of the public. Lacking a professional sense in this capacity, therefore, is problematic.

homes. This lack of direct interaction is detrimental to the nuclear engineer in terms of really understanding the social responsibility of the profession. If there is a lack of professional responsibility, then can the nuclear engineer truly be serving the public good?

19.7 Regarding Public Communication as a Form of Professionalism

Because nuclear engineering is fundamentally based on the integration of the technical with the institutional, and based on interpretation of discussions at the Summer School by the both the third generation and expert lecturers, in terms of professional responsibilities, routine communication with the public by nuclear engineers must be improved. This problem is derived directly from this absence of 'face to face' interaction of the nuclear engineer with the 'client'. In terms of general communication issues, some nuclear engineering topics may be reported in the news, but these are usually when accidents, or potential accidents, occur. This is not a condemnation of the media and reporting practices. Most of the daily news is largely negative in terms of subject matter. Nuclear engineering is one of the subjects that suffers probably more than others, due to historical inertia, in that it is perceived mostly negatively normally. When accidents occur, this usually reinforces the negative public opinion. Conveying accurate information regarding nuclear engineering issues is also very difficult even for those trained in the profession, and further underscores the need for the nuclear engineer to realize that part of the professional responsibility involves public communication.

As an example, based on first-hand observation, in the weeks following the Fukushima Daiichi accident, news crews from ABC, NBC, and CBS frequently interviewed the faculty Department of Nuclear Engineering at UC-Berkeley for technical communication about the accident and related events [6]. However, even this level of communication flows only in one direction, as the nuclear engineer basically just tells the interviewer the state of the subject at hand. This is needed and it is important to do, but a deeper level of public interaction is required, where both the nuclear engineering professional and the public can see one another as both part of the society. Therefore, without regular and direct interaction, or failing to realize that the profession must include some level of this, is an encroachment on professional responsibilities. This is not to place the 'burden of proof' on the public to motivate themselves to hold a more positive attitude regarding nuclear engineering; indeed, this burden is part of the professional responsibility of the third generation nuclear engineer to develop ways that public interaction can be increased.

Meaningful public interaction has been a challenge since the inception of nuclear engineering and drawbacks to this are related to its historical inertia. This has led many times to an 'us versus them' mentality which only fosters antagonism. This has historically shown to be the wrong approach. This can occur when so-called ‘technocrats,’ while well intentioned, try to make decisions based solely on science and engineering by relying on a responsibility for ‘good of the public,’ without experiencing or communicating directly with the public, whom these decisions affect. Generally, most repository siting issues are examples of this. In the case of low-level waste repository siting in South Korea, technocrats with a strong voice in the federal government attempted to unilaterally establish a waste site and were met with strong public opposition at sites around the country for nearly two decades.[14] Separation of the nuclear engineer from the public leads to an adoption of a paternalistic attitude. Rather, the nuclear engineer must understand that they are in fact part of the public that they purport serve. Because of this, technical communication should be developed in a more inclusive manner. This task is still rather difficult, but a more evolved approach to public communication should be considered within the responsibility of the nuclear engineering professional.

19.8 Beginning to Understand Professional Ethics as a Responsibility

Building on the premise that engineers must recognize themselves as part of the society, it becomes clear that engineering solutions have some functional relationship with the society. This can be attained by realizing that the professional engineer is an ethical engineer. The third generation must develop this self-awareness. How then can the connection between professional responsibilities and professional ethics be recognized?

Developing professional ethics is a continual process. This can be defined as the design of conduct in engineering practice.[15] Professional ethics can only really be developed by the nuclear engineer with time. This topic is very broad ranging and there are many different ethical approaches that can be considered based on realistic, personal experiences of each nuclear engineer. However, self-awareness of an ethical responsibility at the start of professional development could prove instructive.

To start, for the third generation, a critical aspect of developing an ethical point of view, as a professional nuclear engineer, is culture. This is becoming very important as the world becomes smaller, and therefore more interrelated and complex. Consideration of ethics in engineering is essential for all engineers themselves in order to work in and be a part of the global community. This goes beyond simply reading the codes of ethics provided by the professional society. The third generation of nuclear engineer needs to consider a new definition of what it means to be professional which will include ethics. Codes of ethics can serve as an interface between the profession and expectations for the public, but these are

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[14] Although, it should be noted that there is still a political factor to these issues.

[15] This is a formal definition provided by experts in the field at the Summer School.

constrained. They are based on universal principles of morality, which is needed, but lack context. This is where cultural understanding is critical. This requires not only honest communication, but also a combination of honesty and sincerity. This will be essential in establishing a new professional outlook.

From a micro-ethics perspective, the third generation can consider their individual research or professional goals in terms of responsibility to society. This perspective was alluded to in the Summer School discussions in that in the immediate events after the accident the student body had concerns about their appropriate individual response to the public concerning the accidents. The macro-level perspective can also be addressed at this stage of professional development for the third generation as well, as the Summer School was clearly designed as a forum to discuss the role of nuclear engineering and engineers within the society. This macro-level also may be the most important viewpoint that requires serious thought and change by all engineers in the post-Fukushima society, but especially by the third generation, in that relationships with the public are still nascent and are not encumbered by prior experience, whether positive or negative. Part of the goal of this chapter is to address the need for an understanding that nuclear engineering itself is a profession with related and defined responsibilities; this is a meso-level ethical understanding. The meta-level of ethical understanding may not yet be achievable as the third generation, as this seems to require some hindsight that is developed with professional experience, though, at the least, being receptive to questioning the nature of engineering could be a constructive development moving forward from Fukushima.

Additionally, in terms of ethical considerations and societal context as part of the professional responsibilities, there were many conversations at the Summer School that focused on premises such as, ‘We need to convince the public of the benefits of nuclear power’ or ‘we have to show what the risks really are.’ However, it was strongly implied and at times outright stated that if the public does not agree with such benefits, then they are ‘wrong’ and ‘acting irrationally.’ This direction of thought is a misguided form of communication and does not serve the public. This is professionally unethical in that there is a failure to comprehend the societal context in which the ‘benefits’ are proposed.

Engineering is fundamentally based on a logical reasoning. The dominant paradigm in engineering of any discipline is utilitarianism; i.e., the probabilistic risk assessment or cost/benefit analysis. While these do contain some degree of subjective judgment, overall, they are overwhelmingly mathematically and logically based. However, to expect the engineer to conduct himself or herself professionally strictly by logic would be misguided. This is again a problem with the separative and erroneous concept of ‘engineers’ and ‘the public,’ in that this leads to a tendency, also observed at the Summer School, with engineers that thinking strictly in logical terms will lead to the only ‘correct answer.’ The ‘correctness’ of any answer is determined by the functional relationship with engineering as part of the public sphere.

For example, the risks and benefits of nuclear power in Germany, Switzerland, or the USA really did not change after the Fukushima accidents; however, the societal context for this certainly did change, and the question as to whether nuclear power should be discontinued is not strictly dependent on engineering solutions in any nation. In Germany and Switzerland nuclear power will be phased out, but in the USA current policies will be maintained. This is not to imply that engineering solutions are without merit. Probabilistic risk assessments must be conducted in order to determine whether if such measures as backfitting, etc., will reduce risks at any power plants. This is being done in response to the accidents in many nations, including the USA. Ultimately, if these risks can be reduced significantly, this does not mean that if a nation elects not to continue nuclear power development that this is the 'wrong' decision. The consequences of the accident, emotionally or monetarily, may be too great for the society to bear.[16]

To consider that all of these issues can be 'correctly' determined by purely logical means, is professionally unethical. Frankly, it is nonsensical that anyone should be expected to act strictly in a logical manner, devoid of emotion [7].[17] This overemphasis on logic contributes to the lack of understanding about the relationship between nuclear engineering and society; real, practical solutions just cannot be attained in this way. The nuclear engineer must recognize his or her own relationship within the society in order to perceive the larger, functional relationship of engineering with the society. This can potentially be achieved by considering their own value systems and working to apply these to the precepts of the profession, i.e., for the public good, as well as the values of the society within which they are also members themselves.

19.9 Final Remarks Regarding Nuclear Engineering as a Profession

Contemporary challenges to nuclear engineering, as a profession, will be affected by historical inertia. Much of the public currently would think of a bomb first, when prompted to remark about nuclear engineering topics. This is not an unreasonable public reaction; the proliferation of nuclear technology in this way is still problematic. More and more nations seek access to nuclear technology for energy-producing purposes and this presents a growing security and proliferation risk regarding the use of nuclear technology for nefarious purposes.

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[16] This of course raises the issue of alternative energy sources, which can be also debated at length, but the main point is that none of these decisions can be made without considering the society.

[17] Even the epitome of the rational individual, the singular Mr. Spock, expressed outright joy when he realized that he did not kill Captain Kirk during the *kal-if-fee* (Amok Time, TOS#30). The myth of the engineer, that individual, acting in a strict logical manner, devoid of emotion, and arriving at a single 'correct answer,' is itself, highly illogical. Extensive scholarly endeavors are currently devoted to the subject of emotions in engineering and the manner in which professional ethics can be developed in this way. While not specifically discussed at the Summer School, further contemplation of this may be a good start for the developing identity for the third generation nuclear engineer.

Nuclear engineering, as a profession, is also challenging because although the profession is technically based, the professional cannot reside strictly in this technical arena. In understanding nuclear engineering as a profession, the third generation must grasp that technical approaches are necessary, but not sufficient, and that both social science literacy and professional ethics development are required to achieve solutions to contemporary nuclear engineering problems with any modicum of practicality. A social and political awareness will always frame nuclear engineering issues and this must be internalized as part of an inherent sense of professional responsibility. This may not be fully achievable currently, but if the third generation can begin to think about the profession with a more expansive scope, then their role can grow stronger, professionally. Research and technological development alone does not solely support and extend the goals of the profession in relation to society, without collaboration with the society.

References

1. International Atomic Energy Agency (2009) INES: The international nuclear and radiological event scale user's manual. Vienna, Austria
2. Government of Japan, Ministry of Economy, Trade, and Industry (12 April 2011) News release
3. Nuclear Energy Institute (2011) Nuclear energy insight. Washington, D. C.
4. BBC News (25 May 2011) Swiss to phase out nuclear power
5. BBC News (30 May 2011) Germany: Nuclear power plants to close by 2022
6. ABC news (17 March 2011) Other options to help Japan's nuclear crisis?
7. Roeser S (2012) Emotional engineers: Toward morally responsible design. Science and Engineering Ethics 18:103-115

Chapter 20
Nuclear Engineers for Society: What Education can do

Takuji Oda

Abstract Engineering education is a key factor in determining the range of engineers' expertise, the attitude and the behavior of engineers, and the culture of the engineering professional community. This chapter is devoted to nuclear engineering education post-Fukushima Daiichi nuclear accident. Prior to education itself, knowledge and attitudes required of nuclear engineers are firstly discussed, focusing on social aspects of nuclear technology. I emphasize the importance of mutual communication with society, not only with the general public but also with experts in other fields, by referring to 3 points which are essential for appropriate advancement of nuclear engineering and can be reinforced with mutual communication: social legitimacy of nuclear technology, introspection within the nuclear professional community, and public trust in nuclear technology and the professional community. These points are not only needed for smooth utilization of nuclear technology, but also, and more importantly, needed for enhancing the safety of nuclear technology utilization and advancing nuclear technology to provide more benefits and welfare to society. Finally, I propose 4 items for education reform, which are mainly designed to make mutual communication with society more effective while maintaining a high level of technical expertise: standardization and internationalization, transparency and sharing, social-scientific literacy education, and development and evaluation of faculty.

Keywords Nuclear engineering education · Social aspects of nuclear technology · Social legitimacy · Introspection · Trust

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20.1 Introduction

When an accident or a scandal related to science and technology occurs, education—especially higher education such as undergraduate-school and graduate-school education—often draws social attention. This social reaction is natural because higher education is the first opportunity for to-be-experts to gain expertise in a comprehensive manner for several years and is thus influential. Indeed, engineers continuously update and reinforce their expertise even after the completion of higher education, mostly through on-the-job experiences. However, what they learned at the beginning of their professional career inevitably affects how they improve their expertise and what they learn from the experiences. Therefore, higher education is a key factor in determining the range of expertise as well as the attitude and the behavior of engineers. It also affects the culture of professional community because the culture is constructed by collective behaviors and attitudes of community members.

Considering its extensive influence, this chapter presents a discussion on nuclear engineering education. However, since the goal of education largely depends on human resources required in society, a major part of this chapter is devoted to clarifying the knowledge and attitudes required of nuclear engineers, especially focusing on social aspects of nuclear technology, as follows.

In Sect. 20.2, first of all, I look back on some actions on educational reform which were carried out in Japan before the Fukushima Daiichi accident. We see that Japanese nuclear professionals were aware of the importance of social aspects of nuclear technology and then tried to incorporate some relevant contents into nuclear engineering education.

Indeed, the importance of social aspects, which often includes communication with society on science and technology, was recognized not only in nuclear engineering but also in other engineering and science fields in those decades. In Sect. 20.3, I briefly review why the social aspects were increasingly thought to be important with focus on communication with society.

In Sect. 20.4, some key efforts made in relation to social aspects and the communication with society on nuclear technology are introduced. However, I must say that these activities hardly brought fruitful results in the reality.

In Sect. 20.5, the causes of the unfruitful results in communication are discussed. There was/is often a big gap in the purposes of mutual communication for the general public (or society) and for nuclear engineers (or nuclear professional community): the former expects changes in nuclear engineering and its professional community, while the latter expects changes in the general public and society.

In Sect. 20.6, I reconsider the significance of mutual communication in advancing nuclear engineering. I bring three viewpoints for this: legitimacy, introspection, and trust. I try to explain that they are requisite to the safe utilization of nuclear technology and to the appropriate advancement of nuclear engineering, and that they are underpinned by mutual communication with society. Here, communication with society is extended: not only with the general public but also with experts in other science and engineering fields.

In Sect. 20.7, I discuss what kinds of communication are doable and effective in practice.

In Sect. 20.8, I propose 4 ideas on higher education reform based on the discussion given in the previous sections.

Section 20.9 ends this chapter with some concluding remarks.

Finally, before entering the main contents, I would like to briefly introduce my educational and professional background. I am a researcher in nuclear materials science and engineering. I am interested in both nuclear fission and fusion reactors technology. I received my primary, secondary, and higher education in Japan. After them, I worked in a Japanese university for about 6 years at its nuclear engineering department, worked in a U.S. university for 1 year at the materials science and engineering department, and now work as an assistant professor at a Korean university since 2013 in the nuclear engineering department. Due to this background, the description in this chapter is centered on Japan's situation and history. Non-Japanese readers may feel some strangeness in the contents. However, based on my experience and observation in Japan, U.S., and Korea, I believe that there are large similarities in the characters of nuclear expert communities in Asian countries and some similarities even between Asian countries and Western countries, more than expected, because the culture of a nuclear engineering community is strongly influenced by the nature of nuclear technology itself.

20.2 Nuclear Education Reform Before the Fukushima Daiichi Accident

Before the Fukushima Daiichi accident, there were several initiatives in Japan to reform higher education in nuclear engineering. The classical engineering higher education predominantly aims to make students acquire natural-scientific and technological knowledge and skills relevant to nuclear engineering. Here I want to introduce an education-reform project undertaken by the Department of Nuclear Engineering and Management, the University of Tokyo. The project was named "Nuclear Education and Research Initiative" (GoNERI). GoNERI was financially supported under the Global Center of Excellence (GCOE) program led by the Ministry of Education, Culture, Sports, Science and Technology of Japan (MEXT). The general objectives of the GCOE program were to "establish education and research centers that perform at the apex of global excellence to elevate the international competitiveness of the Japanese universities" and to "strengthen and enhance the education and research functions of graduate schools, to foster highly creative young researchers who will go on to become world leaders in their respective fields through experiencing and practicing research of the highest world standard" [1].

GoNERI was selected as one of the GCOE subjects and the program ran during FY2007-FY2011. GoNERI aimed to "develop a well-rounded research and education program in response to a variety of world-wide nuclear utilization subjects such as protection of the global environment, supply of safe and stable nuclear energy, radiation application for healthy, productive and prosperous lives" and to "perform the first systematic education on nuclear energy in the world, incorporating the social, liberal arts and technical subjects as they relate to nuclear utilization [2]." GoNERI specified three realms for education and research, which were nuclear sociology, nuclear energy, and radiation application, and intended to implement them into the curriculum in an integrated manner [2]. Among them, "nuclear sociology" is of particular interest. It involves nuclear energy law, nuclear non-proliferation, and harmonization of technology and society, and puts a special focus on "public understanding for harmonization between society and technology" [2].

There was another similar education reform program led by Tokyo Institute of Technology in FY2003-FY2007. In its purpose statement [3], "the relationship between nuclear energy and society" was frequently mentioned. Considering these two reform programs in different universities, it would be reasonable to assume that the awareness of the importance of social aspects of nuclear technology, especially harmonization with society, was widely shared in the nuclear professional community. It was recognized that some social-scientific disciplines related to the social aspects of nuclear technology should be taught in nuclear engineering education. This awareness and recognition must have been brought about by long-lasting frictions in society over the utilization of nuclear technology, such as the delay in selecting a high-level radioactive waste disposal site.

20.3 Communication on Science and Technology

The importance of social aspects in the development and utilization of science and technology has been increasingly recognized not only in the nuclear engineering field but also in other science and engineering fields. The cause for this realization is the increase of social conflicts related to science and technology, such as environmental problems, ethical concerns in frontier engineering (e.g. genetics), etc. [4].

In this context, two cases immediately draw our attention [4]: the study by Wynne [5] on how the general public understands and deals with scientific knowledge about environmental contamination in the vicinity of the Sellafield-Windscale site in U.K., and the circumstances of U.K.'s government response to the Bovine spongiform encephalopathy (BSE) issue [6]. It is explained, for example, that the "deficiency model," which considers that miscommunication and misunderstanding on science and technology mainly rest on the deficiency of the citizen's knowledge, is not plausible in many cases [5]. Then, not only the importance of the trust in information of science and technology but also the importance of the trustworthiness of an organization which deals with the information are claimed [4]. One of the effective ways to foster the trust and the trustworthiness is mutual communication between citizens and experts, not one-way communication from experts to citizens, such as teaching and enlightening. The mutual communication may include the reflection of public opinion in the development and the utilization of science and technology, public involvement in the decision making process for science and technology issues, etc.

In Japan, the importance of communication on science and technology has been clearly recognized since around the year 2000, and methods to collect public opinions via *public comment* or *consensus meeting* have been widely implemented [4]. In higher education, three universities (The University of Tokyo, Hokkaido University, and Waseda University) embarked on education of science and technology communication in 2005 under the support of MEXT. For example, The University of Tokyo launched a *Science Interpreter Training Program* [7]. All three universities had a similar motivation, which was that "even though the importance of science and technology in our daily lives has increased, the distance between society and science-and-technology has been stretched and people's distrust of science and technology is emerging. So we need human resources who can bridge society and science-and-technology" [4].

20.4 Attempts in Nuclear Engineering Community

Regarding public involvement and technology communications in the nuclear engineering field, the *Round-Table Conference on Nuclear Power Policy* was launched by the Atomic Energy Commission (AEC) in 1996, which aimed to "seek the views of all levels and sectors of society in Japan, and to incorporate their diverse opinions as part of future nuclear energy policy" [8]. Public comment and consensus meetings were also widely held ancillary to meetings or conferences organized by national/local governments or governmental agencies. It can be said that activities to increase transparency in the decision-making process and to foster public involvement in the decision-making process have been formally built up year by year. However, when a nuclear-related topic is the agenda, it seemed that both pros and cons become extreme, and they do not reach any agreement. For example, at the round-table conferences, it was frequently observed that the participants for nuclear technology tried to persuade the citizens. In addition, it is often criticized that such an activity is utilized as mere "evidence" of public involvement [9].

In the Atomic Energy Society of Japan (AESJ), which most Japanese nuclear professionals belong to, social aspects of nuclear technology were also recognized as a key issue. Such recognition was materialized as the foundation of the Social and Environmental Subcommittee (SES) in AESJ in 1999. The prospectus of the subcommittee was set as follows [10]:

> … A significant relationship with society is a notable characteristic of atomic energy technology, and the Society and Environment Subcommittee was established to engage in academic research of social aspects, as well as to exchange and disseminate the resulting information.
>
> We analyze the features and the characteristics of nuclear technology from the viewpoint of technological theory and cultural theory. We study various aspects of nuclear energy which appears in realms of politics, economics, laws, society, international relations, environmental harmonization, etc. Then, we search for nuclear technology which is adjusted so as to go well with the age of competition, global environmental concerns, post-cold war and global economics. Namely, we search for an appropriate form of nuclear technology under strong correlations between human beings, societies, environment and technologies….

This prospectus says that its main objective is to reconsider the roles and meanings of nuclear technology in society and to find how nuclear engineering should be, not to inform society about nuclear policy nor to promote public acceptance of nuclear technology utilization. Communication on nuclear technology is often attempted to change the perception of the general public on nuclear technology by modifying the way of showing and explaining the technology. In this case, reformation of nuclear engineering itself is not taken into account. What the prospectus explains seems contrastive to it. To achieve the aims written in the prospectus, releasing information to enlighten the general public is clearly insufficient. Instead, nuclear professionals are required to listen to and to understand society so that they can reflect the opinions of society in the development and the utilization of nuclear technology.

20.5 Unfruitful Results from the Attempts

I became interested in the social aspects of nuclear technology around 2008. At least since that time, I saw many research presentations by social-aspects experts at biannual meetings of AESJ (Fig. 20.1). This indicates that social-aspects experts had secured a certain position in the nuclear professional community. It must have made them feel at ease and made technological experts feel free from struggles to communicate with society, as the communication was often time-consuming and tough for engineers. This new situation, where technological experts can focus on their conventional engineering work and social-aspects experts face society, seemed to be reinforced in the last decade. The reinforcement is reasonable because it was beneficial for both experts. However, I think fruitful results were hardly achieved in line with the prospectus of SES.

One of the reasons of the unfruitful outcome is that social-aspects experts were prone to turn their faces more toward citizens and less toward nuclear technology experts. Most of communication practitioners and social-aspects experts do not have enough knowledge and skills about nuclear technology to advance the technology by

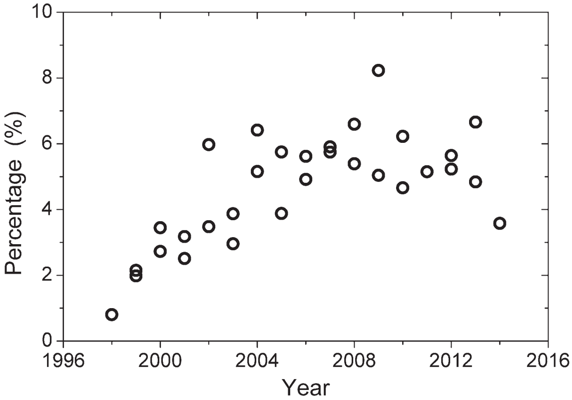

Fig. 20.1 The number of papers on the social aspects (categorized in general issues session), which were presented in the biannual AESJ meetings since 1998. We see a clear increasing trend

themselves. Hence, in order to reflect what they gathered from society on nuclear technology development and utilization, social-aspects experts should have transferred opinions from society to engineers so that engineers could consider and reflect it in their work; however, this was not done sufficiently. Even when mutual communication is carried out between citizens and social-aspects experts or communicators, if the accumulated information is not appropriately transferred to engineers, the communication is virtually no different from enlightenment-type one-way communication.

In addition, it should be recognized that the opinion of society hardly appears on opinion polls or answers to questionnaires, such as agreement rates on “Do you agree with nuclear power utilization?” Many data from opinion polls and questionnaires have been accumulated over these decades. These data are resourceful, but the data in raw formats are not significant enough to stimulate engineers so as to bring some changes in the technology. Furthermore, such raw data sometimes gave engineers misleading perceptions on the opinion of citizens.

For example, after the occurrence of an incident, we nuclear experts are often anxious about opinion polls and regard their results as the opinion of citizens. Then, when the polls start to become more positive, we engineers often simply assume that the public sentiment has recovered and society has forgiven the incident. However, in most cases, this is not due to forgiveness, but mainly due to oblivion because nuclear energy is not the sole agenda for society. Even after the opinion polls recover to around the level before the incident, some bad memories are deeply and subconsciously inscribed in public minds. Then, when another incident occurs in the future, society reacts excessively due to the accumulated bad records in the past. Such an excess reaction puzzles nuclear engineers and makes engineers think that citizens are irrational.[1] To avoid such misunderstanding on the behavior and the intention of citizens, we engineers should seek out the true opinion and intention of citizens rather than apparent ones.

To extract more true opinion and intention of society, those raw data should be carefully and thoroughly studied considering historical, cultural, and political contexts, as described in the prospectus of SES. For this, some disciplines in social sciences, and even sometimes humanities and literature, should be useful. However, as far as I know, most social-aspects experts in the nuclear professional community did not have enough educational background in social sciences.[2] Probably partly

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[1] We engineers usually believe that we can improve technology so as to prevent future occurrence of mistakes that have happened in the past. Due to this belief, we tend to evaluate the status of the engineering as separate from the fact that the mistake happened in the past. On the other hand, citizens usually do not separate the current status of engineering from the previous mistakes, because the current status is regarded as a point on the line continued from the past and continues into the future. In this sense, public reaction is reasonable and rational. The difference from that of engineers is mostly how they construct the framework to look at technology advancement.

[2] Although the statistics need to be carefully checked, many social-aspects experts chose their focus of expertise in graduate courses and did not receive comprehensive social-scientific education in undergraduate courses in Japan.

due to this, most information shown to nuclear engineers from social-aspects experts was not deep enough to motivate nuclear engineers to think about it.

Of course, the problems did not exist only among social-aspects experts but also among nuclear engineers. They did not have an attitude of sincerely listening to and collaborating with social-aspects experts. As seen in the previous sections, nuclear engineers became aware of the importance of social aspects. However, it was mostly done in a passive and reluctant manner, and they did not really understand how social aspects are related to nuclear technology. Then, engineers left most things about society up to social-aspects experts so that they can be free from mutual communication with society.

In summary, I observe two types of miscommunication between nuclear-technology experts and social-aspects experts, rather than between social-aspects experts and citizens: (1) a quantitative one, which is due to insufficient communication between nuclear-technology experts and social-aspects experts, and (2) a qualitative one, which is due to the fact that most information provided from social-aspects experts to nuclear engineers was not deep enough to stimulate nuclear engineers. Consequently, it may even be said that the mutual communication between citizens and nuclear engineers was further reduced and the distance between society and nuclear technology could not be decreased in the last decade, although frameworks to conduct mutual communication was nominally established and deployed (Fig. 20.2).

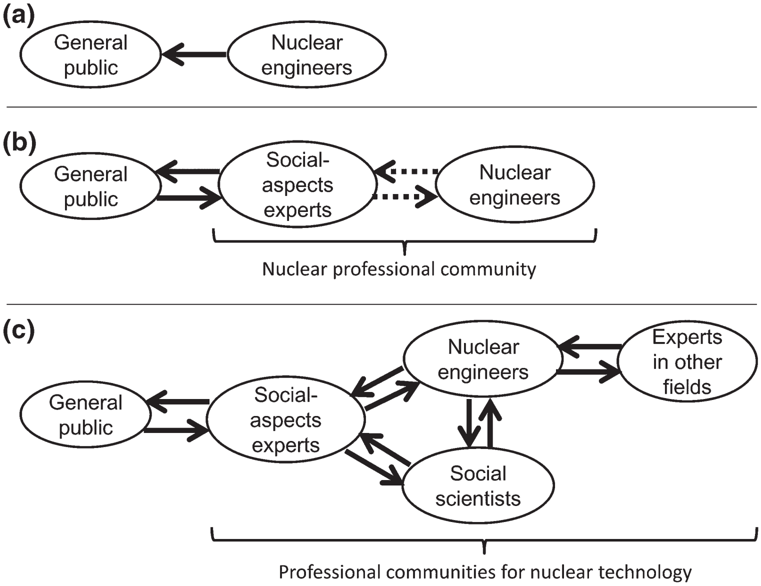

Fig. 20.2 Three structures for nuclear technology communications: **a** enlightenment-type one-way communication with society, where information as knowledge is transferred from engineers (experts) to the general public; **b** mutual communication with society via social-aspects experts (including communicators), where miscommunication occurred between social-aspects experts and nuclear engineers; **c** an effective mutual communication with society which I propose in this chapter

20.6 Is Communication Essential for Advancing Nuclear Engineering?

There is no doubt that nuclear engineers recognize the importance of social aspects including mutual communication with society, as can be seen in the education reform programs, the round table discussions, and the establishment of the SES subcommittee in AESJ. However, in reality, it is not completely clear or convincing for engineers whether mutual communication will really contribute to the safe utilization of nuclear technology and the advancement of nuclear engineering. This is one of the key reasons why nuclear engineers have not been positively involved in mutual communication. Many engineers think that the communication does nothing for the performance and advancement of nuclear technology but is just required to let the general public know the importance of nuclear technology and make them accept nuclear technology. In this sense, the communication with society is often considered to be a reluctant obligation and an additional burden for engineers, and its purpose to change the public perception.

Citizens usually do not think that they have to change; rather they think engineering or experts (community) as well as the governance of technology need to change, especially when they participate in mutual communication. The goal of engineers is to change society, while the goal of the general public is to change nuclear engineering and the nuclear expert community. Thus, in most events of mutual communication, both sides cannot achieve what they want; engineers cannot foster public acceptance, while the general public cannot have any changes in the technology and the expert community so as to make them more acceptable to them. Repeating such fruitless communication makes engineers tend to keep a distance from the communication.

However, when we see the significance of the communication from a different direction and appropriately define it, mutual communication with society seems vital to safely utilize nuclear technology and to advance nuclear engineering. I hereafter discuss this point from three viewpoints: (1) legitimacy, (2) introspection, and (3) trust.

20.6.1 Legitimacy

Historically, the civil use of nuclear technology has not been separable from the military use of nuclear technology, politically and socially. Related to this fact, there are many features that make nuclear technology distinct from other technologies. For instance, nuclear non-proliferation has been one of the main international political issues after World War II. The transparency on nuclear technology needs to be limited. National governments participate deeply in the development and utilization of nuclear technology under the international non-proliferation regime. Nuclear security concerns, which have been largely escalating during this decade, also require a decrease in transparency.

Economically, in comparison with other methods of electricity generation, the percentage of initial investment (capital costs) is higher and designing an insurance system is more difficult due to the large uncertainty in calculating possible damages from potential accidents, which requires some support from the government. There are also issues on waste disposal whose radioactivity lasts a very long time, which requires responsible involvement from the government.

Such characteristics of nuclear technology increase government commitment to the technology in its development, utilization, and evaluation. It is hard to put nuclear technology under a full market mechanism, which can act as a kind of screening process for technology in society. If a product does not fit society, the product is swept out from the market or is modified so as to become one more acceptable to society. In many countries, products made with nuclear technology, such as nuclear power plants, are nearly fully detached from the market mechanism. Someone may claim that there are market mechanisms within the nuclear industry, like nuclear export competition, bidding in procurement of fuel, etc. However, it is competition after the decision for nuclear technology utilization has been made by the government or by a semi-governmental utility company in most cases. Nuclear power plants are there whichever company wins the contract.

In history, we can find clear traces of such extensive government participation. For example, Japan built 1–2 nuclear power reactors every year since the beginning of the introduction of nuclear power in 1960s, until the mid-1990s, when the power demand declined because of the economic recession [11]. Partly thanks to this, electricity has been stably supplied, the economy rapidly grew, and Japan has established and maintained a high standard of technology for the manufacture of nuclear power plants. The long-term steady promotion and development were approvingly and proudly related in the field of nuclear engineering education before the Fukushima Daiichi accident. However, considering that there have been anti-nuclear movements since 1970s, and that the Chernobyl accident in 1986 stopped new construction of nuclear reactors in most Western countries, it is quite unusual to have the steady increase of nuclear power plants in Japan. Such a situation would not happen for other engineering products which are put under the market mechanism.

While the fleet of commercial nuclear power reactors expanded steadily, research and development (R&D) of advanced reactors was not so successful in Japan; the development of the advanced thermal reactor (ATR) was not realized, and the development of the fast breeder reactor (FBR) did not proceed according to expectations in spite of huge R&D outlays [11]. These unsatisfactory R&D results seemed to be overlooked, probably because they were a part of national policy.

These facts mean that nuclear technology and its expert community did not go through the usual procedure to obtain social legitimacy in comparison with other technologies; a pseudo-legitimacy was given and endorsed by the government. This may be one of the reasons why nuclear technology has often suffered strong negative reactions from society. Most citizens may not necessarily explicitly think about the legitimacy issue; however, they may feel some uneasiness in the fact that the government, not the citizens, made the decision, different from other products.

It is hoped that mutual communication with the public will enable its opinions to be reflected in the development and utilization of technology, and lead to social legitimacy. It should be noted that there must be feedback and adjustment after listening to the public; otherwise mutual communication is no different from one-way communication.

20.6.2 Introspection

Having these historical circumstances, nuclear engineers made light of the opinions of society and citizens, and made much of governmental decisions and the harmonization of the professional community. As a result, the nuclear expert community turned to be inner-looking and closed, regarded as it is as a "nuclear village," "nuclear mafia," etc.

The Fukushima accident reports [12–14] mentioned that although there were some technical issues related to the safety of nuclear power plants, nuclear engineers unconsciously took no measures to deal with those issues. Moreover, many of the issues pointed out in the accident reports were relatively easy to be solved technologically. For example, although scientific uncertainty existed in risk assessment of tsunami, possible counter measures to tsunami, like increasing the water tightness of the reactor building, were technically simple and doable. In addition, there was no clear indication that the safety measures had been denied due to financial reasons [12]. Thus, this problem is not fully technological, but also includes some judgment on what needs to be treated. Significant risks were mistakenly ignored and considered as non-urgent, which was said to be "out of the expectation" [12–14]. The accident reports claimed that this out-of-the-expectation mistake resulted from the non-proactive attitude of the power plant owner and non-independence and from insufficient competency of regulatory body, both of which are largely related to the inward-looking and closed nature of the nuclear professional community [12–14].

Indeed, there are facts indicating that some scientists and citizens showed a concern about possible damages due to tsunami [12–14]; however, these opinions were not valued sufficiently. This indicates that the nuclear professional community persisted in their belief in nuclear safety and assessed opinions as to who had given the opinion. Of course, it is not wise or fair to judge such a fault after its occurrence. In addition, it is a common practice for engineers to prioritize possible concerns according to their significance and solve them one by one. However, the order of the priority may have been biased and inappropriate from the standard of engineering practices.

In order to suppress the inward-looking nature, which comes from intrinsic characteristics of nuclear technology as described above, and then to minimize adverse effects from it, nuclear professionals should listen to opinions and criticisms from the outside, such as those from citizens and experts in other realms. Nuclear professionals need to respect these opinions and criticisms, and then reflect them in their work if needed. This is a kind of introspection function of the nuclear professional community so that adverse effects of nuclear technology characteristics to engineering itself can be minimized. To achieve this, mutual communication with those outside the nuclear professional communities, especially with experts in other fields, is important.

20.6.3 Trust

Frequent concern has been raised on issues of public trust on nuclear technology and the expert community. In the discussion of trust in science and technology and in the professional community in general, the decrease in trust of society and citizens is often emphasized. Possible reasons for the degradation of trust are anxiety of citizens about the closed expert community and disappointment due to that opinions of society not being reflected in the technology utilization and the governance of the professional community. Moreover, there is another point that we should not miss: not only is there public distrust toward technology, engineers, and their community, but also engineers' distrust toward society and citizens. There has been a structure of mutual distrust of each other.

Some engineers may claim that this is because some people and mass-media have irrationally criticized engineers and technology due to lack of knowledge and a biased standpoint. Indeed, there were a number of cases where the "deficient model" can explain the situation, although we should recognize the insufficiency of the "deficient model" in many cases. Engineers are also human beings after all, and thus painful experiences such as receiving irrational criticisms were deeply and subconsciously inscribed in their minds. In addition, it was transferred to younger generations via education and as culture.

Consequently, there are quite a few experts who believe that they have to promote nuclear energy utilization even without endorsement and appreciation from society, because they are convinced that nuclear energy is really needed. Some experts even ignore skepticism and criticism of citizens, relying on the own belief. However, it should be recognized that this attitude is quite inappropriate for professional engineers, and that this attitude further enlarges distrust, disappointment, and opposition of citizens toward the nuclear professional community.

The trust from the general public may facilitate the utilization of nuclear power plants, the site selection of radioactive the waste disposal facility, etc. However, if this is all that is intended, trust cannot be achieved in most cases. Rather, more importantly, public trust is essential for engineers to work positively and proactively. And such positive and proactive attitudes are essential for nuclear experts to deal with a high-risk technology, which the accident reports require that TEPCO and the regulatory body have. In this sense, "trust" can be replaced with "respect." A professional community which is not respected and is not appreciated for its outcome due to distrust and which distrusts the society which they should serve is not a professional community which proactively and continuously makes progress so as to increase the safety level. The degree of public trust is an index of the healthiness of the professional community. To heighten it, active mutual communication—in practice (1) understand public opinion, (2) come up with measures based on it, and (3) show the measures to the general public, and then (4) again listen to and understand public opinion—is important.

Legitimacy, introspection, and trust are inter-related. Being trusted/respected is needed to proactively work, which results in increase of legitimacy. However, due to the nature of nuclear technology, there is a driving force that makes the nuclear expert community inward-looking more than the other technology communities. Thus, an introspective attitude is needed to keep the community open and more active, which results in increase of trust and legitimacy. All of these three aspects may be underpinned by mutual communication with society including experts in other science and engineering fields.

20.7 Effective Communication

20.7.1 Communication with Society and the General Public

Even after recognizing the importance of mutual communication, it is not easy for nuclear engineers to understand and catch up with the general public that has different beliefs, preferences, cultural backgrounds, and often negative views on nuclear technologies. Nuclear technology has an intrinsic complexity regarding social context; and agreement/disagreement on the technology itself may become a topic of dialogue.

Public opinions are also complex. They cannot be understood by asking simple questions, such as “Do you support nuclear power utilization?” We nuclear engineers should not readily think that we can draw out these opinions ourselves. There should be experts who can analyze the raw data from opinion polls and interpret them in societal and historical contexts. Such experts are expected to indicate what people’s desires and concerns are so that nuclear engineers can utilize the findings in developing their technology.

To realize this, engineers should acknowledge public opinion and have basic knowledge of social sciences, which is not the case in the current situation, so that they can adequately communicate with experts in these fields. I recognize that this is the central motivation for considering nuclear engineering education that highlights social-scientific literacy.

20.7.2 Communication with Experts in Other Fields

As nuclear engineering consists of systems engineering, there are many connections with other disciplines. It is advisable and natural to deepen the communication with other experts through such connections. In order to activate such communication and collaboration, nuclear engineering needs to be scientifically and technologically attractive. However, the level and quality within each sub-discipline field are not as high as those in its parent field, although a relatively large research budget has been funded for nuclear technology utilization and development. This could be due to lack of competition and openness. Indeed, pursuing scientific originality and frontier research are often incompatible with pursuing technology development specialized for nuclear engineering. Nevertheless, it is of crucial importance, especially for academia, to recover superiority in scientific originality in the nuclear engineering field, for activating competition and communication with other fields of science and engineering, which will ultimately help restore public trust.

20.8 Reform of Education

Most nuclear engineers are not ready to carry out the communication methods described in Sect. 20.7 at present. In addition, the Fukushima Daiichi accident indicated that even natural-scientific and technological standards of nuclear professionals are not adequately high. To improve the situation, nuclear engineering education needs to be reformed. I here propose the following 4 reform items.

20.8.1 Standardization and Internationalization

Even if social aspects are essential and need to be taught to nuclear engineers, natural-scientific and technological knowledge and disciplines are always the core of nuclear engineering. Without a high standard of these, nuclear safety cannot be ensured, social legitimacy and trust will never be achieved, and mutual communication and collaboration with experts in other fields cannot be activated. To make fulfilling a high standard of technological expertise and cultivating social-scientific literacy compatible in nuclear engineering education, the thoroughness and the effectiveness of education on the core technological expertise must be adequately heightened.

The core technological expertise includes reactor physics, radiochemistry, fluid dynamics, materials engineering, nuclear fuel cycle engineering, etc. Although these contents are taught as mandatory subjects in most universities, each subject may not necessarily be well optimized for each university. For example, when I teach materials science related to nuclear materials, even if I am careful, the contents are biased by my expertise and converged around my specific expertise. If the contents are common basics and the core for experts, they should not be too biased by the expertise of the lecturer but be more generalized and normalized so that nuclear professionals can share fundamental expertise independent of universities and nations where they have received their education. As an increasing number of countries plan nuclear power plant construction, developing and sharing standardized course materials is also beneficial to maintain the quality of nuclear professionals all over the world.

20.8.2 Transparency and Sharing

In addition to the core contents, advanced and applied contents are important. In this aspect, the feature of each university should emerge. In these contents, a variety of expertise and knowledge should be maintained. Some contents which let students experience trials and errors may be intentionally involved. Here, the most important point is to clearly show its pedagogical meaning to students, experts inside and outside the community, and to society. There are 3 reasons to do so.

1. Society can see what the nuclear professional community aims at in education. The curriculum is a kind of design sheet on how to nurture professionals. To show the design sheet is a social responsibility of the university. Responding to this accountability also helps to make the purpose of education clearer. It is also effective to increase the transparency of the expert community and then increase trustworthiness and introspection.
2. Each university can see the educational resources of other universities. As scientific disciplines involved in nuclear engineering are vast, it is difficult for one university department to sufficiently cover all the necessary subjects. If the educational resources are open to other universities, it would foster collaboration.
3. Universities can mutually monitor the status of other universities' (and thus other countries') education. Also experts in other fields can check the educational conditions. The Fukushima Daiichi accident re-confirmed to us that the consequences of nuclear technology including accidents are intrinsically international. Knowing about the situation of other universities would spur us to work hard together with each other, and also would function as introspection. This is also a responsibility to nuclear experts in other countries as well as to the public in other countries.

20.8.3 Social-Scientific Literacy Education

The importance of understanding the opinion of society was described in above sections. For to-be-experts, they first need to realize this importance as their own feeling and then recognize that its consideration and reflection are highly important to safely utilize nuclear reactors and to advance nuclear engineering. Then, they need to cultivate social-scientific literacy through education about engineering ethics, philosophy of science, history of science, science and technology and society (STS), social psychology, politics, economics, organizational theory, cultural theory, etc. As a result, the ability to collaborate with experts in social sciences as well as communicators to engage citizens can be fostered. To my knowledge, most nuclear engineering curriculums only include some of these subjects in a piecemeal fashion. There is no consensus which contents are more relevant and important for engineers.

Personally, I believe education on nuclear history is effective. This must involve not only positive history such as how nuclear R&D succeeded and technologies were developed, but also negative history such as failures in R&D, scandals, accidents, and how mutual distrust between society and engineers have come about. As mentioned above, nuclear technology has some unique features that other technologies do not usually have. Studying and knowing history also reminds us of this nature of nuclear technology.

In education of social aspects, international collaboration is also important. On societal issues in the community or in the society where one belongs, it is hard to be fully objective: sometimes one becomes too critical or too defensive. If the issues are of other nations, one can be more objective and keep an appropriate distance from the issue. For example, if international collaboration is made on nuclear history education, students would discover similarities and differences in these histories, and can find that many countries follow the mistakes of advanced countries. Whether good cases or bad cases, histories and situations of other countries teach a lot.

20.8.4 Faculty Development and Evaluation

Most education reform attempts focus on evaluation of students: e.g., how many times students attended research conferences, what papers were published, etc. This is quality control at the exit of an educational system. We should pay more attention on the system itself, specifically evaluation of faculty and facilities.

While the speed of social advancement/change has been increasing, the work period of an engineer has been extending. Even for nuclear engineering whose development speed has become relatively slow, technologies are largely renewed within the work period of an engineer. To construct an effective education system, it is imperative for the faculty, especially senior faculty, to put themselves in the forefront, update their knowledge, and continuously learn. Such activities by faculty should be systematically supported by the university. When all faculty members have such an attitude and update their knowledge as well as their views on the role and position of nuclear technology in society, the accumulation of these knowledge and views would form the basis of an appropriate education system.

Regarding evaluation of faculty, it should not be so straightforward and simple. Although some outsiders should be involved in the evaluation, it cannot be done mainly by outsiders. As the complexity of technology increases, indeed due to that, the importance of experts and their knowledge is more keenly highlighted, particularly in the case of balancing and managing multiple different disciplines relevant to technology utilization. Hence, it is better that the details of faculty development support and faculty evaluation criteria are discussed and determined primarily by the nuclear engineering department at each university and then shown to society and experts in other fields so as to reflect outsiders' viewpoints. In the discussion, the aforementioned 3 viewpoints, i.e., standardization and internationalization, transparency and sharing, and social-scientific literacy education, should be considered.

20.9 Concluding Remarks

This chapter was devoted to nuclear engineering education for the post-Fukushima Daiichi accident era. Prior to education itself, the knowledge and attitudes required of nuclear engineers were discussed with focus on the social aspects of nuclear technology.

First of all, we should clearly recognize that nuclear technology has some intrinsic differences from general technologies, which come from its relation to weapon technology, potential risks of reactor accidents, long-lasting radioactivity of spent fuel, etc. Most of these features require government commitment. Thus, in most countries, nuclear technology has not achieved much social legitimacy, which makes the social context of nuclear technology complex. Consequently, we nuclear engineers are required to communicate with society more thoroughly and more openly than engineers in other technologies. One may feel that this additional requirement for nuclear technology is "unfair," but we should realize it is an essential characteristic of nuclear technology.

To achieve social legitimacy, mutual communication with society, which includes communication not only with the general public but also with experts in other fields, seems vital. In addition to social legitimacy, it is hoped that mutual communication will foster an introspective attitude in the professional community and will help nuclear technology and the professional community regain public trust. It must be clearly understood that these points are not only needed for smooth utilization of nuclear technology, but also, and more importantly, for enhancing the safety of nuclear technology utilization and advancing nuclear technology to provide more benefits and welfare for society.

Finally, I proposed 4 items for education reform, which are mainly designed to make mutual communication with society more effective while maintaining a high level of technical expertise: standardization and internationalization, transparency and sharing, social-scientific literacy education, and development and evaluation of faculty. These ideas are not necessarily concrete, and may be nothing new. Most universities may already have taken some actions to materialize these ideas. However, what they are doing now is mostly insufficient to fully realize its purpose. If they just think it is needed to do so formally or to make their departments look better to attract the next generation, its aim may have been achieved. However, if the purpose is to acquire social legitimacy, to cultivate an introspective attitude in our community, and to gain trust for nuclear technology and the nuclear professional community, the contents are far from satisfactory and thus should be redesigned and then reconstructed.

Most engineers have been deeply involved in responding to the Fukushima Daiichi accident for the last 3 years. Now should be the time to deeply consider what kind of professionals we want to be and what nuclear engineering education should do to achieve it. I hope that this chapter will stimulate discussion in the nuclear professional community and draw more attention to nuclear engineering education on the part of the general public and experts in other fields.

References

1. Japan Society for the Promotion of Science (2010) Global COE program. https://www.jsps.go.jp/j-globalcoe. Accessed 1 Jun 2014
2. Department of Nuclear Engineering and Management, The University of Tokyo (2012) Final report on Global COE of Nuclear Education and Research Initiative: The University of Tokyo (2007) Global COE program on Nuclear Education and Research Initiative. http://www.n.t.u-tokyo.ac.jp/gcoe/eng/program/index.html. Accessed 1 Jun 2014
3. Tokyo Institute of Technology (2008) Ex-post evaluation report on innovative nuclear energy systems for sustainable development of the world. http://www.jsps.go.jp/j-21coe/08_jigo/index.html. Accessed 1 Jun 2014
4. Kobayashi T (2007) The age of trans-science. NTT publishing, Tokyo
5. Wynne B (1992) Misunderstood misunderstandings social identities and public uptake of science. Public Understanding of Science: 281–304
6. Matravers W, Bridgeman J, Ferguson-Smith M (2000) The BSE inquiry: The report. http://webarchive.nationalarchives.gov.uk/20060715141954/http://bseinquiry.gov.uk/index.htm. Accessed 1 Jun 2014
7. The University of Tokyo (2005) Science interpreter training program. http://science-interpreter.c.u-tokyo.ac.jp. Accessed 1 Jun 2014
8. Japan Atomic Energy Commission (2000) Round-table conference on nuclear power policy. http://www.aec.go.jp/jicst/NC/iinkai/entaku/H11/index.html. Accessed 1 Jun 2014
9. Kasei K (2011) A consideration on round-table conference on nuclear power policy. Social Design Studies for 21st Century 10: 63-72
10. Social and Environmental Division, Atomic Energy Society of Japan (2014) Prospectus. http://www.aesj.or.jp/~sed. Accessed 1 Jun 2014; Atomic Energy Society of Japan (2014) About us. http://www.aesj.or.jp/en/about_us/divisions.shtml#subcomittees. Accessed 1 Jun 2014
11. Yoshioka H (2012) A social history of science and technology in contemporary Japan (new edition). Asahi Shimbun Publications Inc., Tokyo
12. Independent Investigation Commission on the Fukushima Nuclear Accident (2014) The Fukushima Daiichi Nuclear Power Station disaster: Investigating the myth and reality. Routledge, London
13. The National Diet of Japan Fukushima Nuclear Accident Independent Investigation Commission (2012) Final report. http://warp.da.ndl.go.jp/info:ndljp/pid/3856371/naiic.go.jp/en. Accessed 1 Jun 2014
14. Investigation Committee on the Accident at the Fukushima Nuclear Power Stations of Tokyo Electric Power Company (2012) Final report. http://www.cas.go.jp/jp/seisaku/icanps/eng. Accessed 1 Jun 2014

Part V
Education in Future

Chapter 21
Engineers, Social Scientists, and Nuclear Power

A Narrative from Within

Cathryn Carson

Abstract The PAGES collaboration (University of Tokyo and University of California, Berkeley) brought together nuclear engineers and social scientists to try out new ways of engaging engineering graduate students with societal issues around nuclear power. The program was built around seminars and summer schools. Because of the Fukushima Daiichi disaster, it ended up culminating in a weeklong program for students in summer 2011 to examine the Fukushima Daiichi accident as a socio-technical catastrophe and an invitation to rethink nuclear engineers' possible roles in a post-Fukushima world. This chapter reflects on the PAGES collaboration and the Fukushima Daiichi summer school from the perspective of one of the social scientists involved. It narrates the experience of collaborating across disciplinary boundaries at a moment of challenge and in a space where social science is not well anchored to start. Out of this narrative, the chapter aims to draw some potentially generalizable suggestions for social scientists who are trying to engage engineers and graduate students, given the constraints of time, attention, and trust.

Keywords Nuclear engineering · Social science · Methodology · Collaboration · Engineering education · Graduate education · Nuclear waste management · Fukushima Daiichi nuclear accident

21.1 Introduction

This book is the product of an exchange between nuclear engineers and social scientists, one that has been productive and unsettling for all of us involved. Like many productive encounters, it came about somewhat by chance—a set of

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contingencies, relationships, and openings that shifted shape as they unfolded. Like many unsettling processes, the participants went into it with a mixture of attraction and wariness, unclear how we would be defining our roles. I have been involved in the collaboration called Program for Advanced Graduate Education System for Nuclear Science and Engineering with Social Scientific Literacy (PAGES) in a looping fashion, moving in and out of phases of more intense engagement as PAGES's own dynamic evolved. As other chapters in this book explain, that collaboration had been underway for several years when the Fukushima Daiichi disaster turned our heads around.

As a historian and social scientist, I came into the collaboration with a set of internal questions: Where are the openings for social scientists to be part of nuclear engineering graduate education? What could social science literacy for nuclear engineering students even mean? Are there ways to bring social science to bear that do not simply instrumentalize it as another tool in a toolkit? The PAGES effort became an exercise in trying out answers to these questions. In my own sense of things, it proceeded with a deep curiosity about how to think about the problem systematically, yet in what I have come to think of as an engineer's fashion: testing out several things with more or less theoretical justification, seeing what worked and learning from what failed.[1]

At the end of the process, my conclusion is threefold:

- It does not work to come at this challenge by lecturing on the great insights and results from the social sciences that ignorant engineers need to be taught. Engineers are social analysts, too—more or less observant and savvy, depending on personality and experience, but sometimes incredibly astute in their own professionally conditioned way. That shift of perspective is, for me, a key piece of reflexivity. If their expertise is constructed, then mine is as well, a recognition that has led me to be more explicit about explaining where my own disciplinary strategies come from.
- If social scientists choose to try to be useful to engineering students, it works better to start with them where they are, with their own observations, puzzlement, and questions, and then see where those connect with social science analyses. This at least starts the process. Having a crisis to work with can help. The challenge is to get far enough down the road that "social science" has some actual bite. Otherwise it just comes across as an invitation to soft-focus reflections on pre-formulated dilemmas that engineers already believed they could tackle with their own informal theories about how the social world works.
- Then the biggest open question for me is how to crystallize what social science has to offer. There is a ready tendency to reduce it to its subject matter: generically, engineers understand "social science" to be about "society," conceived in flat terms as this thing other than the engineering they do. But social scientific inquiry is defined not just by subject matter, but by methods. Thinking

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[1] Downey [1] and Sørensen [2] have been critical touchstones.

> like a social scientist means not just knowing stuff about society, but asking particular kinds of questions using distinctive concepts and analytical strategies. Conveying these in short educational interventions is hard.

The PAGES experiment, and especially the 2011 summer school around the Fukushima Daiichi disaster, was most satisfying when it was able to build on students' preexisting dilemmas, addressing questions they did not have answers to and using language they spoke. This is an approach that is educational in a sense of the word that is only somewhat in tune with contemporary understandings within nuclear engineering.[2] In nuclear engineering, education within classroom settings is still largely a matter of one-way conveyal of preselected information, a model of communication that also governs the nuclear community's interactions with the public. One of the main contributions that social scientists made to the PAGES program, in fact, was to simultaneously pry open the concepts of communication and nuclear engineering education, particularly students' agency within it.

Any engagement of social scientists with engineers (at least as social scientists analyze it) is structured by differentials of power. But those differentials are not always the obvious ones. They can be modulated through personal connections, and for us they shifted across the boundary of the Fukushima Daiichi disaster. My aim in this chapter is to offer some reflections on that experience from the perspective of a participant whose professional trajectory has been profoundly shaped by it—but whose professional position does not require particular canons of presentation (starting from technical facts, downplaying confusion or conflict). At the same time as my reflections make a move of deliberate abstraction, they are structured by an admiration for my colleagues' intellectual and personal honesty that I hope can shine through.

21.2 Paths into the Project

My own training is as a historian of science and technology; my intellectual affiliations bring me into the arena of science and technology studies (STS). For scholars who share this training and mindset, the rise of nuclear power is part of a standard historical narrative of the scientization of twentieth-century life, as a new class of technical experts emerged around the conjunction of nuclear energy, both civil and military, with the post-World War II state. Some of the concepts we use for making sense of the nuclear present include the traces of a top-down policy regime structured by decide-announce-defend (DAD) rather than deliberative engagement, legacies of public distrust of nuclear institutions and spokespersons, and a strong sense of a historical alliance between the state and the nuclear industry in countries around the world. These are not always concepts whose

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[2] See especially Sunderland [3] and Oda [4].

articulation is welcomed by inhabitants of the nuclear world, at least not in the way that social scientists who live outside of that world have chosen to do it. In working within GoNERI, it was important to acknowledge that mismatch, for instance, by pointing to scholarship (books) that had shaped my work that nuclear engineers would probably never read (Fig. 21.1).

I am consciously neither pro-nuclear nor anti-nuclear; my preference is to work on topics about which I am profoundly ambivalent. In the background is a long-term fascination that I myself do not totally understand with nuclear power and the nuclear industry, a engagement anchored a childhood that included excursions to nuclear power plant visitor centers (back when those were easy to get into) and a high-school trip to learn about the Three Mile Island cleanup at first hand (I still have a t-shirt with the plant systems diagrammed on the front). For better or worse, that early technical fascination with systems and accidents gave me an unusually refined knowledge, at least for a historian, of PWRs and BWRs and LOCAs and accident sequences and other such things. It was that exposure, combined with the training I had in physics, that played into my comfort with tackling a long-term project of historical research on the intellectual technologies of risk assessment in nuclear waste management. Formalized risk analysis is a great topic for historically minded social science, given the way it alternately rationalizes and repudiates living experiences of being at risk.

Fig. 21.1 Slide of background literature, late 2008. (*Top row* [5–8]; *Bottom row* [9–12])

In the context of that project on radwaste and risk, I came to know my colleagues in the Berkeley department of nuclear engineering over the span of a decade and more. In 2006–2007 I was lucky enough to take a year off from my own teaching and attend graduate and undergraduate classes in the Berkeley NE department, with a focus on nuclear waste management (and thus the greatest number of classes with my co-editor, Joonhong Ahn). Along with the technical material, I was learning the ways of thinking and modes of analysis that create knowledge in this domain, sitting with the students in classrooms and seminar rooms as they took in the professional cues and formation that made them into nuclear engineers. It was this curiosity that made it interesting to agree when my faculty colleagues invited me to participate in an early 2008 workshop of the Global Center of Excellence program called "Nuclear Education and Research Initiative" (GoNERI) that bridged recently initiated efforts (in 2007) at the University of Tokyo to a local Berkeley base.

21.3 Searching for Fit

The topic of this GoNERI meeting on January 6–8, 2008, was "Nuclear Technology and Society—Needs for Next Generation." A historian who has spent time among engineers has expectations about how these meetings unfold. There are ceremonies and speeches expressing aspirations to serve society with advances in technology.[3] There are lots of technical talks from professors and other high-status people, supported by powerpoint slides. In this case the meeting's technical agenda was overlaid with an emphasis on international collaboration and a getting-to-know-you-better function between engineers from Berkeley and Tokyo. Because of the formalities of sponsorship by the Japanese authorities, there was a significant effort at documentation; the proceedings of the workshop were prepared and ran to nearly 400 pages [13].

In meetings such as these, historians often get slotted to provide a historical perspective, or to generally speak about nuclear power and society. The nuclear community has long-established ways of thinking about society, which can be pretty well captured in a schema like Fig. 21.2.

This was in fact the first slide from my GoNERI talk. It was a move of abstraction, using the license afforded by distance to speak in a direct voice. The second slide (Fig. 21.3) got a bit more theoretical.

I was hoping to bring something foundational into view. Even when engineers are savvy operators, they often work from folk theories of society: familiar framings of societal processes and social order that live within a structure of their professionally reinforced ways of understanding their experience [14, 15]. Without pointing this out this openly, was there any hope of making the case for something else? In my first try at speaking in this setting, what came next was too abstract

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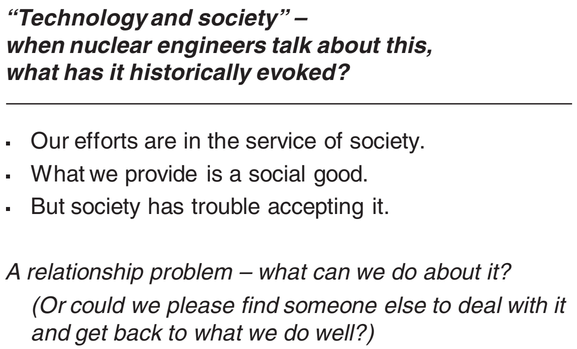
[3] There is no irony or sarcasm in my voice here or elsewhere in this chapter.

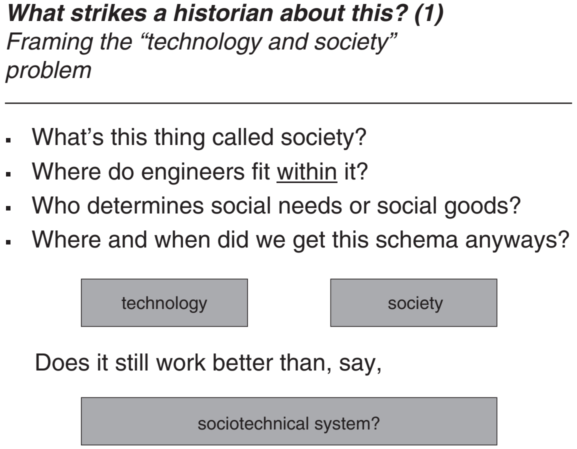


***"Technology and society" –
when nuclear engineers talk about this,
what has it historically evoked?***

- Our efforts are in the service of society.
- What we provide is a social good.
- But society has trouble accepting it.

A relationship problem – what can we do about it?
(Or could we please find someone else to deal with it and get back to what we do well?)

Fig. 21.2 Slide 1, early 2008. *Source* Cathryn Carson, UC Berkeley, 7 January 2008. Workshop on "nuclear technology and society—needs for next generation." © Cathryn Carson 2008



What strikes a historian about this? (1)
Framing the "technology and society" problem

- What's this thing called society?
- Where do engineers fit within it?
- Who determines social needs or social goods?
- Where and when did we get this schema anyways?

Does it still work better than, say,

Fig. 21.3 Slide 2, early 2008. *Source* Cathryn Carson, UC Berkeley, 7 January 2008. Workshop on "nuclear technology and society—needs for next generation." © Cathryn Carson 2008

and theorized. Engineers can be polite when they are being presented with things that don't really speak to them. I am still left with the puzzle: Why is it the case that concepts that to me feel so powerful for grasping the world (e.g., sociotechnical system) fail to capture the experience of the people actually living that life?

On the other hand, it was interesting to see where the direct language of opening gambit resonated. And the move to situate the speaker (myself) within a particular disciplinary tradition seems to have been both interesting and curious. The notions of perspective and subject position are fundamental to the way I do my research, but these seemed so disablingly relativistic to non-social scientists that they did not quite believe I wanted to play them up.

Over the next years, as the GoNERI team pulled me in, we all grappled with different ways to connect social science with questions that nuclear engineers and their students found worth engaging. One entry point was a focus within PAGES on societal issues around nuclear waste management, a specificity that was more manageable than the whole narrative of nuclear power, even as it could be backed up against that larger history for context. In general, if social scientists hope to provide more in engineering education than the cultural patina of "breadth," specificity feels like the way to go. In seminars and discussions I tried presenting substantive historical episodes that I found instructive for my own thinking—stories from my radwaste research about the negotiated processes that created the present set of (sometimes arbitrary-feeling) regulatory specifications, the partly contingent paths by which current technically favored approaches came to the fore, past disposal concepts that in their day had wide acceptance but now looked startlingly simple-minded, or the history of the US radwaste program's attempt to engage social scientists in what was framed at least from the 1970s forward as a social as much as a technical problem. Thinking through cases is my bread and butter as a historian. However, I never sensed that anything I said about specific historical examples stuck with my listeners. At most, the concreteness of the cases was an occasion to build credibility by displaying a decent mastery of radwaste language and facts.[4] A related strategy had even less uptake: working through comparison cases in order to suggest generalizations. We were supposed to be talking about nuclear engineering, so lessons from, say, nanotechnology did not feel relevant to my partners—though the comparison cases profoundly shaped my own ways of analyzing societal dynamics around nuclear power [14, 17].

Another strategy was foregrounding methodology, highlighting the different ways to get one's head around a question. One big goal here was just to make visible that there *are* different ways to analyze the world: questions it makes sense to ask, strategies to delimit a researchable problem, research approaches and tools to use, ways of talking and arguing that govern how we analyze and discuss. Then part of the value of social science is just that it tackles things differently from engineering, and that has a reflexive payoff—the insistence that there is not some single univocal understanding of a situation, one that (in our students' case) engineering analysis delivers. In that sense, the point was to underline that there are sightlines that engineering does not provide on its own. A more refined goal was to name and experiment with particular social scientific methodologies, since social science is not a univocal thing either. In PAGES we did a fair amount of naming, but only a little bit of experimenting, which was a source of disappointment if one sees value in learning by doing.

I would have liked to create more space to try out scenarios, simulations, and encounters with real participants, creating practical experience that analytical approaches could be set to work on. Some of that work was done by PAGES collaborators, as mentioned elsewhere in this volume. For the students I staged one example as an exercise in one of the summer schools [18], and, judging by the short-term discussion, it made some impression. The exercise took students through a puzzle: What would be the right way to clean up the Asse II Research Mine in Germany? Asse II was a former salt mine where the "testing" of methods

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[4] I relate this to interactional expertise as in Collins and Evans [16].

for of low- and mid-level radioactive waste in the 1960s and 1970s had set the scene for a massive conflict thirty years later, once it was revealed that the mine (assumed perfectly dry) was actually subject to water entry, with radioactivity now accumulating in brine pools, and structurally unstable to boot [19]. Specifically, the students were asked: what questions would an engineer need to get answers to in order to decide what should be done? A non-linear powerpoint deck let us explore student questions in the order they brought them up, starting with the geology and technical parameters, then taking up the local setting, the national context, and the path-dependencies of the history and the institutional and regulatory environment. In the end, the conclusion may have been there was no single right answer for what to do next, a notion that was very comfortable for social scientists, but felt troublesome for nuclear engineers.

Some of these messages and approaches felt incredibly simple, so much so that I was afraid I was being patronizing. But still they resonated with some subset of engineering students and colleagues: staking out a subject position as an analyst, listening for an interlocutor's concerns without going immediately to judge whether they were rational (i.e., technically correct), applying social science analysis to oneself and not just to "the other" (e.g., the public). In practice, this way of working meant presenting social science (itself already a broad and diverse thing) as a set of tools and techniques for tackling a problem, which was an engineering framing itself. Probably for obvious reasons, the tools of social science that seemed most comfortable for engineers to make recourse to have come from economics, along with simplified versions of political science for national policymaking and international relations. Approaches from anthropology, sociology, and history were harder to make stick.

The format, too, was constrained. Any educational changes we tried were likely to sit outside the regular graduate curriculum for now, at least on the Berkeley side. For interpretive social science we could experiment with voluntary seminars and optional summer schools. What was understood to have a place in regular graduate training was, again, those parts of economics and political science/IR that were already appropriated and built in. There are institutional and professional structures that enforce this division of competencies. In addition, across the engineering curriculum here, both graduate and undergraduate, there is a reluctance to have engineering students officially taught by anyone other than engineers.[5]

21.4 Voice, Tone, Trust, and Power

And yet there was real sincerity in the formulation of social scientific goals within GoNERI. The engineers who were involved put this on record early on. Out of their own experience and initial contacts, they felt that they needed to collaborate

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[5] Sunderland et al. [20] on Berkeley, more generally Besterfeld-Sacre et al. [21], Christensen and Ernø-Kjølhede [22].

with social scientists, and in order to do that, they needed to understand the social sciences better—their domain, concepts, terminology, and methods. This would mean going beyond the standard nuclear engineers' view (as my colleague Joonhong Ahn described it at one point) that what was needed was better ways of getting societal acceptance of nuclear energy. Instead it would take actually understanding societal structures and processes and listening to the public in order to develop engineering options (note the plural) to explore in some kind of societal partnership. The framing of social scientific literacy, as I understand it, was intended to point to a foundational kind of learning that engineers were willing to take on.[6]

This openness was encouraging against the backdrop of the history of the nuclear community's engagement with social science, which has often been marked by selective listening and instrumentalization, using social scientific techniques in the service of affirming an existing agenda or calling in outside analysts and then doing nothing with their work.[7] What made it plausible to speak plainly within the PAGES project was trust—my confidence in my Berkeley colleague and others he invited in, his openness to the social scientists on the Tokyo side, and our shared willingness to try out controversial ideas on each other. In a strange way, the last of these was facilitated by the language barrier. It was possible to get away with framing things sharply and then apologizing when I could be the bull-in-a-china-shop American, at least by Japanese standards. My understanding is that my Japanese colleagues spoke fairly directly with each other, but that voice rarely surfaced in formal written materials, at least until the present book. Part of the trust also came out of working and traveling (and drinking) together on site visits, including the Waste Isolation Pilot Plant in Carlsbad, NM, and the Swedish interim storage facility, Clab, near Oskarshamn. The challenge was then taking this shared basis for communication and putting it to work for others who were not in the same boat.

This was especially challenging in our summer schools, where other nuclear-world experts were invited into say things that sometimes felt far too simple. And without wanting to reinscribe all social scientists as critics, it felt important to get a critical position in view. That meant finding ways to speak within a polarized nuclear scene where social science is a pretty low-status, half-formalized thing. There were times when my language reflected real frustration—frustration of my own, and that of decades of social scientists before me. Within the PAGES project we had discussions about "nuclear socio-engineering," something that some of our colleagues thought we should be doing in order to generate trust and public

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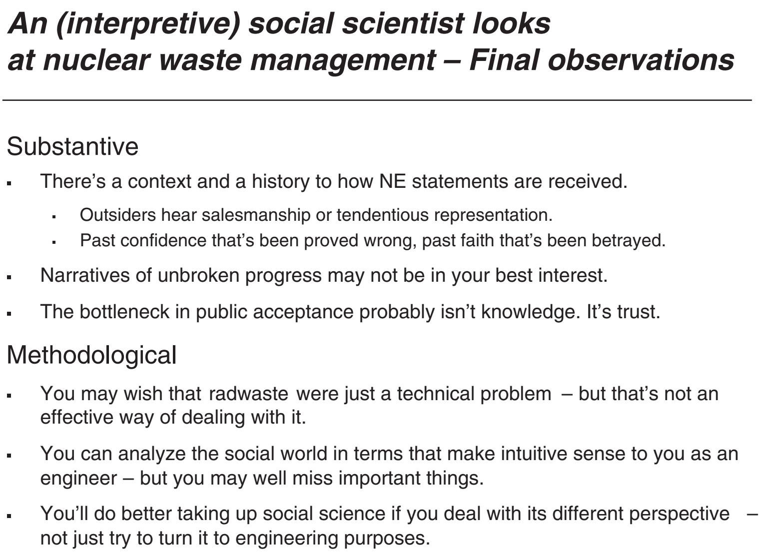
[6] On cross-disciplinary collaboration in engineering education see Borrego and Newswander 2008 [23]. As much as my own instinct is to dig into the "literacy" framing, I took it as a zeroth-order approximation I could work with. It did significant work for the team that pulled together the GoNERI social scientific component before I was involved.

[7] Years of discussions with Gene Rochlin and Todd LaPorte made this point clear to me. For Japanese reflections see Oda 2014 in this volume [4].

acceptance for the nuclear field. The concluding slides of my presentations—everything always has to be presented in powerpoint—sometimes marched through a set of sharply phrased bullets, seeing how far I could exploit my license to speak.

This *was* an effective way to make certain points. When I used this slide (Fig. 21.4), it kept the NE graduate students and postdocs in the room for several hours. Some of the above bullets showed up in other PAGES participants' powerpoints later, attributed to this presentation I gave. The move to frame things aggressively worked, I am guessing, because within the PAGES group and some parts of the Berkeley NE community there was already a basis for trust, so that I was something more than a frustrated outsider expressing critical views.

And on the public side, it was instructive when my frustration met others'. The 2009 summer school focused on "Radioactive Waste Disposal with Social-Scientific Literacy" [25]. It came just months after the US Department of Energy announced its intention to terminate the Yucca Mountain nuclear waste repository project. The radwaste community was raw with frustration about what was seen as irrational, emotion-driven political interference with good technical work. The tone filtered in and out of a packed program of lectures—rarely in the powerpoints, sometimes in the Q&A, everywhere in conversations in hallways, break times, and meals. It felt like one way to address it, without getting it aimed at myself, was to use a spot in the closing panel to reflect "ethnographically." (I should acknowledge that while I draw on and learn from ethnographic methods in science and technology studies, I am not formally trained in them and put the word in quotation marks out of respect for those who are).



An (interpretive) social scientist looks at nuclear waste management – Final observations

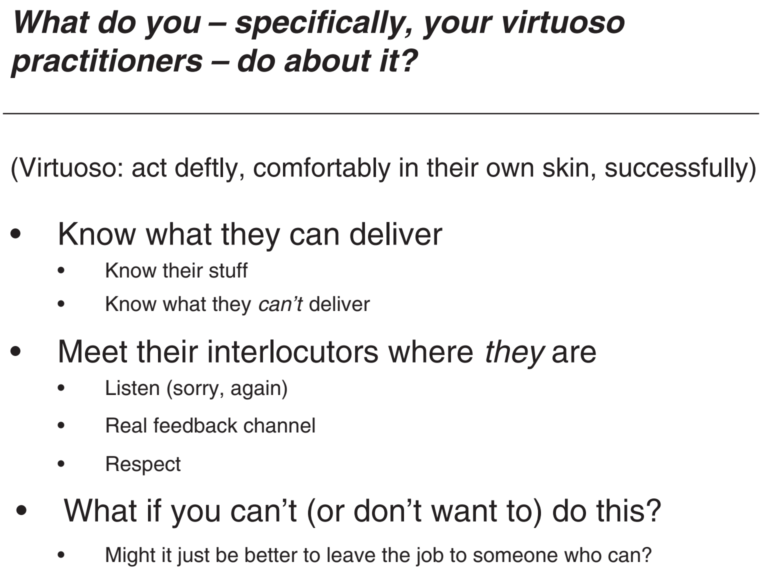
Substantive

- There's a context and a history to how NE statements are received.
    - Outsiders hear salesmanship or tendentious representation.
    - Past confidence that's been proved wrong, past faith that's been betrayed.
- Narratives of unbroken progress may not be in your best interest.
- The bottleneck in public acceptance probably isn't knowledge. It's trust.

Methodological

- You may wish that radwaste were just a technical problem – but that's not an effective way of dealing with it.
- You can analyze the social world in terms that make intuitive sense to you as an engineer – but you may well miss important things.
- You'll do better taking up social science if you deal with its different perspective – not just try to turn it to engineering purposes.

Fig. 21.4 A concluding slide, late 2008 [24]



What do you – specifically, your virtuoso practitioners – do about it?

(Virtuoso: act deftly, comfortably in their own skin, successfully)

- Know what they can deliver
  - Know their stuff
  - Know what they *can't* deliver
- Meet their interlocutors where *they* are
  - Listen (sorry, again)
  - Real feedback channel
  - Respect
- What if you can't (or don't want to) do this?
  - Might it just be better to leave the job to someone who can?

Fig. 21.5 A concluding slide, 2009 PAGES summer school

Struggling hard to be constructive, I ended up with this slide (Fig. 21.5) about (generic) nuclear situations where relations between those two supposedly different things, technology and society, seemed so profoundly frayed.

Actually, the final, cranky bullet point was left undisplayed. It was better to have held it back. The most instructive thing about the summer school was a quiet remark by Joonhong Ahn pointing out that nuclear engineers often feel powerless vis-à-vis societal forces. I had been assuming that social scientists were the only powerless ones.

In truth, much social science scholarship on things nuclear is voiced as critique from below. That is justified in so many ways. At the same time it constrains the repertoire by reinscribing a polarization that blocks other kinds of engagement. Kohta Juraku, one of the core social scientists in PAGES, kept prodding us to try another way: start from the shared value of doing better for the public, de-privilege all participants' contributions, and stop making immediate recourse to the move of critique.[8] Even when this felt impossibly sunny, the reminder was useful. There is a kind of second-order complacency in a lot of critical social science—the world is what it is and will not be practically changed by our work until our views are recognized as right. In PAGES we were grappling with ways to jar that complacency. Ultimately it was jarred from the outside.

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[8] Developing this point in both directions, see Juraku [26].

21.5 After the Accident

The Great East Japan earthquake, the tsunami that followed, and the Fukushima Daiichi nuclear accident crossed with our planning for the 2011 radwaste summer school. Initially projecting a meeting in Sweden, our organizing committee was drafting background materials on Thursday evening, March 10, Berkeley time, when one of the Berkeley-based PAGES collaborators emailed with worries about the effects of the shaking in Japan. The next morning, on Friday, we were transfixed by the devastation left behind by the tsunami. Over the weekend, the threat to the Fukushima Daiichi reactors began to come into focus—station blackout, emergency cooling with seawater, hydrogen explosions, indications of at least a partial core melt, external radiation levels far above normal. By Monday, March 14, in the offices and seminar rooms of the nuclear engineering department there was no doubt there was a disaster unfolding. The question was scale. As word came in via websites and even emails of steam explosions and spent fuel pools, the sense in Etcheverry Hall was of an open future potentially spiraling out of control.

Someday I will write down my narrative of a social scientist camped out for long days and late nights among the nuclear engineers that week. It was a pivotal experience of my professional life. The reflections relevant to PAGES center directly on the NE graduate students: their questions about how to speak to their friends and their families, their unrest about the tone of the American Nuclear Society's press statements, their admiration for Joonhong Ahn's counsel of approaching the challenge with—his words—listening and humility. There was a sense among some of the students that this moment would mark a "before" and "after" in their careers, defining them as agents who would choose where to follow their teachers and where to chart their own course.

Already on March 14 we were revising the plan for the 2011 summer school. We were shaken enough that we could not do anything else. The school was relocated to Berkeley and refocused around the Fukushima Daiichi accident. The new topic, in all honesty, was the easy part. The hard part was grappling with what it could mean to meet the students where they were, as independent agents with their own concerns.

In my own teaching, I work in the space between my students' subject positions and the drive to produce intersubjectively compelling accounts. I start from behavioral science literature that indicates real payoffs from having students write down first-person goals and set intentions for themselves. Using "I" in engineering seems to be basically forbidden, however. So is using direct language, at least most of the time. As summer school organizers, we found our way to put a full-page essay question on the application form:

> Outline your current thinking about the Fukushima nuclear accident of March 11, 2011. Describe the issues you see it raising for nuclear engineering professionals and for societies pursuing nuclear power. Discuss what you see as the relevant background and fundamental causes of the accident.

This was abstract enough that it probably did not scare away too many students. And yet as straightforward as it was, to my ear it did not capture the sense of urgency I know we all felt. I still wonder what we would have gotten if we had openly asked for answers to other questions in our minds: Why do you want to come here? What do you want to get out of it? How do you think you will be changed?

21.6 Discussing the Fukushima Daiichi Catastrophe

Other chapters in this book convey the experience of planning and hosting the summer school. The week in August 2011 was eye-opening in so many ways. The students showed an unusual willingness to play along with an experiment that went against much of their previous training. Social scientists are used to deeply unresolvable problems; in fact, we often take pleasure (at least the academics among us) in societal complexity and the absence of a single right answer. Our summer school attendees remarked on their bewilderment: how to chart a course through the thicket of conflicting perspectives and options.

To my mind, the most compelling parts of the summer school were not about content—the lectures by experts, the formulation of problems to be tackled, or even the conclusions that the student teams articulated on the last day. What was most impressive was the process, how it all unfolded. The organizers and discussion leaders managed to make space for future engineers to speak analytically and non-defensively about the failures that led into the Fukushima Daiichi disaster. It was not out of line to talk about the "nuclear village"—and also to subject that concept to some pretty stringent critique. Some students found a voice to speak from their own experience in ways that I doubt they would have tried in a regular NE classroom. Several said that whatever the caveats attached to formal projections of risk, they had never believed that an accident of this sort could actually happen. And now that it had happened, it could happen again. It also took deliberate social engineering to make room for open-ended discussions. Along with turning off the video camera (documenting for the purpose of Japanese reporting to funders) and a no-powerpoint rule for final presentations, it made a difference that we were in a setting outside the classrooms in Etcheverry, in downtown Berkeley, near several bars.

It is tempting to live out of the inspiration of the summer school and to present it in the reporting language of demonstrated success. And yet I do not think of it as a straight-ahead model for future educational programs, at least not in this one-shot form. Asking the students to do little preparation, in a week of lectures and Q&A we could only get so far. When we made our way past the initial technical presentations to take up societal issues, it was not clear that social scientists were seen as having anything different to offer from engineers speaking in the same vein. And in the student discussions, inevitably, the content of "social science" was largely topical, without much sense of methodological challenge. Social science ended up being about its subject matter, society, rather than about ways of querying human behavior at a level above an individual's consciousness, analytically looking at institutions, structures, or patterns.[9]

I wish I had made more time and space to speak directly to questions about method. (My role in the week was as a co-organizer of the school and an intervener in discussion, but not a formal presenter, for once.) What I believe we actually accomplished in the summer school was learning how to start and structure these exchanges. My own sense is that their success (or not) will be seen off in the future, as the conversations we have started will continue to play out. Reflections in the wake of the summer school by our students and their postdoctoral mentors give me hope [4, 26–28].

21.7 Closing Observations

I have come out of the PAGES project with a more informed willingness to engage with engineering students, structured by a strong sense of the operational constraints. Really engaging the students successfully means starting with them where they are, iteratively exploring with them rather than lecturing at them—whatever the expectations that their own field sets about how education actually works. Exploring in this way is a challenge to do within the framework of their existing curriculum. At least, it is a challenge to do in a satisfactory way. More time and depth are needed to get past the flattening of social science to a set of recognizable tools or a body of largely pre-intuitable societal knowledge. We will need more, and longer-term, engagements if we want to get across its power as a set of alternative methodological strategies for getting a grip on the world.

The starting point for the PAGES collaboration was this realization: interdisciplinary collaboration is hard. That proved true all along the way. When it succeeded in PAGES, the outcome had much to do with trust, voice, and personal relationships. The only adequate way to close is with admiration for those colleagues and NE students and postdocs who made it possible for social scientists to engage with nuclear engineers.

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[9] For similar reflections see Sunderland 2014 in this volume [3].

References

1. Downey GL (2009) What is engineering studies for? Dominant practices and scalable scholarship. Eng Stud 1:55-76
2. Sørensen KH (2009) The role of social science in engineering. In: Gabbay DM, Thagard P, Woods J (eds) Handbook of the philosophy of science. Philosophy of technology and engineering sciences, vol 9. Elsevier, Amsterdam, pp 93-115
3. Sunderland ME (2014) Educating the post-Fukushima nuclear engineer. In: This volume, ch 18
4. Oda T (2014) Nuclear engineers for society. What education can do. In: This volume, ch 20
5. Amundson MA (2004) Yellowcake towns. Uranium mining communities in the American West. University Press of Colorado, Boulder
6. Gusterson H (1998) Nuclear rites. A weapons laboratory at the end of the Cold War. University of California Press, Berkeley
7. Wellock TR (1998) Critical masses. Opposition to nuclear power in California, 1958-1978. University of Wisconsin Press, Madison
8. Kuletz VL (1998) The tainted desert. Environmental and social ruin in the American West. Routledge, New York
9. Hamblin JD (2008) Poison in the well. Radioactive waste in the oceans at the dawn of the nuclear era. Rutgers University Press, New Brunswick, NJ
10. Masco J (2006) The nuclear borderlands. The Manhattan Project in post-Cold War New Mexico. Princeton University Press, Princeton
11. Perin C (2004) Shouldering risks. The culture of control in the nuclear power industry. Princeton University Press, Princeton
12. Ackland L (1999). Making a real killing. Rocky Flats and the nuclear West. University of New Mexico Press, Albuquerque
13. Nuclear Education and Research Initiative (2008) Proceedings of the joint international workshop nuclear technology and society—Needs for next generation, University of California, Berkeley, 6-9 Jan 2008, UCBNE-5113/GoNERI-0003, http://goneri.nuc.berkeley.edu/pubs/GoNERI0003-UCBNE5113.pdf. Accessed 11 April 2014
14. Rip A (2006) Folk theories of nanotechnologists. Science as culture 15:349-365
15. Rogoff B, Lave J (eds) (1984) Everyday cognition. Its development in social context. Harvard University Press, Cambridge, MA
16. Collins H, Evans R (2007) Rethinking expertise. University of Chicago Press, Chicago
17. Mody, CM (2008) The larger world of nano. Physics today, Oct 2008:38-44.
18. Organizing Committee (2010) 2010 Advanced summer school of radioactive waste disposal with social-scientific literacy (PAGES 2010). http://goneri.nuc.berkeley.edu/pages2010/index.html. Accessed 6 June 2014
19. Bundesamt für Strahlenschutz (2010) Optionenvergleich Asse. Fachliche Bewertung der Stilllegungsoptionen für die Schachtanlage Asse II. http://www.asse.bund.de/SharedDocs/StudienGutachten/2010/gutachten_optionenvergleich.html. Accessed 6 June 2014
20. Sunderland ME, Taebi B, Carson C, Kastenberg W (2014) Teaching global perspectives. Engineering ethics across international and academic borders. J Resp Innov, doi:10.1080/23299460.2014.922337
21. Besterfeld-Sacre M, Cox MF, Borrego M, Beddoes K, Zhu J (2014) Changing engineering education. Views of U.S. faculty, chairs, and deans. J Eng Ed 103:193-219
22. Christensen SH, Ernø-Kjølhede E (2012) Socio-technical integration in engineering education. A never-ending story. In: Christensen SH, Mitcham C, Li B, An Y (eds) Engineering, development and philosophy. Springer, Heidelberg:197-213
23. Borrego M, Newswander LK (2008) Characteristics of successful cross-disciplinary engineering education collaborations. J Eng Ed 97:123-134
24. Carson C (2008) A social science perspective on nuclear waste management. http://goneri.nuc.berkeley.edu/tokyo/2008-11-25_Carson.ppt. Accessed 6 June 2014

25. Organizing Committee (2009) 2009 Advanced Summer School of Radioactive Waste Disposal with Social-Scientific Literacy (PAGES). http://goneri.nuc.berkeley.edu/pages2009/index.html. Accessed 6 June 2014
26. Juraku K (2014) Towards more open-minded nuclear engineering. In: This volume, ch 22
27. Borrelli RA (2014). Reflections on developing an identity for the third generation nuclear engineer in the post-Fukushima society. In: This volume, ch 19
28. PAGES 2011 Students (2014) Students’ reflections. In: This volume, ch 17

Chapter 22
Towards More Open-Minded Nuclear Engineering

Diversity, Independence and Public Good

Kohta Juraku

Abstract The implication of the PAGES project especially in Japan's post-Fukushima context is examined in this chapter, summing up the arguments of sister chapters in Part IV at the same time. Social scientific literacy is not just an "additional" component for nuclear engineers. Rather, it is one of the most "essential" parts of engineering competences and practices. This point has not been fully recognized, at least in the Japanese context so far. In this chapter, an epoch-making judgment by a Japanese court and the responses from nuclear engineers in Japan will be taken as a case to explore this issue. Japanese nuclear engineers misunderstood the judgment's argument and could not make appropriate counter-arguments against the court. This kind of misunderstanding of voices from society can result both in loss of political legitimacy and stagnation in technical evolution. Looking at the original nature of engineering itself, the need for fundamental change to re-establish diversity and independence in nuclear engineering, and the significance of social-scientific literacy to realize it, will be discussed.

Keywords Human rights · Post-Fukushima accident · Legitimacy · Innovation · Diversity · Independence · Open-minded · Public good

22.1 Introduction

This brief chapter tries to examine the implications of the PAGES project, especially in the post-Fukushima Japanese context, summing up the arguments of sister chapters in Part IV at the same time. The PAGES project and its participants consider social scientific literacy not just as an "additional" component for nuclear

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engineers. Rather, it is one of the “essential” parts of engineering competences and practices. In our understanding, the importance of this perspective even becomes greater and greater, especially in this post-Fukushima nuclear scene.

However, the author regrettably has to say that this perspective has not been fully and appropriately recognized by nuclear engineering experts as well as some of the other stakeholders at least in the Japanese context, though it has been over 3 years since the Fukushima Daiichi nuclear accident unfolded. In the sections below, an epoch-making judgment by a Japanese court and the responses from nuclear engineers in Japan will be taken as a case to explore this issue. Japanese nuclear engineers’ misunderstanding of the judgment’s argument will be examined critically. Then, looking at the original nature of engineering itself, the need for fundamental change in nuclear engineers’ mindset and the significance of social-scientific literacy will be discussed.

22.2 Denial of Nuclear Power: A Message from Japanese Court

On May 21, 2014, Fukui District Court delivered a judgment about the operation of Oi Nuclear Power Plant (NPP) owned and operated by Kansai Electric Power Company. The court ordered the prohibition of operation of Units 3 and 4 of the power station, siding with a group of 189 citizens, the plaintiff. It was the first case of loss of nuclear power operator at a court since the Fukushima nuclear accident occurred.

There had been several court decisions that supported nuclear opponents’ arguments even before the Fukushima nuclear accident, but this judgment ordered the halt of the nuclear power operation directly based on Constitutional human rights—personal rights—for the first time in Japanese legal history. The sentence points out the reality of the damage caused by the Fukushima accident and characterizes it as a critical threat to fundamental human rights. It says as follows:

> Nuclear utilization [in Japan] is limited to civilian use so that the operation of a nuclear power plant is a means of electricity production, which belongs to the freedom of economic activities [guaranteed by the Constitution], and is inferior to the core part of personal rights, legally speaking. Then, it cannot be imagined that the fundamental [human] rights could be exceptionally broadly denied as much as by a nuclear accident, except for a huge natural disaster or war…. It makes sense that any commercial activities which have such concrete risk should be prohibited… [1].[1]

The court clearly distinguishes the risk posed by a nuclear accident from other risks generated by general industrial activities, not by its probability but by the qualitative nature of its potential hazard (i.e., long-term radioactive contamination of the environment and evacuation and damage to the community as a result).

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[1] Translated and supplemented by the author.

It also determinably denies the application of cost-benefit analysis for nuclear risk through very strong criticism.

> The court thinks that we are not allowed to participate in nor decide something about the discussion that compares the rights of many people to their life itself to the cost of electricity production… There is a discussion about outflow or loss of national wealth as regards this cost issue; we should not consider the huge trade deficit generated by the halt of the operation of these nuclear power stations as outflow nor as loss of national wealth. National wealth consists of productive land and people's life upon that land, thus the court thinks that irreparable damage of the national land is loss of national wealth [1].[2]

In other words, this judgment argues that our society can no longer allow the existence of nuclear power utilization (at least in Japan, thinking about its narrow national territory and density of population). It is not the health effect of radiation exposure to the public that is the central problem of the risk of a nuclear accident, but the disastrous effect on people's life, according to their formulation. It points out that what happened and is happening in Fukushima is clear evidence and this fact validates their understanding. This is an extraordinary fundamental criticism of nuclear power technology and its utilization.

22.3 Responses from Nuclear Engineers in Japan

This radical message by the court promptly attracted strong attention from nuclear engineers in Japan, as well as from other stakeholders and citizens. Almost all responses from nuclear experts were vivid criticism, or even outrage, against the decision. They found many faults among the technical descriptions in the judgment and concluded the decision had serious deficits because of "misunderstanding" about the upgraded safety measures of the Oi NPP.

The Atomic Energy Society of Japan (AESJ), the most comprehensive professional and academic body in the nuclear field in Japan and the counterpart to the American Nuclear Society (ANS), published their press release about the court's judgment on May 27 and strictly criticized it because "it might cause serious misunderstanding among people about improved safety measures at the nuclear power plant"[3] [2]. It accuses the court's formulation of the problem as "an opinion that calls for 'zero risk'" and as "not appropriate as the legal decision by court." It criticizes the court their denial of "engineering safety" because it is accepted in "almost all fields of science and technology" and "it is unfair that the court does not accept it for nuclear power stations though they should be impartial."

It also argues that another Fukushima-class nuclear accident is preventable by implementation of appropriate counter-tsunami, anti-severe-accident, and disaster prevention measures so that it would not violate personal rights.

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[2] Translated and supplemented by the author.

[3] Translated by the author. The following quotations are also.

Many nuclear experts showed quite similar opinions in newspapers, on the web, and in other media. It was an “unscientific” or even “anti-scientific” challenge from a legal expert—the Chief Judge of the Fukui District Court—who doesn’t have sufficient and appropriate technological expertise. Conservative newspapers (Yomiuri, Nikkei and Sankei newspapers) also published their editorials and extend their support to such opinions [3–5], while their liberal counterparts (Asahi, Mainichi and Tokyo newspapers) admired the court’s decision [6–8].

However, such criticisms themselves contain many “misunderstandings.” For example, AESJ’s press release criticizes the denial of the nuclear risk by the court as “zero-risk” oriented thinking but it is not the case. The judgment distinguishes the nuclear risk by its nature and the scale of hazard potential, not by its probability or so-called “death-ratio” as the author introduced earlier. It never naively calls for “zero-risk.” Rather, it questions the destructive nature of nuclear risk itself in terms of qualitative considerations.

Also, some arguments cited judicial precedent sentenced by the Supreme Court about the appropriateness of the safety review of nuclear facilities and point out the contradiction between it and this judgment, but it is also incorrect.[4] The former one was an administrative lawsuit so that the court reviewed the legality of the safety review, but this case was a civil case about human-rights violation. These two types of lawsuits have different nature and the points in dispute are also different. Therefore the judgments can be legitimated by different logics. The later judgment carefully clarifies the differences of the jurisdictions before it comes to the detailed considerations of the illegalness of the NPP operation in terms of the constitutional human-rights violation.

The critics of the decision by the Fukui District Court seems to misunderstand, or at least not to read the sentence carefully, before they expressed their outrage against the legally powerful and fundamental denial of nuclear power utilization. Why could not they catch the point raised by the Court? Why did they show such reaction against the decision?

22.4 Don’t Refuse, but Inspired by the Voice from Society

As Sunderland points out in Chap. 18, the problems centering around the nuclear power utilization “are not amenable to engineering’s traditional utilitarian reasoning and optimization studies” in Post-Fukushima era [9]. However, the outraged experts seemed not to recognize this important and irreversible change. As she

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[4] Ikata NPP (owned and operated by Shikoku Electric Company) safety review case is cited in their arguments. This was the first case of a lawsuit that dealt with the legality of the national Governmental safety review for commercial nuclear power stations. In that case, the Supreme Court of Japan established their criteria on the legality of safety review. It admitted relatively broad administrative discretionary powers on each case for governmental ministries and agencies and limited their jurisdiction to the appropriateness of the process of safety review.

argues, “one of the core issues with the problems surrounding Fukushima is that the answers rely on more than numbers” [9]. Fukui District Court’s critical point is tightly connected to this notion. In fact, the discussions in our Summer School covered this issue and “much time was devoted to searching for ways that nuclear power could be justified without weighing its costs and benefits in numerical terms” [9].

It is regrettable that the mainstream Japanese nuclear engineers still refuse this change and look aside from the crisis of “legitimacy” as Oda concerns about it in his chapter [10]. They have seemed to be stubbornly attached to defend the “current” nuclear system and its logic of safety and to try to make the world friendlier to them. There have been no alternative ideas to safety improvement of the current nuclear fleet by so-called backfitting and to increase emergency preparedness explicitly suggested by the Japanese nuclear engineering community. They have been eager to ‘explain’ those improvements but reluctant to do something fundamentally different with their past practices.

However, if the expert community interpreted the voices from society more sensitively and humbly, they could suggest much more drastically different answer to make nuclear power technology more preferable for society, in the author’s opinion. For example, they could suggest clear commitment to dry-cask storage system of spent fuel with passive safety feature to substantially decrease the risk of spent fuel management. The court’s judgment points out the vulnerability of barriers of spent fuel pool and considers it as one of the most contributory sources of possible massive radioactive release. Their critical criterion of risk acceptance is the scale of potential hazard so that the inventory of nuclear fuels is the most critical factor to discuss nuclear safety. This safety improvement should have much bigger impact on Judge’s impression about the efforts by the nuclear community than a set of ‘explanations’ of sufficiency of current safety measures.

Also, some nuclear engineers could have suggested the introduction of so-called small- and medium-sized reactors (SMRs), instead of huge 1 GWe class power plant, which have been the mainstream in Japanese nuclear power utilization. If we think about the issue of inventory of radioactive materials on each site and the discussion on the promotion of renewable energy utilization and the shift to more distributed power system, we can understand the advantages of SMRs technology. Of course, it is unclear whether the society successfully would accept these ideas and would agree to continue the nuclear power program with improved risk management and compatibility with distributed power system. There seems to be a great deal of possibility that people say “no” even if nuclear engineers suggest such ideas.

However, the most important thing here is not the result of such suggestions, but the spontaneous efforts by nuclear engineers to be “introspective” themselves as both of Sunderland and Oda argue [9, 10]. People can think about the substantial difference between the efforts to defend their legacy by some ‘explanations’ and to overcome the failure by their wisdoms and innovations. It should have totally different impact on the people’s respect for their nuclear engineers regardless of the appropriateness of the policies and behaviors by the Government and other responsible organizations (such as TEPCO).

Nuclear engineers should not refuse the questions and criticisms from the other members of society, but should listen to them carefully, think about the implications for them deeply and response to them sincerely in proactive manner.

22.5 Democratization of Nuclear Engineering: Not Just for Political Correctness, but Also for Innovation of Technology

As Bollerri discusses, nuclear technology is not a market-oriented enterprise. It has been strongly committed and controlled by the governments so that "there is a lack of experience with direct interaction between the nuclear engineer and the public" [11]. He also mentions about the consequences of this "detachment from their 'client'" as follows:

> This has led many times to an 'us versus them' mentality which only fosters antagonism. This has historically shown to be the wrong approach. This can occur when so-called 'technocrats,' while well intentioned, try to make decisions based solely on science and engineering by relying on a responsibility for 'good of the public,' without experiencing or communicating directly the public, whom these decisions affect [11].

What the author discussed in the previous sections can be interpreted as a case of this phenomenon. Historically speaking, Science and Technology Studies (STS), Sociology of Science and Technology and History of Science and Technology have critically examined such mechanism motivated by the improvement of political legitimacy and the democratization of science and technology. In other word, they have problematized this issue for the sake of the other members of society, not for engineers. However, the author would like to argue that this situation is critically problematic not only for the rest of society, but also for engineers themselves at the same time, when we think about the future of (nuclear) engineering *in* society.

Achievement of engineering is not limited to *improvement* of technology. *Innovation* of technology should also be, or sometimes more, important and exciting for engineers. Of course, improvement also requires substantial innovation in many cases. But, what is really admired by their colleagues and 'clients' is the epoch-making breakthrough that provides brand-new options for society.

This kind of innovation is sometimes not a direct evolution of preceding technology and its appraisal. Christensen sheds new light on mechanism of innovation by examining many cases of "disruptive innovations" in his famous book *The Innovator's Dilemma* [12]. He emphasizes the importance to be free from stereotypical, conservative mindsets that prevent such breakthrough. It should be noted that experts tend to be possessed by conventional appraisal standard of technical merits. Sony's engineers could not change their goal for the best portable audio player from its sound quality, battery life and compact body to something another. Their product—the Walkman—had monopolized the market in the past, but their position was suddenly replaced by a new comer with the huge storage capacity–Apple's iPod, although it was not superior to Walkman in terms of the conventional advantages listed above. Apple's engineers were free from the traditional belief in the business, found a potential need in the market—to bring personal jukebox—and realized it by existing technical components. As Sony's engineers, nuclear engineers who cannot free from the traditional belief—bigger output for centralized power distribution system and conventional cost-benefit analysis—could be left by their 'client' in the Post-Fukushima society. Rapid promotion of renewable energy and liberalization of power industry is inevitably and irreversibly being carried out now, though Japanese national policy has not chosen the clear commitment to rapid phase-out from nuclear power so far. If nuclear engineers could not provide any suitable nuclear power system that is nicely compatible with distributed power system provided by renewable power sources, they might not be able to keep their presence both in energy technology field and in society.

If Japanese nuclear engineers had understood this need and another need for intrinsic safety, which was discussed in the previous section, more rapidly and precisely, some of them might have suggested different nuclear power system with SMRs for society, not just to say something about the safety improvements of the existing large-scale NPPs across Japan. It is not necessary that every engineer defends the appropriateness and advantages of current nuclear power system and supports the Governmental and the utility companies' policy of nuclear power utilization. However, there have been only a few fundamentally different proposals of nuclear power utilization for Post-Fukushima era so far. Almost no engineer is trying to change such a big picture at least in Japan. This is quite unnatural and unsound situation when we think about the competitive nature of engineering practices.

22.6 Concluding Remarks: Independence and Diversity of Nuclear Engineering for Unprecedented Challenge

Engineering is inherently dynamic activity. Many engineers are doing their works under competitive circumstances and love it. Difference makes advantages. Diversity motivates technological evolution. As the author cited Christensen's analysis above, so-called the B to C (Business to Consumer) fields, such as consumer appliances business, have such a nature in fact. However, nuclear technology is unfortunately much more "national capitalistic" because of its technical nature and historical origin [13]. Furthermore, the power utility business also has bureaucratic constitution because it is a vital infrastructure system and never allowed to make any serious failure. These factors make the mindset of the members of "nuclear village" more and more conservative and closed-minded. These characteristics of nuclear industry and policy-making system have created a path-dependent, failure trajectory and resulted in the occurrence of "structural disaster," as Matsumoto discussed in Chap. 10 [14].

However, as briefly illustrated in this chapter, what society requests to engineers is being changed fundamentally now. This change had been unfolded even before the Fukushima Accident happened, but both of magnitude and velocity of it has been even increased so much in this Post-Fukushima society. If nuclear engineers don't listen to people's voice, don't change their thinking, don't suggest alternative picture of nuclear utilization for society, the future of nuclear technology could never be positive one. What people would like to have is never intentionally unified, stereotypical answer that suggests the existence of bureaucratic control on the nuclear engineering community. But, citizens and all other stakeholders desire to have more diversified and organized options that have been elaborated through unfettered discussion and sincere efforts by independent engineers. They are waiting for the nuclear engineers to break their fetters of "nuclear village". As Borrelli argues, we need 'third generation' nuclear engineers "that will lead and shape perspectives on nuclear technology and develop new relationships with society" [11].

It is the era of unprecedented challenges in nuclear field. Innovation in nuclear power system, treatment of contaminated environment by the Fukushima Accident, decommission of damaged Fukushima plants, management of various kinds of radioactive wastes, almost all contemporary challenges in the nuclear field have no established paradigm or concrete model-cases. It's not the era of "long-term plan" set by the Government as the rock-ribbed law. Most of them are not just technically solvable in the sense of conventional engineering practices. They "rely on more than numbers" [9].

Social-scientific literacy is not a tool to manipulate public sentiment, rejecting their voices. It is a method to listen to it carefully, to find and grasp needs in society, to suggest engineers' proposal to society in humble and sincere manner and to collaborate with other stakeholders than nuclear engineers' 'old friends.' Engineers can take its advantages to make their thoughts and practices more open-minded ones as discussed in this chapter. It can become a strong tool to break their fetters, of course.

Return of diversified and independent nuclear engineers is now being waited by society.

References

1. Fukui District Court (21 May 2014) Judgment, Case (wa) No.394 (2012) and Case (wa) No.63 (2013)
2. Atomic Energy Society of Japan (27 May 2014) Statement for the juridical decision of prohibition of Oi nuclear power station units 3 and 4 operation. Available via AESJ website http://www.aesj.or.jp/info/pressrelease/PR20140527.pdf. Accessed 20 July 2014
3. Yomiuri Newspaper (22 May 2014) Editorial: Oi restart case: Denial judgment led by unreasonable reasoning
4. The Nikkei (23 May 2014) Editorial: Questions for the Oi prohibition judgment
5. Sankei Shimbun (23 May 2014) Editorial: Restart of Oi was refused: Unscientific and unrealistic judment
6. Asahi Shimbun (22 May 2014) Editorial: Oi prohibition judgment: It cannot be 'Neglected'
7. Mainichi Shimbun (22 May 2014) Editorial: Prohibition of Oi NPP: Warning for restart without debate
8. Tokyo Shimbun (22 May 2014) Editorial: Oi prohibition case: A judgment to protect people's life
9. Sunderland M (2014) Educating the Post-Fukushima Nuclear Engineer. In: this volume, Chapter 18
10. Oda T (2014) Nuclear engineers for society: What education can do. In: this volume, Chapter 20
11. Borrelli RA (2014) Reflections on developing an identity for the third generation nuclear engineer in the post-Fukushima society. In: this volume, Chapter 19
12. Christensen CM (1997) The innovator's dilemma: When new technologies cause great firms to fail. Harvard Business School Press, Boston
13. Yoshioka H (1999/2011) Shin-ban genshi-ryoku no shakai-shi: Sono nihon-teki-tenkai. Social History of Nuclear Power: The Trajectory in Japan (2nd ed.). Asahi-shimbun Shuppan, Tokyo
14. Matsumoto M (2014) The "structural disaster" of the science-technology-society interface: From a comparative perspective with a prewar accident. In: this volume, Chapter 10

Chapter 23
Lunchbox-Toolbox: GKS1350021 and Nuclear Engineers

Gayle K. Sato

Abstract This is a personal essay, written from the viewpoint of an ordinary citizen to nuclear engineers, on the necessity of communicating vital information about radioactive contamination to the public during times of normalcy as well as times of crisis. I have no expert knowledge of nuclear energy, nor was I involved in the PAGES 2011 Summer School from which this book emerges. I was invited by the chief editor to contribute a chapter about communication from my point of view as a literary scholar, ESL instructor, and American living in Japan (since 1987). In this chapter, I advocate the creation of a "library" of essential knowledge of nuclear energy in general, and radioactive contamination in particular, to serve the needs of a non-expert public. This "library" would be online, constantly updated, robust, truthful, transparent, comprehensible to lay readers, and politically neutral. My appeal to nuclear engineers to undertake such a task is presented through six topics which allow me to address the social needs and concrete skills involved in knowing what, how, and why to communicate: (1) transparency and comprehensibility, (2) the Ex-SKF blog/ger, (3) meeting Joonhong Ahn, (4) teaching "Fukushima" in my literature course, (5) the concept and practice of a "scientist citizen" (referring to Cecile Pineda's *Devil's Tango* as one model), and (6) the reciprocal entity "citizen scientist."

Keywords Communication between nuclear experts and laypersons · Online nuclear science library · Lunchbox-toolbox · Scientist citizen · Citizen scientist · Ex-SKF · Joonhong Ahn

23.1 A Request: From GKS1350021 to Nuclear Engineers

This chapter is about communication between nuclear experts and the public in the wake of the accident at Fukushima Daiichi NPP that began on March 11, 2011.

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As GKS1350021—the alphabets are my initials; the number is my zip code in Tokyo—I write in the spirit of an open letter to present and future nuclear engineers around the world. I am not a nuclear engineer or social scientist involved in the project reported on and responded to through this book. I have no special expertise regarding any aspect of nuclear energy. I am a literature scholar born and raised in Hawai'i, and citizen GKS1350021. The potential value of what I have to say regarding issues addressed in this volume derives solely from personal values shaped through many years of studying and teaching literature, social relationships acquired in the communities that raised me, and what I have experienced as an American citizen residing in Japan since 1987. But I call attention to these facts because paying attention to someone's specifically sited existence underpins successful communication in any situation, all the more so in times of crisis.

In the case of Fukushima Daiichi NPP as it was handled by the Japanese government and TEPCO, communication grounded in a sense of accountability to specific individuals was profoundly lacking. Citizens like GKS1350021 suddenly needed hard facts about nuclear power plants and wanted their information from experts, not politicians or industry insiders, yet we looked to Government and TEPCO to facilitate getting that information to us. We sought this information from our standpoints as individual human beings; our concerns as consumers of electricity, owners of TEPCO stock, or supporters of this or that political party were also real, but secondary in those first days and weeks. On March 11, our first thoughts turned automatically to ascertaining the safety of family, relatives, neighbors, and friends. As images of survivors throughout the Tohoku region materialized on television and computer screens, we struggled to grasp and respond to their need for shelter, water, food, and medical care. But within days our energies were taken over—if our homes had escaped damage, if we had not lost electricity, if we were not caught up in the confusion of evacuation zones—by the shock of water and food contamination fanning out from Fukushima Daiichi NPP. Panic, dread, anger, and depression set in, fueled by a shortage of reliable information, by Government and industry leaders who refused to tell us clearly and precisely what was really happening, or at the very least, whatever they themselves knew.

Citizens like GKS1350021 expected the Prime Minister and his staff, if not TEPCO management, to facilitate dissemination of information from nuclear experts as to what exactly was happening at Fukushima Daiichi NPP, and to transmit information from specialists in radiology, medicine, and nuclear physics as to what the nuclear meltdowns meant in terms of short- and long-term environmental contamination and how that contamination translated into specific dangers to water, food, and the human body. But however much citizens like GKS1350021 looked to their political and industry leaders to receive such information in a timely, continuous, and accessible manner, we waited in vain. As days turned to weeks and months, alongside images of earthquake-tsunami survivors searching for family members and adjusting to life in shelters or stranded communities, alongside surreal scenes from a nuclear power plant in tatters, we were also forced to witness the political jousting in Nagata-chō as the LDP, DPJ and other parties devoted themselves to exploiting the nuclear accident to regain or retain political power. Radioactive contamination filled me with dread; the landscape of ruin along the coasts of Iwate, Miyagi, and Fukushima filled me with despair. But the sickening spectacle in Nagata-chō filled me with rage.

In a crisis, governments justify censorship with the need to "maintain order" and "prevent panic." I remember thinking then (in March, April, May, June, July 2011), and still believe now, that if instead of communication aimed at pacifying the population and evading accountability, we had been told the stark truth of what was probably/happening, to the extent that it was known or could be reasonably inferred, such communication would have done far more good than harm.

Let us say that one day, I am told in no uncertain terms that my vital organs have suffered a meltdown and I have 6 months left on this earth. I think I would want to know precisely what to expect as things deteriorate, so that I could decide how best to live those 6 months. Although it's possible that I might panic or fall into debilitating depression when I get the information I demand, it's equally imaginable that, motivated by a heightened appreciation of my own life and a sense of responsibility to others, I would neither panic nor plunge into despair, but work productively to put my affairs in order for the benefit of those who will survive me.

I know, of course, that this is not a perfect analogy for arguing the probable or possible impact on, say, the 13.5 million residents of Tokyo if they had been told immediately and straightly that there were three meltdowns and exactly where the toxic plumes had gone and which cancer-inducing elements were in them. No one can say for sure what percentage of Tokyo's 13.5 million would have tried to flee Tokyo (beyond whatever number who actually did in March 2011) in response to a hypothetical government strategy of 100 % truth-telling. No one can say with certainty what new crises would have been triggered by such an exodus as it clogged transportation routes and consumed all available shelters and food supplies, which were already disappearing due to hoarding. Even if only 1 % fled the metropolis, could 135,000 people so easily find a new place to live, and for how long if they left their former workplaces? If 10 % of Tokyo fled, that's 1,350,000 people looking for a place to live and work. So let me acknowledge again that I have no "scientific" basis for imagining responses other than mass panic and chaos if government and TEPCO had chosen the path of relentlessly truthful communications regarding the hourly and daily condition of Fukushima Daiichi NPP.

Nonetheless, a very different scenario remains a possibility, and therefore deserves as much consideration as the more automatically envisioned scene of mass panic. In other words, it is possible that large swaths of the Japanese citizenry would have responded to accurate, comprehensive, straightforward information about the nuclear accident in the way I like to imagine I would respond to a diagnosis of impending death with 6 months left to live. Large swaths of the Japanese citizenry, *in response to witnessing the ethical courage of their government and industry leaders* in stating the facts about the meltdowns and their probable consequences, and thereby demonstrating genuine concern for the effect of the nuclear accident *on the individual lives* comprising the body politic, would be moved, reciprocally, to pool and coordinate their individual specialized knowledge—as farmers, doctors, chemists, geologists, physicists, psychologists, therapists, caregivers, bankers, teachers, cooks, emergency aid workers, artists, trauma victims, NGO administrators, mothers, and carpenters, to name just a few domains of expertise. They would be joined by thousands more across Japan, ordinary citizens like GKS1350021 without any particular expertise but able to furnish physical labor and time to help deliver the organization of specialized knowledge to specific groups of people in specific places whose situation would then be alleviated immediately upon receiving such help. In other words, I imagine that a different concept and practice of communication would have created a scenario quite different from what actually happened in the wake of 3/11. We might have witnessed a breathtaking, nationwide, coordinated emergence of individual human resources via a grassroots crisis management movement. In other words, a people's crisis management made possible and brought into being through a vastly different kind of communication from Government and nuclear industry leaders: unrelenting truthfulness via transparency and comprehensibility.

23.2 Invisibility Versus Transparency: The Ex-SKF Blog

If the radioactive contaminants released from the crippled reactors were terrifying because of their invisibility, communications from Government and the nuclear industry induced profound anxiety for precisely the opposite reason—because they lacked transparency.

For GKS1350021 in the immediate and prolonged aftermath of the nuclear accident, negotiating everyday life choices in order to minimize radioactive contamination always came down to the issue of "communication," defined here as the goal/s, content/s, and method/s of every act of sending and receiving information, and the aggregation of such individual acts. Every act of communication is a decision originating in the minds of one or more specific individuals, about why and how to communicate what, whether in the course of routine work or times of crisis.

Indeed, my personal belief is that we can only exercise in times of crisis the forms and goals of communication we have practiced or attempted to devise during the course of our routine work. There is a lot of talk these days about "thinking outside the box," but in fact such thinking cannot be expected from most of us if we have never been encouraged to understand or perform "thinking outside the box" as a viable form of response in ordinary life. Nor can we suddenly care about "society" as individuals if we are not used to conceptualizing Japan's 127 million residents as individuals. In 2011 and since then, Government's concept of "the people," by and large, has been "a faceless entity to be pacified, deceived, and ignored."[1] Their concept of "responsibility to the citizenry," judging by their actions and more tellingly their non-actions, has meant protecting the political life of politicians, or doing whatever was necessary to enable the nuclear industry to carry on business as usual. On NHK and other TV stations, although there was nonstop "coverage" of the nuclear accident in the first weeks after March 11, I cannot recall seeing any instance of Japanese nuclear experts organizing themselves as an independent professional community to address the public in comprehensible language about what they were observing or surmising was happening at Fukushima Daiichi NPP, or what they understood to be the consequences for the human body of what they were seeing as it unfolded each day.

What does transparency look like when communication is dedicated to converting the invisibility of radioactive contamination, and the invisibility of political and industrial practices, into tangible, graspable knowledge in the service of public discussion and decision-making regarding nuclear energy?

By September 2011, I had discovered the Ex-SKF blogger.[2] To be precise, I requested an email subscription to Ex-SKF on September 16, 2011, and that is when I started to read this blog each time a new post arrived in my smartphone email box. This was the first watershed in the relationship between GKS1350021 and Fukushima Daiichi NPP. In the half year from March 11 to September 11, I had become extremely worn out with the effort to search for, sift, grasp, assess, and correlate information on the situation in Fukushima as well as my residential neighborhood in Tokyo's Koto Ward. I live about 6 km north of Tokyo Bay, where radioactive ash has been deposited as landfill, and about 4 km west of the Arakawa River, where an incinerator for regular household garbage burns debris trucked in from Tohoku. These policies were part of the unfathomable thinking of Government that spreading the toxic debris throughout Japan constituted an act of patriotism, democracy, and solidarity with those who had borne the brunt of loss and injury from the triple

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[1] When I wrote these sentences, it had been almost 48 h since a man set himself on fire near Shinjuku station, Tokyo (29 June 2014) to protest PM Shinzō Abe's determination, despite widespread opposition from the public, to enable Japan's Self-Defense Forces to engage in combat overseas by simply changing a longstanding interpretation of war-renouncing Article 9 of the constitution. The day after the attempted self-immolation, Abe's "re-reading" became a fait accompli when it was passed by his cabinet. Abe's Chief Cabinet Secretary Yoshihide Suga's response to the incident captures the irony of political leaders proclaiming sincere efforts to protect the country's citizens while dismissing the importance of their individual identities or the injury done to their individual bodies. Suga declared, "The government should protect people's lives and property as well as the country's safety," but as for the self-immolation, he brushed it aside by saying that while he was "aware of the incident" he was "not in a position to comment on an individual case" [1].

[2] The first post about the triple disaster reports that the blogger was able to make phone contact with family in Tokyo soon after the earthquake struck at 2:46 pm on 11 March 2011 [2].

disaster. In the first 6 months after March 11, there were many things I felt I needed to know but couldn't find answers to, because in the limited time I could devote to internet searches the information I sought in English was not easily discoverable on the web, or because the information I was able to access spoke of radiation in general terms or for sites other than Fukushima, and thus was not easily applied by a layperson like me to the produce making its way into my local supermarket, let alone all the foodstuffs I was ingesting whenever I had lunch or dinner near my workplace.

At my local supermarket, it was now taking me one hour to get through what used to be a 10 min trip, because now I was trying to read every label completely to figure out exactly where every item of food came from. But at the same time I couldn't help thinking: surely the labels are not 100 % trustworthy. No one who has read Eric Schlosser's *Fast Food Nation: The Dark Side of the All-American Meal* (2001) can ever fully trust food labels again. And what exactly does screening for radiation levels consist of or mean, since presumably not every single bean or carrot can be tested? Meanwhile, husband (an experimental psychologist) and son (a college student majoring in business) were weary and aggravated by my constant nagging at them: to not get wet in the radioactive rain, to avoid going too close to street drains and trees and shrubbery because cesium concentrations would be highest there, to not (for the same reason) enjoy wading through the fallen leaves that autumn of 2011; my list of Avoid This and Don't Eat That was long. Meanwhile, I couldn't very well launder every item of clothing as soon as someone stepped into the house, or have all of us shower down as soon as we got home, and what about our shoes and coats and bags (filled with personal belongings neither washable nor replaceable every day) and non-food purchases that had passed through so many unknown locations before we picked them out and brought them home? I split into two people: the woman who nagged to keep from screaming, and the woman who watched the nagger and understood that she needed to figure out a better strategy for living in the post-Fukushima Daiichi world. It was in this state of mental and physical fatigue that I found Ex-SKF, and my heart leaped up when I beheld the original website featuring a fearless yet comical Ultraman as its mascot. The humor was bracing, the bilingual information a lifeline.

The Ex-SKF blogger does paste-ins of Japanese-language articles, often in their entirety, and provides links to the original sites of these articles along with translations into English, rendered in near native fluency. Besides textual information, this blog's archive includes videos, photographs, data in graph or chart form, and coverage from English-language newspapers and websites around the globe. (There is also a Japanese-language version of the blog.) In sum, the English version of the Ex-SKF blog is a bilingual database with extensive coverage, and these two features have several important consequences.

First, readers who are fluent enough in both Japanese and English are enabled and practically invited to crosscheck the blogger's rendering of Japanese-language information into English. Second, English-dependent readers like GKS1350021 gain access to a huge amount of information not available anywhere else, and impossible to locate on a daily basis short of devoting oneself, like the blogger, to such a project. Third, transparency is a guiding principle for re/presentation of information: Links to original sources as well as other relevant material are provided, and when necessary, tips on how to access and read the information at these sites are also given, based on the blogger's own prior experience in navigating those sites. Transparency means that little or no energy need be wasted on wondering how reliable or partisan the presentation of the information might be. I myself have never bothered to do a cross-check, not because I trust this blog completely but because I've always known that I can check up on things whenever I want to. The archival trail followed by the blogger is clearly marked for others to follow. This blog is not motivated by a desire to get the journalistic scoop, although it does take (justifiable) pride in pointing out when it first took notice of something that others did not begin to discuss widely until much later. Such transparency in reporting creates a deep sense of reliability and trust. I read this blog because it is dedicated to delivering accurate, comprehensive, constantly updated, comprehensible information to readers, all of which becomes instantly accessible for future reference in the blog's archive.

In addition to culling articles on the same topic from different media sources, and in addition to a continuous flow of English translations of Japanese-language sources of information, Ex-SKF also provides personal analysis of the information culled. When the blogger offers opinions or speculations, they are clearly presented as such. The line is always clearly marked between what constitutes the blogger's commentary or analysis and what constitutes the information gathered and re-presented from a variety of media.

Finally, the Ex-SKF blog contextualizes the nuclear accident within global politics and economics. Events from around the globe are not ignored just because they are intrinsically unrelated to things nuclear. Quite the contrary: posting news about the Arab Spring, Obama's reelection, or Tokyo's winning bid to host the 2020 Summer Olympics in a blog called "Covering Fukushima I (Daiichi) Nuclear Accident since March 11, 2011" [3], with the accompanying November 2013 photo of the spent fuel pool in Reactor 4 (which eventually replaced Ultraman as the blog's mascot), makes the point that a nuclear accident cannot be understood in isolation from the flow of global history. Further, this flow of "external" news includes, from time to time, events that will never be news anywhere except on this blog—things like the Ex-SKF blogger's personal selection of music to celebrate Christmas or a birthday. Such apparently "unnecessary" contextualization of information about Fukushima Daiichi NPP is also part and parcel of Ex-SKF's policy of transparency. We are asked to take notice of this blogger's existence as an individual, although we are always aware of it in the personal voice that infuses the blog while not compromising its commitment to transparency. In the Ex-SKF blog, we receive our information from one individual human being, not a disembodied voice that covers over the speaker's stakes in the matters being spoken of.

Over the past 18 months, Ex-SKF's rate of posting new material has declined noticeably.[3] Perhaps personal circumstances might be partly responsible

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[3] Archive information at the blog site indicates more than 1,300 posts between 13 March 2011 and 1 January 2012; 1,160 posts in 2012; 601 posts in 2013; and 127 posts in 2014 up through July 28 [3].

(on January 26, 2014, Ex-SKF mentions being in bed for a week with the flu), but I think the decrease is largely the result of less and less information generated about Fukushima Daiichi NPP 3 years and 4 months after the start of the accident. A certain stability has been achieved, even despite the fact that (a) on-site contamination is still extremely high and far from being fully ascertained or mapped, (b) a number of dire problems remain unresolved even if they are no longer regularly reported on in mainstream media (e.g. where to put the continuously generated radioactive water that cools the broken reactors; likewise where and how to dispose of contaminated dirt, leaves, and other debris that have been collected throughout Tohoku and presumably will continue to be gathered up for disposal at future dates), and (c) we have no idea how much knowledge about the nuclear meltdowns was and still is being withheld from us by Government, TEPCO,[4] the nuclear industry, or the media. To repeat: despite the immensity of the unknowns alluded to in (a), (b), and (c), a certain stability seems to have been achieved at Fukushima Daiichi NPP, which would explain the sharp decrease in postings by Ex-SKF. But this is not to suggest that Ex-SKF has become obsolete as a source of information or that its value has peaked. No, precisely because the current stability at Fukushima Daiichi NPP (or any other nuclear power plant anywhere in Japan) is quite fragile given the uncontrollable probability of a large earthquake occurring too close, and precisely because of Government's unconscionable disregard of (a), (b), and (c) in its push to restart idled reactors and keep Japan dependent on nuclear energy without allowing the public a say in decision-making, the Ex-SKF blog remains indispensable as a bilingual, open-access, comprehensive, unfolding-in-real-time archive of events at Fukushima Daiichi NPP, that prioritizes transparency.

For all these reasons, then, the Ex-SKF blog models what I think ought to be the key elements of an online "library" of information on Fukushima Daiichi NPP set up and run by nuclear engineers, who would also be dedicated to truthfulness, political neutrality, and transparency, and not averse to adding the occasional touch of Christmas music or other expressions of the human being of the library's creators and operators. I envision this "library" as a necessary point of reference for both pro-nuclear and anti-nuclear groups, such that both groups can be enabled to see what they currently do not see, admit, or accept.

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[4] A recent example of not being told what happened when it happened is TEPCO's belated announcement on 23 July 2014 that on 19 August 2013, more than 1 trillion becquerels of radioactive substances were released over the course of four hours during a cleanup procedure at the No. 3 reactor of Fukushima Daiichi NPP [4]. As early as March 2014, the Ministry of Agriculture informed TEPCO that its decontamination work on 19 August 2013 had contaminated rice harvested from Minami-Soma during the same month, but the Ministry did not inform the people of Minami-Soma about the contamination [5].

23.3 Lunchbox-Toolbox: Meeting Joonhong Ahn

If discovering the Ex-SKF blog was the first watershed for GKS1350021 in the wake of 3/11, the second watershed was meeting Joonhong Ahn at a 2-day symposium—Fukushima: Lessons Learned?—convened at Oberlin College on 9–10 March 2012, to assess the wake of the nuclear disaster on its one-year anniversary.[5]

Besides Joonhong, who presented a paper entitled "Fukushima from Environmental Remediation, Waste Management, and Back-end of Nuclear Fuel Cycle," other panelists included Kennette Benedict, executive director of The Bulletin of the Atomic Scientists, Akira Tashiro, executive director of the Hiroshima Peace Media Center, David Lochbaum, director of the Nuclear Safety Project for the Union of Concerned Scientists, and Allison MacFarlane, then associate professor of environmental science and policy at George Mason University, and since July 2012, chair of the U.S. Nuclear Regulatory Commission. But among all the panelists, it turned out that only Joonhong possessed detailed knowledge of the Japanese nuclear industry and actual work experience within Japan's "nuclear village" [7].

So during lunch break on day one of the conference, I grabbed a seat next to Joonhong. His presentation turned out to have been the most technical, and the least familiar to me (a literary critic) in terms of format and presentation style, but as a specialist in remediation (one of several technical terms I picked up that day), I judged that he had the technical knowledge to answer my most pressing questions about radioactive contamination and the internal structure of the nuclear industry.

I no longer remember everything I asked him nor how exactly I phrased my questions, but I cannot forget one thing he said that became the most important piece of information I took away from the conference: that even if all parties agree to switch immediately and completely to renewable energy, the nuclear power plants cannot simply be shut down. It is not a matter of simply turning off a switch or dismantling the reactor buildings. The plants would need expert tending for a very long time, and it was of paramount importance to maintain a fleet of nuclear engineers capable of doing first-rate maintenance work on decommissioned reactors.

Thus I was made to understand, over lunch, the naiveté of an anti-nuclear activism that calls for "shut down" without any idea of the actual procedures and time

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[5] Oberlin professor Sylvia Watanabe (Creative Writing) came up with the idea for the symposium, and it was co-organized with two other Oberlin faculty, Nanette Yannuzzi (studio art) and Ann Sherif (East Asian studies). In addition to main sponsor Oberlin Shansi, many departments and offices at Oberlin College lent their support to this event [6]. I had been corresponding with Sylvia since 2008 regarding mutual research interests that included atomic history, and so I knew about the symposium in advance. I went because I needed to hear, in a language I could understand fully, expert assessment of what had happened and where we now stood, and I was able to attend because the conference fell during spring break at my university.

frame involved in decommissioning a reactor even after it can be agreed upon to do so. How the absence of active nuclear power plants makes it difficult to train the next generations of nuclear engineers who must carry out the long-term work of shutdown. At this point I made the connection to what I had learned recently about the "gerontology" of aging nuclear weapons at Los Alamos National Laboratory, including the problem of how to equip new generations of nuclear weapons scientists with the knowledge they need to care for increasingly fragile, volatile bombs if they do not have "active" sites of nuclear weapons production to learn and maintain their expert knowledge [8].

Lunchbox-Toolbox is my shorthand expression for insisting that a nuclear engineer's work must not be conceptualized and undertaken apart from the everyday lives of citizens. The mission of technology and science—the toolbox—is to serve the daily well being of citizens—the lunchbox. It is fairly easy to observe when this mission is being upheld and when it has been abandoned by noticing which one retains priority. If the lunchbox is sacrificed, it can only mean that the toolbox is perceived as accountable to no one but itself.

The literary critic Elaine Scarry has pointed out that a tool can be a weapon depending on whether it falls on a sentient or nonsentient surface.[6] An axe is a tool when the human hand is on the handle and the blade is toward a tree, but an axe is a weapon when the blade is directed towards human flesh. Actually any object, not just tools but things like chairs or bottles of wine, can also become weapons. It all depends, observes Scarry, on whether an object is being used to alleviate or inflict pain.[7] A chair is originally created to alleviate pain, to provide comfort; likewise a bottle of wine, or the axe that fells a tree for firewood to warm a home in winter. But each of these objects can become weapons when the intended or predictable result of their deployment is the infliction of pain: if the chair is thrown at someone, if the bottle of wine is poisoned, if the ax strikes down a tree simply to kill or maim it.

Lunchboxes, too, can inflict pain. Japanese schoolchildren were fed contaminated beef,[8] and TEPCO stopped providing free boxed lunches ("obentō") for the workers decontaminating Fukushima Daiichi NPP. The beef that young schoolchildren in Yokohama were made to eat could and should have been screened by people who knew how to do it properly, since by the start of the school year in April 2011 it would have been impossible for anyone genuinely concerned about children's safety to dismiss widespread fears of extensive radioactive contamination as "baseless rumors" rather than trying to ascertain, through trustworthy testing by trustworthy agents, whether the ingredients of school lunches were

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[6] Scarry [9], 173.

[7] Scarry [9], 144–150.

[8] 67,000 children were fed tainted beef between April and July 2011 [10]. Yokohama schools undermined the well being of children in other ways [11]. Fukushima cattle, contaminated from being fed contaminated rice straw, got past government inspections or the farmers had not received instructions to stop feeding them rice straw; meat from these cattle was shipped to various parts of Japan [12]. Free lunches were stopped for Fukushima workers [13].

contaminated or not. After all, the fact that children face elevated risks of developing cancers compared to adults was already common knowledge prior to the nuclear accident. As for the termination of free lunches for decontamination workers at Fukushima Daiichi NPP, that cost could and should have been borne as a sacrifice to someone else—if not the ratepayers whose household electricity bills went up 15 % since March 11, 2011, and who, for decades in fact, had already absorbed the cost of paying $25,000,000 worth of bribes to seven Prime Ministers as part of regular business practice,[9] then surely the top echelon of TEPCO management, or former and present prime ministers, could take the hit to their own pockets to feed the front line of workers at Fukushima Daiichi NPP.

There were, however, many individuals with expert knowledge in nuclear contamination who did step forward with their toolboxes, or were sought out by concerned citizens who did not themselves have the necessary expertise, and these various individuals each labored to maintain the mission of technology/science to promote the well being of citizens. Though their individual names and contributions remain relatively unknown, their work demonstrates the power of the 99 % to change things no matter how inept or callous Government and TEPCO continue to be, or no matter how unfathomably inactive nuclear experts in Japan—as a collective—remain.

One example that I can speak of with firsthand knowledge, because I attended his lecture at Temple University Japan on 3 July 2012 [15] and soon after had the privilege of interviewing him for more than two hours on 12 October 2012, is nuclear physicist Ryūgo Hayano, who was instrumental in organizing early on a systematic, broad-based program to test school lunches in Fukushima for cesium contamination.[10] His results from screening school lunches in Fukushima put many people at ease, illustrating how crucial it is to get experts on site as quickly as possible, who are capable of gathering and analyzing information properly. Swift and skilled intervention from experts enables the various problems arising from a crisis to be prioritized, and the most appropriate concrete responses applied.

But as we continue to seek out and look to the Ryūgo Hayanos of Japan for guidance and models of social responsibility from nuclear experts, let us always remember that lunchboxes and toolboxes are only as good as the hands that make

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[9] A former top official at Kansai Electric Power Co. has come forward to reveal a nearly 20-year history of doling out 'top secret' huge donations to Japanese prime ministers, funded on the backs of ratepayers. Chimori Naito, 91, a former KEPCO vice president, said that for 18 years from 1972, seven prime ministers received 20 million yen (about $200,000 now) annually from Yoshishige Ashihara, who served as both KEPCO president and chairman" [14].

[10] Hayano gave a PPT talk at CERN (The European Organization for Nuclear Research in Switzerland) on 4 April 2013 explaining his work in and for Fukushima: measuring cesium contamination in school lunches, assisting several hospitals with the proper use of whole-body counters, and figuring out a system for calculating radioactive iodine contamination in order to provide a basis for future government subsidizing of medical expenses for Fukushima residents who develop thyroid cancer [16].

or use them, at each step of the way. Every single time a lunch is eaten or a tool deployed, an individual conscience has guided—or not—the action of the hands that assembled the lunch or wielded the tool.

The importance of speaking out about this crucial relationship between hands and toolbox took shape in my mind after I'd spent many weeks reflecting on the impact of my lunchtime conversation with Joonhong. Eventually I realized that I had received a significant piece of information from him not simply because he was an expert who could tell me such things, but because the telling was guided by personal values and communication skills that virtually guaranteed the transmission of his knowledge to me, and my thoughtful reception of it in turn. I had gone to that conference carrying a year's worth of anger, fear, and depression, and so I'm pretty certain that I came across aggressively and convinced of my moral rightness when I asked Joonhong how anyone in the nuclear industry could justify continuing to work for it in the wake of the nuclear accident at Fukushima. The way he chose to respond says a lot about the indispensability of communication skills for nuclear engineers, and what those skills consist of.

First off, there was the courteous demeanor without a trace of condescension but plenty of patience. He received my vehement criticisms of various individuals or groups of individuals with a smile while remaining diplomatically neutral; this had the therapeutic effect of letting me vent frustration while politely implying that it was not the most enlightened way to discuss exiting nuclear energy. Second, his technical expertise was informed by a personal take on the social politics of nuclear energy, for example his observation during the final roundtable at the conference that every nation has the right and responsibility to decide whether they want to be nuclear or non-nuclear. Third, his patient, low-key manner suggests a generous pragmatism when dealing with entrenched systemic flaws or difficult individuals, which I surmise underlies his ability not only to have let a perfect stranger monopolize his lunch break and spend half of it venting, but to have worked so long within Japan's nuclear village amongst colleagues or established ways of thinking he may not particularly like or respect.

That Joonhong would invite a literary critic to contribute a chapter to this book speaks volumes about his commitment to lunchboxes. For many weeks after the end of the conference, I kept trying to pin down exactly what it was that continued to linger in my mind, over and beyond that crucial piece of knowledge I had been given regarding the reality of decommissioning nuclear reactors. Eventually I realized that it was the felt experience of the conversation itself, my direct experience of Joonhong's way of communicating his expertise to me, that had transmitted what lingered in my mind long after the conference ended—my strong sense of his reliability and genuine concern for fellow citizens, and the hope this inspired in me. Writing about this episode now, I am struck by the indispensability of our most "primitive" and increasingly rare form of communication in this age of social networking—the face-to-face dialogue between strangers (to be distinguished also from chatting or light conversation). But let me take these thoughts one step further. Even if communication skills are, finally, what enable transmission of expert knowledge to a layperson, and even if various "communication skills" can be identified, practiced, and learned in order to facilitate such transmission of expert knowledge, in regard to the lunchbox-toolbox relationship—the obligation of science and technology to serve the well being of citizens—successful communication means something more fundamental than this or that communication skill. It's about whether engineers *want* to place expert knowledge in the service of others, and whether they succeed in communicating *that* fact when they speak to laypersons.

23.4 Remediation and GKS1350021: Teaching Contamination as a Literary Critic

As I said earlier, I live only a few kilometers from both Tokyo Bay and the Arakawa River; the Tobu sludge plant is located where the Arakawa empties into Tokyo Bay. In March 2012, Tokyo began receiving contaminated debris from the earthquake-tsunami to be burned in incinerators located in densely populated areas and built only to handle regular household garbage. Some of the ash residue (I wasn't able to confirm how much) ends up as landfill in Tokyo Bay.[11] In the fall of 2011, Tokyo Governor Shintaro Ishihara embraced this plan as a way to patriotically share the suffering of victims of the triple disaster, and he finalized negotiations without bothering to consult Tokyo's 13.5 million residents. Certain aspects of Japan's post-3/11 "recovery plan" are the psychological pathology of certain species of politicians: Who needs engineering expertise in remediation when patriotism as defined by one man can become the basis for carrying out "decontamination" and "cleanup"?

Because I was not out on the street supporting anti-nuclear protests, I tried to amplify their work in other ways. Twice a year since spring 2012, I have required the students enrolled in my lecture course, History of American Literature, to watch a video featuring 10 women from Fukushima who participated in a 70-woman die-in on 7 June 2012 in front of the Prime Minister's Official Residence in Tokyo. It was a protest against his plan to restart the idled reactors at Ōi Nuclear Power Plant in Fukui prefecture. Before the start of the die-in, the women visited the Cabinet Office and met with officials to voice their concerns and submit a letter of requests to then PM Yoshihiko Noda. In the video, the women speak in turns, directly addressing their questions and statements to a prime minister who is not in the room. At the end, the woman who hands over their letter asks him: "Prime Minister Yoshihiko Noda, what are you looking at?

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[11] From December 2011 to March 2012, radioactive debris from Onagawa, Miyagi was brought to Tokyo [17]. In May and June 2011, radioactive ash from incinerated sewer sludge, and sludge from water purification plants, was dumped in Tokyo Bay as landfill [18, 19]. On 3 November 2011, radioactive debris from Iwate was brought to Tokyo [20].

What are you looking at when you decide your policies?"[12] This is not a question for the prime minister only; it is a question that any nuclear expert whose expertise affected the siting and operation of Fukushima Daiichi NPP should be able to answer.

Sometimes I pair the video with a poem by American poet Lawson Fusao Inada, "To Get to Fresno" [23]. Inada was born and raised in Fresno, California, except for the three years from 1942 to 1945 that he spent in a concentration camp for Japanese Americans. But he left Fresno after college, and never returned. So the poem, "To Get to Fresno," is about how to remember and cherish a home/land that you have left permanently. Inada takes us on a trip around the world to enact the knowledge of different cultures and universal human being that Fresno gave him, and still gives him, whenever he chances to re-call this place in his heart. The poem leads us on a slow journey around the world, from Fresno to Fresnillo, Mexico, to the Ganges River, to Zimbabwe, to Moscow, to the tundra with its polar bears, and to many other places along the way, before returning to Oregon where Inada made his second home. I was hoping to get everyone to think about what it means to leave a home/land forever, and yet to remain there forever in heart and mind, and what it means to enter this phenomenon as a bystander. What does it mean for us in Tokyo, post-3/11, "to get to Fukushima"?

Sometimes I pair the video with a classic American picture book called *A Tree Is Nice*, written by Janice May Udry and illustrated by Marc Simont [24]. This is the first book I remember borrowing on my own from the public library in Kapahulu, Oahu, where I lived from age five through eight. My mother read it to me countless times, and later I read it for myself many more times. Trees are nice, we read and see, because they give us apples and a place to hang a swing, play pirate, or sit and think. They protect cows from the noonday sun, our homes from winter storms, and cats from dogs. We can rake up leaves in the fall and build a bonfire, or draw pictures in the sand with fallen branches. Trees make everything beautiful, we read and see, and if we plant a tree, we can watch it grow up year by year and point proudly to it, saying, "I planted that tree." As a child I loved this book with a fierceness not easily articulated in words even now. I was able to buy a copy of it when I was in my thirties, after I happened upon it by chance in Maruzen Bookstore in Tokyo, some time during the first years after my move to Japan in 1987 and well before Amazon.com could prevent me from experiencing such joyous serendipity.

I like to think that teaching Fukushima alongside *A Tree is Nice* or "To Get to Fresno" is an act of remediation of the sort I am capable of in my line of work,

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[12] The video can be viewed [21]. Some of these women also appear in the documentary film *Women of Fukushima* (2012, Kugi Productions), by Paul Johannessen, Jeffrey Jousan and Ivan Kovac [22]. On June 8, the day after the die-in, PM Noda announced his intention to restart the two reactors at Ōi Nuclear Power Plant in Fukui prefecture. They were in fact restarted in July 2012 amidst widespread protest, but went offline again in September 2013 for a scheduled checkup. In May 2014, in a landmark decision, the Fukui District Court ruled in favor of a lawsuit representing Tokyo, Fukui, and twenty other prefectures to ban the restart of Ōi NPP.

and therefore have a duty to perform. I believe that teaching "Fukushima" has become a moral obligation for Japanese high school and university instructors across the board, so as to equip present and future generations of students with a clear understanding of nuclear energy—its historical development, socio-political contexts, and medical and environmental consequences—that will guide them when they take over the reins of Japanese society. In the first weeks and months after March 11, I could hardly bear to think about or look at trees, leaves, and dirt, wondering how much cesium had been absorbed into all the plants living and breathing between Tohoku and Tokyo and beyond. And although this acute sense of dread gradually faded, it was not because the cesium disappeared, but simply the lessening of a sense of crisis with the passing of time. The cesium (to mention just one contaminant) is still there, just centimeters below the surface of everyday life, its toxic half-life far from over.

23.5 Scientist Citizen: Cecile Pineda's Devil's Tango: How I Learned the Fukushima Step by Step

A "scientist citizen" is a layperson, an ordinary citizen, who acquires scientific literacy to exercise the right and duty of a citizen to work for the well being of all members of society.

The example I present here is Cecile Pineda, novelist and theatrical producer, whose anti-nuclear activism is based on extensive research into the history of nuclear reactors and radioactive waste.[13] *Devil's Tango* [25] was published on March 11, 2012. It is crammed with facts and figures about fallout from the Chernobyl and Fukushima nuclear accidents, about the process of building nuclear reactors from the mining of uranium to the storing of nuclear waste (including CO_2 emissions at every stage of this process), and about interconnectedness between the production of nuclear weapons and the production of nuclear energy, how depleted uranium from nuclear power plants has been recycled into weapons deployed in the Gulf War, the Iraq War, and the War on Terror in Afghanistan and elsewhere.

In lieu of providing a footnote for every single piece of information that she discovered or rediscovered to write this book, Pineda opts for a reader-friendly yet robust style of citation. Distributed throughout the 200 pages of *Devil's Tango* are roughly 80 parenthetical citations of books, articles, or websites, and 30 substantial quotations, of which many are from sources *not included* in the

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[13] Four years before the publication of *Devil's Tango*, Pineda wrote and produced *Like Snow Melting in Water*, a play based on a true story about the Japanese village of Ogama, located on the Noto peninsula in Ishikawa prefecture. In 2006, Ogama's eight remaining elderly residents decided they had no choice but to move out, and sold their village to the Tashima Company, which planned to turn Ogama into a site for burying toxic waste [26].

eighty citations. Nineteen pages of reference material are provided at the end of the book. This bibliography includes a list of permissions and acknowledgments, and an appeal for donations to the Fukushima Information Center for Saving Children from Radiation/Citizens' Radioactivity Measuring Station, while also identifying:

- 30 organizations which provide information on nuclear energy (such as the Federation of American Scientists, Physicians for Social Responsibility, Union of Concerned Scientists)
- 17 websites concerning nuclear energy (such as Nuclear Resource and Information Service, The Fukushima Project (at SimplyInfo), The Energy Net, and Depleted Cranium (which seems basically pro-nuclear))
- 18 activist organizations
- 40 books
- 48 articles.

Yet no matter how extensive or reliable Pineda's investigation into nuclear accidents and radioactive waste, her scientist citizenship does not emerge through research alone. Acquisition and deployment of scientific literacy is motivated by a certain concept of citizenship, and Pineda sets up two sensory exercises, at the start and end of *Devil's Tango*, respectively, to indicate what this concept is. As we will see, scientist citizenship means protecting the lunchbox.

In March 2009, the spacecraft Kepler was launched from Cape Canaveral to search for other Earth-like planets where life as we know it might exist. Planets sighted by Kepler's telescope become archived as KOIs: Kepler Objects of Interest. In November 2013, based on data collected by Kepler, it was calculated that some 8.8 billion Earth-size planets occupy the "habitable zone" of the Milky Way galaxy [27]. Two years earlier, a team of astrophysicists at UC-Berkley had already begun looking at 86 KOIs in particular from among these potential 8.8 billion [28]. In the first chapter of *Devil's Tango*, called "Habitable Zones," Pineda asks us to think about these 86 planets in a particular way. First, we are asked to imagine each of them containing their own evolutionary history of life, an evolution from one-celled organisms into flowering plants and eventually into intelligent beings with the ability to use tools, compose music, and speak languages. Then we are asked to imagine what it would sound like if all the speech and music produced by inhabitants of these 86 planets were heard at the same time. But whether we want to attempt such a feat of imagination or not, Pineda points out that even the combined sounds of these 86 planets would only amount to 1/600,000,000th of the total sound produced by all neighboring galaxies, and therefore we cannot even begin to imagine how small the sound of our 86 planets would be in comparison to the total sound of the entire universe. Pineda opens *Devil's Tango* with this experiment in imagination to remind us that Earth comprises no more than a mere speck of life within the entire universe of space and time, and yet, our love for life on this particular planet is infinitely weightier and more enduring than a speck of space and time. We can supplement Pineda's exercise by trying to visualize any form of newborn existence, whether plant or animal. As soon as we conjure up the most familiar images of flower buds or young leaves on a tree, or creatures hatching from their eggs, we are reminded that new life is utterly fragile and miraculous, and appeals to us for protection. This is the frame of mind—wonder and humility when witnessing the gift of life, and a sense of responsibility for the well being of all living things—that undergirds scientist citizenship.

At the end of *Devil's Tango*, in the chapter called "What the Light Was Like,"[14] Pineda presents us with another sensory exercise to complement the first one. This time we are asked to imagine a scene called up from the author's past—her memory of gazing at trees bathed in sunlight. Pineda recalls how she was able to comprehend the passage of time by watching how the light moved across a grove. The light embraced in turn each tree and every part of each tree as the earth turned on its axis, a movement normally imperceptible to us yet on that day made perceptible to her through attentiveness to the caressing passage of sunlight over trees.

Both of Pineda's sensory exercises are telling us to direct our gaze away from outer space toward this beautiful planet that we already inhabit, because without total *regard* for Earth, we risk destroying it beyond repair. Especially in the episode of remembering how sunlight moved across a grove, Pineda calls attention to the miracle of in/finite space and in/finite time that we are always capable of perceiving *in the here and now*. These sensory exercises re-inscribe a scientist's understanding of in/finite space and in/finite time in the language and point of view of a poet. For although space and time are foundational concepts in all fields of inquiry, philosophy, art, science, and social science have different ways of representing and thus comprehending space and time. The sensory images comprising Pineda's instructions for imagining the amplitude of 86 planets and thereby re-cognizing our commitment to planet Earth, and the sensory images comprising Pineda's instructions for seeing what she saw on that day of sunlight passing over trees, come from the discipline of poetry and exemplify her placement of the poet's toolbox in the service of the lunchbox. The most prominent example of Pineda's poetic language is of course the metaphor "devil's tango," which is used to illuminate the fact that nuclear history records a dance with death—Homo sapiens' apparent addiction to nuclear technology no matter how great its known record of devastation and irreversible damage.

Poetic language is not something for writers or literature scholars only, but is part and parcel of the language skills needed by a nuclear engineer—by any scientist or technician—to communicate specialized knowledge to laypersons, by virtue of the fact that poetic language is the primary language through which we comprehend and express the beauty of life and the gift of human being. To be a nuclear engineer without literacy in poetic language is to be like a computer with a voice, able to speak one's expert knowledge but devoid of any context of lived life

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[14] Pineda [25], 202.

as Homo sapiens. The same holds true for laypersons. Without acquiring literacy in the data, vocabularies, and concepts that comprise, represent, and valorize the work of scientists, laypersons cannot properly understand, evaluate, or improve their physical environment. Responsible citizenship in a post-Fukushima Daiichi world requires that each layperson have literacy in science, and that every scientist or engineer have literacy in poetic language.

Dear nuclear engineers, I am trying to convey two points about *Devil's Tango*.

The first concerns Pineda's ethics of communication. She is an artist and writer who instructed herself to acquire a scientist's knowledge and vocabularies. Doing so did not require her to discard or demote her expert knowledge and skills as a poet. She operated on the assumption that the domain of science was not separate from or intrinsically superior to the domain of language arts, and that the two domains of knowledge must speak to each other or risk degradation and death to both. She used her expertise as a poet to communicate certain truths about science and technology that may not be readily perceived or admitted by scientists and engineers. For example, that certain forms of technological or scientific "progress" (nuclear energy is one of them) create toxic byproducts with life spans of millions of years; that some things whose origins are beyond human memory, like a grove of trees basking in sunlight for generations, are beautiful and necessary to our lives simply because they are *old-fashioned*, that is: fashioned in a space and time, and embodying a mode of life, that precede and exceed the conceptual categories and practices of modern science. This is not a rejection of science and technology per se, but an invitation to scientists and engineers to reconfirm whether their activities protect or degrade the lunchbox.

Hence my second point about *Devil's Tango*: I would like to suggest that it, and other books like it, become required reading for nuclear engineers. Understanding and appreciating what this book says does not depend on having a brain "wired" for poetry. Homo sapiens are, already, wired for both poetry and science to a remarkable degree. Rather, it's a question of attitude. If scientist citizenship begins by assuming that scientific literacy is necessary for ordinary life, citizen science cannot develop without a reciprocal assumption that the regard for life expressed in *Devil's Tango* is necessary to one's professional life as a nuclear engineer. When I first mentioned this book to Joonhong at some point during 2013, and before I had read it myself, I was surprised (and then not surprised, after all) to hear that he already owned a copy and had put it in the bag he carried to work everyday to make sure he got it read. Later he told me that while he could not agree with everything Pineda said, he respected her endeavor. The significance of this action (reading the book all the way through, making it a priority to do so) and response (partial disagreement anchored in respect for the other's point of view) cannot be overstated. It means that a nuclear engineer met an anti-nuclear activist halfway in an attempt to overcome entrenched oppositions between those working within the nuclear industry and those who seek to abolish nuclear energy altogether. If experts and laypersons both step forward to meet each other halfway, communication is possible and becomes productive.

23.6 Citizen Scientist: From Nuclear Engineers to GKS1350021

Dear Nuclear Engineers, will you take up the work of creating and operating an online, open-access, comprehensive, scrupulously updated, politically neutral,[15] and above all transparent and comprehensible "library" of nuclear science? Which would have all the features, pointed out earlier, of the Ex-SKF Blog, and if not Pineda's poetic skills, at least her ability to communicate scientific concepts and facts in words accessible to lay readers? For this to happen, you must think and act like citizen scientists. You must understand that your value to society is not determined by your expertise; rather, your worthiness as a nuclear expert is determined by your motivations and actions as a private citizen.

Because: every technological artifact, from microchip to nuclear reactor, is developed and deployed by human hands, and each one comes into being through a very long chain of human hands comprising the entire process from manufacture through installation to deployment to maintenance. In a so-called normal state of affairs, we pay scant attention to this chain of human hands despite knowing that each pair of hands is attached to an individual human being whose skills and work ethic affect our lives profoundly through their effect on the final quality of the technological artifact they have helped to produce. On the other hand, the abnormal state of affairs is when a crisis suddenly forces us to pay attention to the chain of human hands. In a crisis, such as the meltdowns at Fukushima Daiichi NPP, not only do we begin to see the human agency behind technology that normally goes unnoticed, we realize how just a few hands can make an enormous and even irreversible difference in the way the technology under crisis will henceforth affect our individual lives.

How communication enters the picture: Although it is true, and not just fashionable, to say that "telling the whole truth" can no longer be expected from mainstream media, one of the lessons learned by GKS1350021 is that turning to alternative sources of information via the internet or personal networks was not inherently more assuring or indisputably more reliable. Short of giving up on filtering information altogether, the same questions will appear before us again and again no matter what the form of communication: How are we to understand, assess, and integrate the information that is before us?

After March 11, before I had discovered Ex-SKF, I succumbed to ostrich syndrome for a while. As the task of collating and sifting information from different sources became too exhausting, I perversely fixed my attention solely on NHK,

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[15] I know that 100 % political neutrality is impossible. What I am advocating is genuine self-monitoring to avoid, as much as possible, having one's analysis and reporting of information influenced by pressure groups, especially for-profit nuclear industries, Government, the military, and organizations who award grant money to underwrite scientific research. This is a tall order, but it can be done, and to do it imperfectly is better than to not try at all.

cynically disengaged yet at the same time desperate for a centralized source of reliable information and praying for a miraculous shift in Government's way of telling us what was happening. In retrospect, I can't help but feel that precisely because of widespread cooptation of mainstream media by industry and Government, now more than ever we must restore the concept and function of "mainstream media" as a centralized, trustworthy, open-access "library" of the most updated information comprehensibly written.[16] Given the enormous complexity of nuclear science, the truly global impact of nuclear waste, and the ease of disseminating misinformation or non-information through the internet just as easily as accurate and reliable information, it is more important than ever to have such a "library." And above all, the technical information accessed here must be communicated in such a way that every GKS1350021 can readily grasp it.

Here is a job for citizen scientists, for "nuclear engineers without borders." The task of creating and operating a nuclear science "library" cannot be entrusted to Government or the nuclear industry, nor should it be delegated to scientist citizens whose knowledge of nuclear science is, in the final analysis, a layperson's knowledge.

At present, information on nuclear energy comes to us primarily through staunchly pro-nuclear or staunchly anti-nuclear media, hindering meaningful dialogue between the two positions. A third party must enter the scene of communication because both pro- and anti-nuclear forces are not planning to go away anytime soon. For advocates of nuclear power, there is simply too much money to be made and the industry is also fatally entwined with supremely entrenched and secretive nuclear weapons production and deployment. Likewise, anti-nuclear advocates are also here to stay. They may seem infinitely disempowered by comparison, as non-profit organizations lacking influence in Government and industry, but they are just as tenacious in their goals and their numbers are growing.

Personally, I agree with the point of view that permitting the use of nuclear energy sanctions, no less than stockpiling or deploying nuclear weapons, the killing of human beings and the destruction of Earth (whether through the effect of nuclear energy's lethal byproducts on all forms of life and the physical environment, or through recycling depleted uranium into so-called conventional weapons). I am anti-nuclear, but I am also deeply pessimistic about whether the anti-nuclear agenda can ever succeed without dialogue (as impossible as that sounds) with pro-nuclear organizations and individuals, and whether

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[16] Also: If this "library" is replicated in different languages (Chinese, French, Korean, Persian, Russian, for starters) working on the library might prove in itself to be a valuable mode of peaceful and truly cooperative diplomacy. For the task of translating between languages to insure that the libraries are identical in contents cannot be accomplished without genuine teamwork. Individuals have to spend many hours in dialogue to confirm that they understand each other and agree upon the translations. Further, creating multi-lingual libraries would raise levels of foreign-language fluency among nuclear engineers, which in turn means higher levels of cultural fluency across national borders that would feed back into the task of maintaining a centralized database with multi-lingual access and relentless commitment to comprehensibility and political neutrality.

the pro-nuclear agenda can ever change without dialogue (as impossible as that sounds) with anti-nuclear organizations and individuals.

Hence my desire to see the emergence of a third party, equipped with expert knowledge of things nuclear, committed to getting expert knowledge translated for comprehension by laypersons, and dedicated to transparency and political neutrality. Will nuclear engineers fill this role? There are sixteen student essays included in this volume, and although at first I had intended to read them prior to drafting my chapter, in the end I set them aside until I had clarified what I wanted to say. And now having read through these sixteen essays by future nuclear experts, I am moved to see how they take up, repeatedly and in different ways, the problems and practices examined and proposed in this chapter. I am filled with hope that the "library" I dream of in this chapter may soon come into being.

References

1. The Japan Times News (2014) Self-immolation fails to slow Article 9 assault amid media silence. Available at: http://www.japantimes.co.jp/news/2014/06/30/national/japan-pushing-on-with-military-reform-despite-protesters-self-immolation/#.U9kRqKW6GlI. Accessed 1 July 2014
2. Ex-SKF (2014) Giant earthquake hits Japan. Available at: http://ex-skf.blogspot.jp/2011/03/giant-earthquake-hits-japan.html. Accessed 29 July 2014
3. Ex-SKF (2014) Covering Fukushima I (daiichi) nuclear accident since March 11, 2011. Available at: http://ex-skf.blogspot.jp Accessed 31 July 2014
4. The Asahi Shimbun (2014) Available via Asia Japan Watch. 1.1 trillion becquerels of radioactivity leak during Fukushima cleanup. Available at: http://ajw.asahi.com/article/0311disaster/fukushima/AJ201407240050. Accessed 29 July 2014
5. The Asahi Shimbun (2014) Available via Asia Japan Watch. Minami-Soma lambastes government, TEPCO for remaining mum on rice contamination. Available at: http://ajw.asahi.com/article/0311disaster/fukushima/AJ201407150040. Accessed 31 2014
6. Oberlin College & Conservatory (2014) http://new.oberlin.edu/home/news-media/detail.dot?id=3869457. Accessed 29 July 2014
7. Kingston J (2012) Japan's nuclear village. The Asia-Pacific journal: Japan focus. doi: 10 September 2012. Available at: http://www.japanfocus.org/-Jeff-Kingston/3822.
8. Masco J (2006) The nuclear borderlands: The Manhattan project in post-cold war New Mexico. Princeton University Press, Princeton
9. Scarry E (1985) The body in pain: the making and unmaking of the world. Oxford University Press, New York
10. Ex-SKF (2014) Covering Fukushima I (daiichi) nuclear accident since March 11, 2011. Available at: http://ex-skf.blogspot.jp/2011/08/yokohama-city-finally-admits-it-may.html. Accessed 31 July 2014
11. Ex-SKF (2014) Covering Fukushima I (daiichi) nuclear accident since March 11, 2011. Available at: http://ex-skf.blogspot.jp/2011/08/radiation-in-japan-somethings-rotten-in.html. Accessed 31 July 2014

12. Maeda R, Baird J (2014) Fukushima: 554 cows fed contaminated feed shipped. In: Reuters. Available via Edition U.S. http://www.reuters.com/article/2011/07/18/us-japan-nuclear-idUSTRE76F09J20110718. Accessed 31 July 2014
13. Ex-SKF (2014) Covering Fukushima I (daiichi) nuclear accident since March 11, 2011. Available at: http://ex-skf.blogspot.jp/2011/09/there-will-be-no-free-lunch-for-fuku-i.html. Accessed 31 July 2014
14. Kamome F, Osamu M (2014) Former Kansai Electric Power executive reveals 18 years of secret payments to prime ministers. In: The Asahi Shimbun. Available via Asia Japan Watch. http://ajw.asahi.com/article/behind_news/politics/AJ201407280041. Accessed 30 July 2014
15. Temple University Japan (2012) Radiating Risk: Food Safety and Public Health After the Fukushima Nuclear Crisis. Available at: http://www.tuj.ac.jp/events/2012/0703.html. Accessed 2 August 2014
16. Hayano R. (4 Apr 2013) Fukushima-Daiichi NPP accident–internal & external exposure of Fukushima citizens. Available via A&T Seminar. https://indico.cern.ch/event/241525/. Accessed 30 July 2014
17. Ex-SKF (2014) http://ex-skf.blogspot.jp/2011/11/radiation-in-japan-tokyo-will-burn.html Accessed 30 July 2014
18. Ex-SKF (2014) http://ex-skf.blogspot.jp/2011/09/radioactive-landfill-tokyo-metropolitan.html. Accessed 30 July 2014
19. Ex-SKF (2014) http://ex-skf.blogspot.jp/search/label/Koto-ku Accessed 30 July 2014
20. Ex-SKF (2014) http://ex-skf.blogspot.jp/2011/11/radioactive-disaster-debris-arrives-in.html Accessed 30 July 2014
21. Women's "Die-In" against the Restart of Ooi Nuke Plant (7 Jun 2012) https://www.youtube.com/watch?v=zYQNd2ybiDg. Accessed 30 July 2014
22. Women of Fukushima (2012) http://www.women-of-fukushima.com. Accessed 30 July 2014
23. Inada LF (1992) To Get to Fresno. In: Inada LF (1992) Legends from camp. Coffee House Press, Minneapolis, p 36–40
24. Udry JM, Simont M (1956) A tree is nice. HarperCollings, New York
25. Pineda C (2012) Devil's tango: how I learned the Fukushima step by step. Wings Press, San Antonio, TX.
26. Onishi N (2006) Village writes its epitaph: victim of a graying Japan. In: The New York Times. Available via Asia Pacific. http://www.nytimes.com/2006/04/30/world/asia/30japan.html?pagewanted=all&_r=0. Accessed 30 July 2014
27. Borenstein S (2013) 8.8 billion habitable Earth-size planets exist in Milky Way alone. In: NBC News. http://www.nbcnews.com/science/space/8-8-billion-habitable-earth-size-planets-exist-milky-way-f8C11529186. Accessed July 27, 2014
28. Reichhardt T (2013) Kepler's new planets: is anybody home? SETI researchers have already listened in for alien transmission. In: airspacemag.com. http://www.airspacemag.com/daily-planet/keplers-new-planets-is-anybody-home-26930821/. Accessed 5 Oct 2014.

Chapter 24
Resilience Engineering

A New Horizon of Systems Safety

Kazuo Furuta

Abstract Having experienced natural disasters, accidents, and economic crises, people are getting skeptical about technological approaches to risk management. The conventional approaches have not considered sufficiently how to manage residual risks that spill out of the design basis of a complex socio-technical system. Resilience, which means the ability of a system to absorb changes and disturbances in the environment and to maintain system functionality, is a key concept for resolving the above situation, and resilience engineering is an area where technical methodologies to implement resilience into socio-technical systems are studied. In this chapter, the prehistory of resilience engineering will be described first where the focal point of systems safety has gradually shifted from hardware component failures to the resilience of complex socio-technical systems. Then some relevant topics in resilience engineering will be discussed: how systems resilience can be evaluated and implemented, and the key issues to be resolved in the future.

Keywords Resilience engineering · Socio-technical system · Safety management · Crisis management · Human reliability

24.1 Introduction

We are surrounded by various kinds of dangers including natural disasters, accidents, medical diseases, economic crises, and crime. Prevention of damage and protection of people's safe living are great missions for engineering. Remarkable efforts have been made in conventional safety, reliability, and disaster prevention engineering to assess risks qualitatively or quantitatively, prevent manifestation

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of damage, and suppress damage to the minimum extent. Such efforts contributed greatly to making our lives far safer. Risk is a measure for representing the degree of danger as a combination of the scale and the probability that damage will occur. When there is a possibility that disasters or accidents may cause damage to human lives, health, or assets, risk is a very useful measure for achieving safety.

Having experienced unanticipated disasters in this century, however, we have recognized that we need a new framework of systems safety that can cover unanticipated situations that spill out of the scope of conventional risk management.

24.2 Shift in the Focal Point of Systems Safety

24.2.1 Era of Technology

Figure 24.1 shows how the focal point of systems safety has changed in the past decades. Some events that characterize the changes are also indicated in the figure.

When socio-technical systems were not very complex, specialists thought that problems occur for technical reasons, such as failures or malfunctions of hardware components, and that they can prevent accidents and disasters by further advances in technologies. Efforts were made, therefore, to carry out safety design and quality assurance based on understanding of failure mechanisms, and most problems with hardware components were successfully resolved.

The world's first commercial jetliner launched in 1951, de Havilland Comet, crashed repeatedly due to metal fatigue, which is a phenomenon in which a material breaks when great loads are repeatedly applied. The phenomenon itself had been known, but the validation testing method was immature at the time. Following the accidents, many technical improvements and redesigns were made, including improvement of the test method and the structural design method to stop fatigue crack propagation.

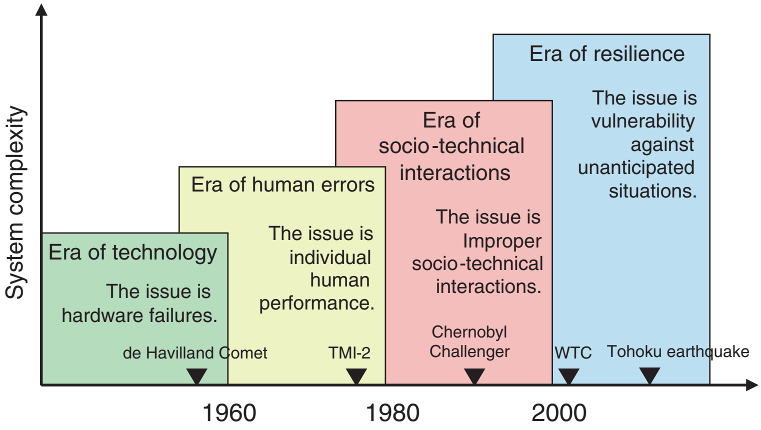

Fig. 24.1 Shift in the focal point of systems safety

Similar problems occurred in the early introduction stage of nuclear power. Stress Corrosion Cracking (SCC) in the recirculation loop piping of Boiling Water Reactors (BWRs) and wall thinning in the steam generator tubes of Pressurized Water Reactors (PWRs) were serious problems for the industry from the 1950s to 1980s. As technical studies revealed the mechanisms of cracking and degradation, which had not been understood at the beginning, the problems were resolved by substituting the materials with newly designed alloys, improving the management of water chemistry, and improving the method of fabrication.

24.2.2 Era of Human Error

As advanced technologies have been introduced, the complexity of systems exceeded the capacity limits of human operators or users, and many accidents occurred due to human error.

The Three Mile Island, Unit 2 (TMI-2) accident that occurred in 1979 was a typical case in this era. The accident started with a minor malfunction in the secondary loop, but subsequent unfavorable events made the situation worse, finally leading to severe damage of the reactor core. Some of the critical events that caused the accident include operators' human errors. The operators, for example, misjudged that the reactor vessel was full of coolant water, and they tripped manually the Emergency Core Cooling System (ECCS) which had been initiated automatically.

The point where humans interact with human-made equipment is called a human-machine interface. Analysis of the TMI-2 accident revealed that there were improper human-machine interfaces behind the operators' errors. At the beginning, for example, more than 100 alarms were initiated at the same time, and the operators were unable to comprehend what had actually happened in the plant. In addition, the indication of the relief valve position did not reflect the actual valve position. This defect in interface design caused a delay in operators' correctly recognizing the internal state of the reactor vessel.

Individual human factors and prevention of human errors became key issues in this stage [1], and efforts were made to design working conditions and human-machine interfaces appropriate for physical and cognitive human characteristics. Suppression of unimportant alarms based on prioritization of alarms is an example of functions that have been adopted in nuclear power plants after the TMI-2 accident. Since consideration of human factors is nowadays the standard requirement in designing socio-technical systems, the probability that human error may cause a serious accident has been greatly reduced.

24.2.3 Era of Socio-Technical Interactions

In the next stage, socio-technical interactions were the main sources of system failures. Many accidents occurred due to inadequate interactions among technologies, humans, management, organizations, and society. The impact of such accidents often goes beyond the boundary of the organization and cause widespread damage to society. An accident of this type is called "organizational accident [2]."

The accident that occurred at Chernobyl, Unit 4, in 1986 was a typical organizational accident. At the beginning, it was thought that operators' violation of the operation rules for accomplishing a special test at the plant had caused the accident. As investigation by the international community progressed, it was revealed that organizational and social factors characteristic of the Soviet system at the time were the root causes of violation. The operators, for example, were not sufficiently trained in background knowledge of operation rules, technical communication was lacking between different organizations, workers' will to obey the rules was low in comparison with what was needed to accomplish the norm, and so on.

In the same year, the Space Shuttle Challenger disintegrated after launch and killed the entire crew. The direct cause of the accident was failure of O-ring seals of a solid rocket booster due to cold weather. It is said, however, organizational factors of the National Aeronautics and Space Administration (NASA), such as lack of communication and face-saving decision attitudes, were present behind the direct cause.

The notion of safety culture was introduced after these accidents. Safety culture is defined as an assembly of characteristics and attitudes in organizations and individuals which establish that, as an overriding priority, safety issues receive the attention warranted by their significance. Researchers and practitioners made efforts to assess the level of safety culture of a particular organization and then to enhance it. Though remarkable progress has been made, these efforts are still on-going.

24.2.4 Era of Resilience

In this century, we have experienced more shocking events such as the terrorists' attack on the World Trade Center (WTC) in New York and the Great East Japan (Tohoku) Earthquake in Japan. Vulnerability of our socio-technical systems in the face of unanticipated situations was clearly shown in these events. In the conventional approaches of engineering, the design basis is determined beforehand based on some assumptions of severe conditions, and safety design is performed so that the system can fulfill the design basis. An event that exceeds the design basis, however, may happen, and its probability is characterized as residual risks. Since losses are unavoidable in such a case, we have to consider how quickly socio-technical systems can recover from the losses.

The conventional approaches have not considered sufficiently how to manage residual risks that spill out of the design basis of a complex socio-technical system. Having experienced natural disasters, accidents, economic crises, and so on, people are getting skeptical about technological approaches to risk management. Now we need a new framework for the safety of socio-technical systems to manage risks not only within but also beyond the design basis.

From the above background, the concept of “resilience” has lately attracted widespread interest of researchers and practitioners in systems safety [3, 4]. The term means the ability of a socio-technical system to adapt to disturbances from the environment and maintain its normal function. If we want to face up to unanticipated situations like WTC and Tohoku, we need to establish a new academic field, which we can call resilience engineering, to devise resilient socio-technical systems that can quickly recover their functions from damaged conditions.

24.3 Progress in Human Reliability Analysis

24.3.1 *First-Generation HRA*

In this section, we will discuss the human reliability analysis method to describe how the primary focus has shifted from a mechanistic view to a systemic view of human performance.

Human Reliability Analysis (HRA) is a method for qualitative or quantitative assessment of the probability (frequency) and the effects of unsafe human acts. In the nuclear sector, HRA had already been an essential step in Probabilistic Risk Assessment (PRA) before the TMI-2 accident, because the probabilities of human errors in plant operations are basic data required for calculating the core damage frequency. In the early stage of development, HRA borrowed primary concepts from reliability analysis of hardware components; human errors were thought of as phenomena similar to hardware component failures. It was assumed, therefore, that operators’ tasks can be divided into elementary task units, and the status of each task unit can be described by the binary logic of success versus failure. In addition, a human was dealt with as a black box without considering the internal cognitive mechanism that determines human performance.

Such methods for HRA are often called first-generation HRA. Technique for Human Error Rate Prediction (THERP) [5] is a typical example of first-generation HRA, which was developed early for the first comprehensive PRA of Light Water Reactors, WASH-1400 [6]. In THERP, a human task is modeled using a binary event tree as shown in Fig. 24.2, which shows an example task composed of three steps: (1) connecting power to the equipment, (2) turning Switch 1 on, and (3) turning Switch 2 on. Each branching

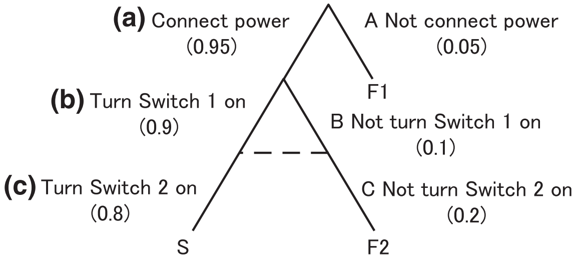

Fig. 24.2 Example of THERP event tree with probabilities in parentheses

node corresponds to an elementary task unit and the left and right branches, respectively, show success and failure paths of the task. It is assumed that the basic Human Error Probability (HEP) of an elementary task unit is primarily determined by the class of the task unit and the error mode. Concrete numbers of basic HEPs can be evaluated by looking up the database attached to the THERP handbook [5].

One of the drawbacks of first-generation HRA is its restricted power to describe situations of human performance. It is therefore applicable only to tasks that are well defined as standard operation procedures. Tasks that require complex cognitive processes of judgment are beyond the scope of first-generation HRA. In the TMI-2 accident, the operators misjudged the internal state of the reactor vessel based on the information obtained from the main control panel and stopped ECCS convinced that it was the correct action. Such an error by conviction or an error of commission occurs through an error mechanism very different from simple mishaps. Internal cognitive mechanisms of a human have to be looked into to deal with errors of commission in HRA.

24.3.2 Second-Generation HRA

Towards the end of the 1980s, many researchers of human factors started thinking that some breakthrough was required for HRA methods [7]. It is imperative to take errors of commission into account, because they may defeat multiple safety barriers and put the system into critical conditions. In addition, people cannot readily detect errors of commission by themselves in comparison with errors of omission.

Human modeling is a key technique to consider the cognitive mechanism of human performance for calculating HEPs. Rasmussen's classification of human performance into the three levels of skill, rule, and knowledge is the most popular example of such ideas of human modeling [8]. As research on human modeling and error psychology has progressed, it has become clear that human errors are not causes but consequences of unsafe incidents. Based on the outcomes of this research, methods for second-generation HRA were developed in the 1990s [9, 10].

Figure 24.3 shows the conceptual framework for human performance and human errors that is the basis of second-generation HRA. The context, which is

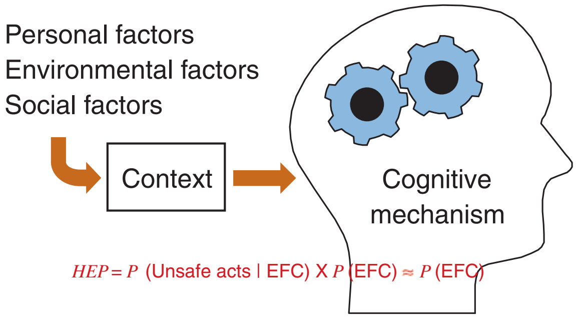

Fig. 24.3 Conceptual framework of human performance and human errors

a set of situational factors and conditions surrounding human performance, is a key concept in second-generation HRA. The context consists of various contextual factors that can be classified into personal, environmental, and social factors. Personal factors include those related to the characteristics of individual personnel such as experience level, skill level, physical and cognitive features, personality traits, and so on. Environmental factors are hardware and software attributes of the workplace such as tools, ambient conditions, design of human-machine interface, available information, and so on. Social factors are attributes of organizational or social institutions such as rules, training programs, workgroup composition, communication systems, and so on.

These factors affect the reliability of human performance through the cognitive mechanism of a human. Since the cognitive mechanism does not differ greatly among individuals, the reliability of human performance does not depend on the functioning of the cognitive mechanism but primarily on the appropriateness of context. A context where humans inevitably commit errors, Error Forcing Context (EFC), should be attended to in particular. EFC is a context in which everybody will commit an error almost certainly; HEP is almost equal to the probability of the appearance of EFC. Since an error of commission will occur under EFC just like a common mode failure of mechanical components, multiple barriers for error prevention can easily be breached. The context of human performance has come to be the target of analysis in second-generation HRA rather than human performance itself. Important contextual factors to be analyzed are chosen based on the consideration of cognitive processes that will produce the expected human performance. This was a great shift of conceptualization from the mechanistic image of human performance behind first-generation HRA.

24.3.3 Cognitive Model of Team Performance

The drawbacks of first-generation HRA are attributable to its basic assumption of the decomposition principle that a human task can be decomposed into elementary task units. It is equivalent to the assumption in the linear system that the whole is the sum of its parts. It will be shown in this subsection that this assumption does not apply to team performance. Since teamwork is used in most business settings, the reliability of team performance must be assessed in PRA, and some model of team performance is required to do so. The simplest approach is to combine multiple models of individual performance and this approach was actually taken in the early stage of development. A team, however, is a nonlinear system so that team performance is greater than the simple sum of individual performance.

The cognitive processes of team performance can be effectively described by the concept of mutual beliefs. Tuomela and Miller introduced a notion of "We-Intentions" to describe the cognitive mechanism in a cooperating team as follows [11]. When a team composed of two members, A and B, intends to do a cooperative task X, the following conditions hold.

(1) A/B intends to do A's/B's own part of X. (intention)
(2) A/B believes that B/A will do B's/A's part of X. (belief)
(3) A/B believes that B/A believes that A/B will do A's/B's own part of X. (belief on belief)

Beliefs like (2) and (3) in the above, which can be recursively defined, are called mutual beliefs. Such an explanation of the cooperation mechanism using one's own cognitive state and a corresponding structure of recursive beliefs can clarify the constitutive meaning of "sharing" intentions by cooperating team members.

Kanno applied the above notion of mutual beliefs not only to team intentions but also to cognitive team processes in general and proposed the Mutual Belief Model (MBM) to represent the team cooperation mechanism [12]. Figure 24.4 shows a recursive structure of cognition and corresponding beliefs of a two-member team. The recursive structure of mutual beliefs can be theoretically defined ad infinitum, but the three layers shown here will be sufficient to describe realistic cooperating situations.

One's own cognition on the state of the external world and oneself is described in the first MBM layer. The beliefs on the partner's cognition are described in the second MBM layer, which is a reflected image of the partner's first layer. The third MBM layer is for describing the beliefs on the partner's beliefs on one's own cognition. It is one's self image through the partner. Since the second and the third MBM layers are nonexistent in the cognitive model of an individual, a model that merely combines individuals will not contain both layers.

Cooperative team performance can be achieved using all of these MBM layers. Cognitive entities on each MBM layer are obtained and related by various types

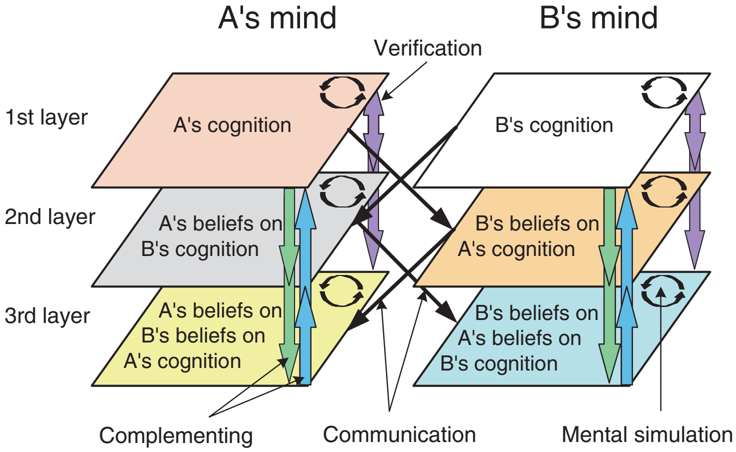

Fig. 24.4 Mutual Belief Model and interactions

of interactions within the layer or between different layers. These interactions are classified into four types: verbal communication, mental simulation, complementing, and verification.

Verbal communication is a process to transfer some cognitive entity from one person to another by explicit utterance. Mental simulation is a process to derive new cognitive entities from some others within the same MBM layer by inference using knowledge and manipulating mental models. Mental simulation is a process for interpretation and prediction not only of the state of external world but also of the partner's behavior. In complementing, some cognitive entity will be copied from one MBM layer to another within the same person. One adopts this scheme, for instance, in an occasion where he/she supposes his/her partner believes X because he/she believes X. Such a supposition, however, sometimes results in false presumption. Finally, verification is the comparison of cognitive entities between different MBM layers to check consistency among mutual beliefs.

The cognitive processes mentioned above are nonlinear effects in terms of a combination of individual cognitive processes, and MBM becomes much more complex for a team larger than a dyad. Team cooperation by humans is more than simple division of labor. Accidents often occur with highly automated systems with no hardware failures, because mutual beliefs and cooperating interactions are lacking in systems where a linear human-machine combination is assumed. Consideration of the nonlinear nature of team performance is necessary also for sophisticated human-machine cooperation.

24.3.4 Safety Culture and High Reliability Organization

Safety culture was a new concept in systems safety that was introduced after the Chernobyl accident. As already mentioned, many organizational and social factors were found behind the direct cause of the accident, the operators' violation of the operation rules. This finding led safety specialists to attend to safety culture. Safety culture resides at the basis of the three factors shown in Fig. 24.3 that form the context of human performance. In order to prevent organizational accidents, safety culture has to be implemented and maintained by organizations.

A key question is how we can implement safety culture in organizations and maintain it. Research on organization science, in particular on high reliability organizations, gives us valuable implications to answer this question. A High Reliability Organization (HRO) is an organization where accidents and incidents are suppressed below the standard level of the related industry sector. The idea first came from the pioneering work by a group at the University of California, Berkeley [13]. This group examined behavioral patterns of work groups under high-risk and stressful conditions such as aircraft carriers, air traffic control, and nuclear power plants. From these studies, the characteristics observable in common among various HROs have been revealed, which is represented in a word, mindfulness. Mindfulness consists of the following five elementary characteristics:

- Preoccupation with failure;
- Reluctance to simplify interpretations;
- Sensitivity to operations;
- Commitment to resilience;
- Deference to expertise.

Organizations that incorporate the above characteristics can handle unanticipated situations skillfully and can recover from emergency rapidly.

Safety culture and HROs first drew attention for solving problems in the era of socio-technical interactions: how to establish proper interactions between technologies, organizations, and society, and how to avoid organizational accidents. These concepts, however, are related also to the ability of socio-technical systems to cope with unanticipated situations as suggested in the fourth item of the above list, and they give us implications for the era of resilience. A High Reliability Organization is sometimes characterized as a learning organization, the ability to adapt to changes and disturbances by restructuring itself is an essential requirement of a resilient system [14].

24.4 What Is Resilience?

24.4.1 Definition of Resilience

The term resilience has been introduced in different domains, and many researchers have given it somewhat different definitions. Holling [15] first introduced the term in ecology to mean a measure of the persistence of systems and of their ability to absorb changes and disturbances and still maintain the same relationships between populations or state variables.

As for disaster prevention, Bruneau et al. [16] conceptualized seismic resilience as the ability of both physical and social systems to withstand earthquake-generated forces and demands and to cope with earthquake impacts through situation assessment, rapid response, and effective recovery strategies. They pointed out resilience can be defined in terms of the following 4R properties:

- Robustness: strength, or the ability of elements, systems, and other units of analysis to withstand a given level of stress or demand without suffering degradation or loss of function;
- Redundancy: the extent to which elements, systems, or other units of analysis exist that are substitutable, i.e., capable of satisfying functional requirements in the event of disruption, degradation, or loss of functionality;

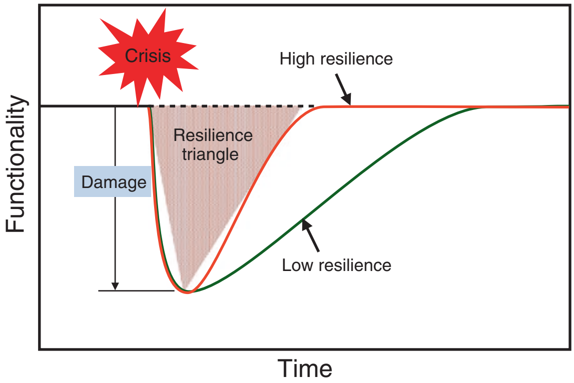

Fig. 24.5 Resilience triangle

- Resourcefulness: the capacity to identify problems, establish priorities, and mobilize resources when conditions exist that threaten to disrupt some element, system, or other unit of analysis;
- Rapidity: the capacity to meet priorities and achieve goals in a timely manner in order to contain losses and avoid future disruption.

They further proposed a measure of seismic resilience, a resilience triangle, which is shown in Fig. 24.5, where time and system functionality are respectively represented horizontally and vertically. The system functionality degrades after the crisis, but it recovers gradually to return to its level before the crisis in the long run. The recovery will be rapid for a system with a high resilience but slow for that with a low resilience. A resilience triangle is the area of degradation in quality of infrastructure over time just after an earthquake to recovery.

The above definition of seismic resilience provides useful insights for discussion on systems resilience. The scope, however, is too restricted within crisis management after disasters. It focuses just on system responses after a critical event like an earthquake, but does not cover everyday activities of risk management in normal system operations. A more comprehensive view of systems resilience, therefore, is desirable.

Another group who adopted the term around 2,000 is researchers of human factors and cognitive systems engineering [3, 4]. In the early stage of development, they applied a behavioristic view of human performance to assess human error probabilities, but soon faced barriers. Then the mechanism of human cognition was considered to model more precisely the enigma of human performance. In the 1990s, however, they came to recognize that it is almost impossible to model human performance and to assess human reliability based on a mechanistic view of human performance [7].

A complex socio-technical system, which includes humans as system components, shows non-linear interactions among different parts of the system. Such interactions make it difficult to comprehend the system by the decomposition principle, which worked well with mechanical systems in the past. Studies on complex systems have made great progress in the last few decades, and new phenomena characteristic to complex systems with non-linearity have been revealed, e.g., emergence, chaos, fractal, stylized fact, and power law. These works have shown that the probability of highly rare events is much greater than predicted from linear system models and normal distribution. Such an improbable event that exceeds people's imagination is called the Black Swan [17]. Risk management based on the assumption of linear systems and the decomposition principle could not foresee such rare events, and people in non-technological domains often criticized this approach [18].

These findings on complex systems, however, stimulated our investigations into the safety of complex socio-technical systems. Kastenberg [19], for instance, pointed out it is necessary to consider the nonlinear, self-organizing, or chaotic nature of complex systems in risk analysis. Researchers of systems safety are now looking at resilience engineering as a more comprehensive and advanced concept of risk management. This new notion is based on a systemic view of accidents that accidents are caused by a nonlinear combination of performance variability of system functions rather than a linear combination of component failures.

24.4.2 Essential Characteristics of Resilience

From a systemic view, resilience is the intrinsic ability of a system to adjust its functioning prior to, during, or following changes and disturbances, so that it can sustain required operations under both expected and unexpected conditions. In contrast to resilience in disaster prevention, the systemic notion of resilience will not distinguish between normal and abnormal system conditions. Resilience engineering is a field that studies technical methodologies to implement resilience into socio-technical systems.

While conventional risk management aims at suppressing risks below the allowable limit, risk management in resilience engineering aims at enhancing the ability of a system to suppress performance variability under changes, disturbances, and uncertainties. Resilience, therefore, deals with every system condition: stable operations in normal conditions, prevention of accidents in abnormal conditions, minimization of losses after accidents, and fast recovery from damaged conditions.

Woods pointed out that the focus is on assessing the organization's adaptive capacity relative to challenges to that capacity and that the following are essential characteristics of resilience [20].

- Buffering capacity: the size or kinds of disruptions the system can absorb or adapt to without a fundamental breakdown in performance or in the system's structure;

- Flexibility: the system's ability to restructure itself in response to external changes or pressures;
- Margin: how closely or how precarious the system is currently operating relative to one or another kind of performance boundary;
- Tolerance: how a system behaves near a boundary, whether the system gracefully degrades as stress/pressure increase, or collapses quickly when pressure exceeds adaptive capacity.

Figure 24.6 illustrates the above four characteristics of resilience. The current state of the system in operation is represented as a point in the two-dimensional state space here, and it fluctuates continuously due to performance variability. Safety boundaries that correspond to the constraints for safe system operations determine the area where the system can be operated.

Margin is a distance between the current operating point and the nearest boundary. Sufficient margin must be maintained so that the probability that the system may run out of the safe area will not exceed the design basis. It is the conventional approach to risk management.

In contrast, the other three properties are relatively new in risk management. Buffering capacity is the ability of a system to absorb or resist changes or disturbances. The resilience triangle mentioned in the previous section can be a measure of buffering capacity, which is represented as the speed of recovery from damage. Tolerance represents how gracefully system functionality degrades outside the safety boundaries. In a system with no tolerance the functionality drops immediately outside the boundaries. Flexibility is related to the ability of a system to adapt to changes and disturbances by restructuring itself, redesigning, maintaining, and learning from past experience.

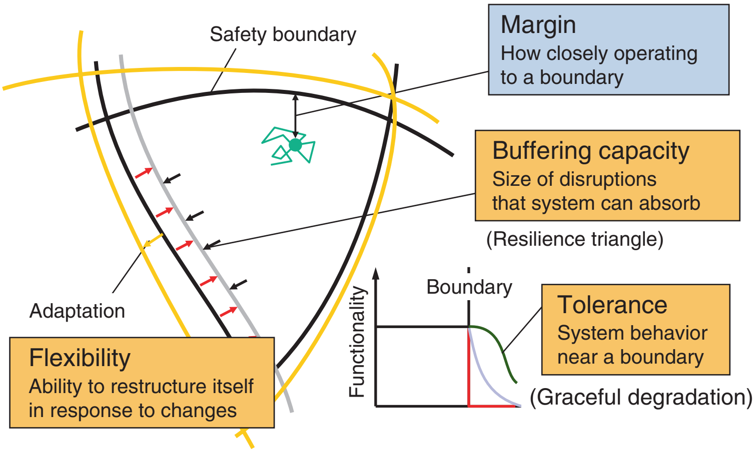

Fig. 24.6 Essential characteristics of resilience

24.5 Social Aspect of Resilience

Assessment of resilience, preferably quantitative assessment, must be the first step to resilience engineering. Since resilience concerns various aspects of system response to changes, there can be multiple measures. The resilience triangle is useful but it cannot be the only measure of resilience.

In addition, we should recognize that resilience is different for different stakeholders. The functionality people expect with a socio-technical system is different for different people, because different people have different interests, sense of values, needs, and so on. In discussing resilience engineering of socio-technical systems, some framework and methodology for resilience assessment that can consider such differences is highly necessary.

Figure 24.7 demonstrates this issue for recovery of infrastructures after the Great East Japan Earthquake. Resilience triangles are drawn here for different stakeholders and for different levels of needs. These results were obtained from the records of activities actually engaged in after the disaster.

Maslow [21] proposed a five-layered hierarchy of human needs, and the levels assessed in this example correspond to the basic three layers in Maslow's hierarchy: physiological, safety, and social needs. Figure 24.7 shows the resilience triangles for physiological and social needs. Physiological needs, which include air, water, food, clothing, and shelter, are the most fundamental needs for survival and they are located at the bottom of the hierarchy. Safety needs are located above physiological needs. They are related to individual safety and freedom from fear, which include personal security, financial security, health, protection against hazards and threats, etc. Social needs, which are located next above safety needs, are desires to be liked by others, to have interpersonal relationships, to belong to community, etc.

The assessment measure of each needs level was divided into more elementary measures until basic data on availability of separate infrastructure services were reached (Table 24.1). The basic data on the recovery rate of infrastructures after the earthquake were collected primarily from Internet web pages.

To consider different stakeholders, the persona method was used. The persona method is an attempt proposed by Cooper [22] in 1980s for reflecting different user needs and characteristics in product design. A persona is an imaginary

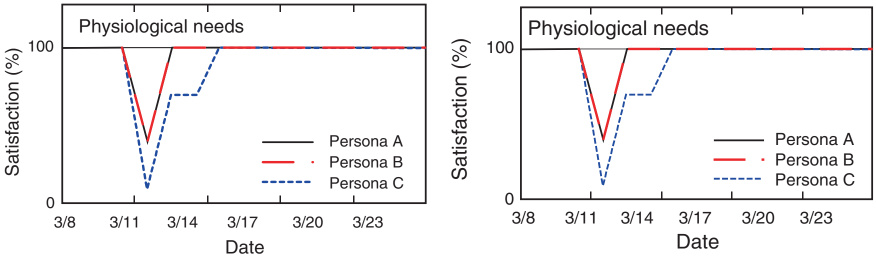

Fig. 24.7 Resilience triangle of utilities after the Great East Japan Earthquake

Table 24.1 Decomposition of assessment measure

Needs level	Item	Basic data
Physiological	Water	Water supply, water wagons
	Food	Shops, distribution
	Dwelling	Home, evacuation centers
	Medical care	Hospitals
	…	…
Safety	Electricity	Electricity grid, generators
	Water	Water supply
	Gas	Gas lines
	Information	Internet, TV, radio
	…	…
Social	Privacy	Home or evacuation center
	Job	Workplace, employer
	Relatives	State of relatives
	Property	House, cars
	…	…

but very specific user model that should be considered in designing products or services. In the persona method, many personas can cover the whole scope of expected users. Three personas of residents in the same town, Kesennuma, but of different features were created and used in this trial referring to opened notes of victims. Persona A is a male employee in his 20s, Persona B is a self-employed businessman in his 40s, and Persona C is a retired male in his 70s. Needs for different infrastructure services were then evaluated for each persona to assess the satisfaction level of physiological, safety, and social needs.

As shown in Fig. 24.7, difference in needs level and stakeholders affect the result of resilience assessment considerably. As for physiological needs, for instance, satisfaction dropped greatly and its recovery delayed for Persona C, because his health condition was poor and healthcare service was relatively critical. As for social needs, recovery of satisfaction was delayed greatly for Persona B, because he could not restart his self-owned business and lost financial independence.

It is a difficult task to establish assessment measures and methods that can cover various aspects of resilience as discussed in the previous section. In addition, however, it is also necessary to consider human perception and human recognition in assessment of resilience as demonstrated in this trial. Otherwise, outcomes of resilience engineering will not match our real needs, and the interests of vulnerable people will be ignored.

24.6 Key Issues in Resilience Engineering

24.6.1 Implementation Process of Resilience

The common characteristics of HROs give us a hint as to how we can incorporate resilience into socio-technical systems. In order to prevent resonance of function variability, the organizations have to repeat the process of four activities: anticipation, monitoring, response, and adaptation. In anticipation, the organization anticipates short-term and long-term threats and changes and gets ready for these threats and changes. In monitoring, the organization monitors operation conditions of the system to detect precursors of unfavorable performance variability that may cause resonance. The organization then takes actions to suppress performance variability so that the system will not go beyond its safety boundaries. Finally, the organization learns from past experience and restructures itself to adapt so that the system can absorb long-term changes.

Most of the base technologies for each step of the above process have already been developed in conventional domains, while more advanced technologies are also expected in the future. Based on these fundamental technologies, the methodologies for synthesizing them, assessing systems resilience, and social installation of the outcomes of research should be pursued. The key issues to be resolved in resilience engineering are as follows.

24.6.2 Assessment of Resilience

Though the resilience triangle shown in Fig. 24.5 is a simple but promising measure for quantitatively assessing systems resilience, the measure for representing system functionality has some arbitrariness. It is also argued that the cost of system recovery should be considered in the resilience measure [23]. The more cost is required, the less resilient the system becomes even if the area of resilience triangle is the same. In addition, the essential characteristics of resilience discussed in Sect. 24.5 should be reflected in the resilience measure. Among these characteristics, safety margin can be represented with risk measures that have been used in the conventional risk management, but the metrics for the other three characteristics have to be established in the future study.

Consideration of different stakeholders as discussed in the previous section is another issue in assessment of resilience. Which function of socio-technical systems is important depends on the situation where a particular stakeholder is placed. As shown in the case of the previous section, the needs for medical services are different between elderly people suffering some health problems and healthy young people. Socially vulnerable groups sometimes have to be taken into account in assessment of resilience rather than considering the average image of the public.

24.6.3 Interdependencies Between Systems

Our society is a complex system of systems that is composed of many systems linked together; it is impossible to understand the behavior of the total system if we look at systems separately. Critical infrastructures, for instance, including the electric power system, the water supply system, the transportation system, and the telecommunication system, are interrelated to each other, and one system depends on the others. The telecommunication system, for instance, does not work without electric power supply, and the electric power system is controlled using the telecommunication system. The breakdown of one system, therefore, sometimes leads to the breakdown of other systems.

A complex system spreads in a physical space and disturbance in one location sometimes propagates to another. It may cause the breakdown of the system over a wide area. The disturbance may propagate further to another system through the interdependencies among different systems. There is a fear that such cascading failures of critical infrastructures might result in serious damage to society.

In order to prevent such cascading failures in case of a devastating natural disaster, terrorist attack, or a crisis of the world market, it is necessary to understand system behavior including the interdependencies and take remedial actions to eliminate vulnerabilities in the system. In order to enhance the resilience of a system of systems, recovery plans must consider the interdependencies among different systems. Technologies allowing for a large-scale simulation are expected to be developed to consider the interdependencies of a system of systems.

24.6.4 Decision Support

In case of a crisis such that the function of a socio-technical system has been severely damaged, some mechanism is highly necessary to collect information on the location, type, and scale of damage, victims' requirements, distribution of resources available for system recovery, and to deliver the information to decision makers. Since fixed sensor-telecommunication networks will be damaged by the disaster, mobile systems that can be deployed over the affected area will be needed. Airborne or satellite sensing systems are often very useful for crisis management.

Collected information has to be delivered in a timely manner to decision makers. The critical information required by the decision makers must be selected from a vast amount of collected information, processed, and presented in a comprehensible manner; technologies such as image processing, data mining, information retrieval, and visualization will be effective for this purpose. While some official information and telecommunication systems were not functioning shortly after the Great East Japan Earthquake, some Social Network Services (SNSs) were very usable. In addition to centralized and specialized information systems, therefore, distributed and general-purpose systems should be focused on.

It should be kept in mind that those who ultimately make decisions are humans. Information is not usable for decision-making, if it does not match the cognitive characteristics or capabilities of a human. Consideration of human factors is still important in designing crisis management systems. In addition, since a group or an organization rather than an individual makes decisions in an emergency, communication, team collaboration, and organizational factors have to be considered.

Decision support is required not only to recognize emergency situations but also for recovery planning in real time, considering interdependencies among different systems. For this purpose, technologies such as disaster simulation, recovery plan optimization, and decision support systems should be developed.

24.6.5 Resilience in Ordinary Situations

Discussions so far have focused primarily on an emergency situation, but resilience is also relevant to safety, reliability, and security of socio-technical systems in ordinary situations. Resilience includes abilities of a system to keep its functionality by maintenance, to renovate itself in response to environmental changes, and to improve itself by learning lessons from past experience. While resilience in an emergency corresponds to recovery from a rapid breakdown of system function, resilience in an ordinary situation corresponds to recovery from a slow degradation of system function.

Maximum efforts are made to detect and eliminate latent flaws in a system in the conventional approach to risk management. It is, however, impossible to operate a complex socio-technical system with no flaws, thus we are forced to accept some latent flaws. Resilience engineering takes the position that function variability in a system is inevitable but that resonance and propagation of function variability have to be damped down to avoid accidents. Flexible response to environmental changes is a key to realizing resilient systems.

Minor incidents will occur frequently in every socio-technical system, but the trends of minor incidents will change following environmental changes. Organizational activities of collecting, analyzing information of such incidents, and renovating the facility, organization, or operations referring to the outcomes of analysis are essential for avoidance of large-scale accidents. Such activities are thought of as organizational learning or system evolution in a larger scale than the conventional activities of accident and incident analysis.

24.6.6 Social Installation

In order to install the outcomes of resilience engineering into society, redesign of social institutions and organizational operations will be necessary. How to motivate people to adopt the outcomes is a key issue here. Side effects, such as people responding to new technologies or new social institutions in an unanticipated manner that cause unfavorable consequences, have to be avoided. Studies on social simulation, organizational management, and project management, will contribute to designing social institutions and organizational operations considering such side effects.

Finally, new technologies must be accepted with consensus among people. When specialists claim that technologies contribute to realizing a better society, they will be asked questions on what are the criteria of social goodness and for whom it will be a better society. These questions should not be answered only by specialist as consensus must be developed among interested people.

24.7 Conclusion

The focal point of systems safety has shifted from technologies to human errors, socio-technical interactions, and now resilience as the scale and complexity of socio-technical systems have increased. Prevention of disasters is the main goal of the conventional approach to risk management, and it is achieved in terms of the design basis that is determined based on certain assumptions. If the reality exceeds these assumptions, losses will occur. Having experienced several disasters, however, like the terrorist attack on WTC and the Great East Japan Earthquake, people have recognized that society has to be ready also for unanticipated situations. Resilience, which is the ability of a socio-technical system to absorb effects of disturbances, maintain its normal function, and recover from damage, is a new frontier in systems safety proposed for answering this issue.

References

1. Dougherty EM, Fragola JR (1988) Human reliability analysis. John Wiley & Sons, New York
2. Reason JT (1977) Managing the risks of organizational accidents. Ashgate, Aldershot, UK
3. Hollnagel E, Rigaud E (eds) (2006) Proc. 2nd Resilience Engineering Symposium
4. Hollnagel E, Woods DD, Leveson N (eds) (2006) Resilience engineering: Concepts and precepts. Ashgate, Aldershot, UK
5. Hall RE, Fragola J, Wreathall J (1982) Post event human decision errors: Operator action tree/time reliability correlation. NUREG/CR-3010, BNL-NUREG-51601
6. US Nuclear Regulatory Commission (1994) Reactor safety study: An assessment of accident risks in U.S. commercial nuclear power plants. WASH-1400 (NUREG-75/014)
7. Dougherty EM (1990) Human reliability analysis—where shouldst thou turn. Reliability Engineering and System Safety 29: 283-299
8. Rasmussen J (1983) Skills, rules, knowledge: signals, signs, and symbols and other distinctions in human performance models. IEEE Trans. Systems, Man, and Cybernetics. MSC-13: 257-267
9. US Nuclear Regulatory Commission (2000) Technical basis and implementation guidelines for a technique for human event analysis (ATHEANA). NUREG-1628
10. Hollnagel E (1998) Cognitive Reliability and Error Analysis Method. Elsevier, Oxford, UK

11. Tuomela R, Miller K (1988) WE-INTENTIONS. Philosophical Studies 53: 367-389
12. Kanno T (2007) The notion of sharedness based on mutual belief. Proc 12th Int. Conf. Human-Computer Interaction. Beijing: 1347-1351
13. Roberts KH (1990) Some characteristics of high-reliability organizations. Organization Science 1: 160-177
14. Senge PM (1990) The fifth discipline: The art & practice of the learning organization. Random House, New York, US
15. Holling CS (1973) Resilience and stability of ecological systems. Annual Review of Ecology and Systematics 4: 1-23
16. Bruneau M, Chang SE, Eguchi RT, Lee GC, O'Rourke TD, Reinhorn AM, Shinozuka M, Tierney K, Wallace WA, von Winterfeldt D (2003) A framework to quantitatively assess and enhance the seismic resilience of communities. Earthquake Spectra 19(4): 733-752
17. Taleb NN (2007) The black swan: The impact of the highly improbable. Random House, New York
18. Perrow C (1999) Normal accidents: Living with high-risk technologies. Princeton University Press, Princeton
19. Kastenberg WE (2002) On redefining the culture of risk aanalysis. Proc. 6th Int. Conf. Probabilistic Safety Assessment and Management (PSAM6), San Juan, 2002
20. Woods DD (2006) Essential characteristics of resilience. In Hollnagel E, Woods DD, Leveson N (eds) (2006) Resilience engineering: Concepts and precepts, pp. 21-34. Ashgate, Aldershot, UK
21. Maslow AH (1954) Motivation and personality. Harper & Row, New York
22. Cooper A (1999) The inmates are running the asylum. Macmillan, New York
23. Vugrin ED, Warren DE, Ehlen MA, Camphouse RC (2010) A framework for assessing the resilience of infrastructure and economic systems. In Gopalakrishnan K, Peeta S (eds) (2010) Sustainable and resilient critical infrastructure systems, pp. 77-116. Springer, Heidelberg, Germany

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Approaches Developed in the GoNERI Program

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