AMERICAN NUCLEAR SOCIETY

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FUKUSHIMA DAIICHI: ANS Committee Report

A Report by

The American Nuclear Society Special Committee on Fukushima

March 2012

Cover photograph: The Fukushima Daiichi nuclear power station (left to right): Unit 4, Unit 3, Unit 2, and Unit 1, pictured on February 26, 2012. (REUTERS/*Yomiuri Shimbun*)

ACKNOWLEDGMENTS

As the news of the historic March 11, 2011, Tohoku earthquake reached the United States, the nuclear community was relieved to hear that the reactors at several locations along the Japanese coast appeared to be undamaged. However, as pictures of the devastation from the subsequent tsunami began to appear, such relief was short-lived. It became clear that the events at the Fukushima Daiichi nuclear power station would mark a significant time in the history of nuclear technology. As nuclear scientists and engineers and as members of the American Nuclear Society (ANS), we knew that we were obliged to present our collective understanding of the facts and to present them in context, without bias. Hence, the ANS Special Committee on Fukushima was organized to do exactly that, in this "Fukushima Daiichi: ANS Committee Report."

We thank the many nuclear professionals, the ANS leadership, and staff, who willingly gave their time to the project. This report would not have been possible without their hard work and dedication. We thank all of them for stepping forward, together, to carry the light of science and truth in a time of crisis to combat fear, uncertainty, and misinformation.

The Fukushima Daiichi accident will be a subject of intense scrutiny and study for years to come. However, the bravery and the courage of the people of Japan and the extraordinary efforts made by brilliant engineers, operators, and technicians who recovered a six-reactor site from one of the worst natural disasters ever seen under horrific conditions are unquestionable. These people inspired our work.

Dale Klein
Co-Chairman
ANS Special Committee on Fukushima

Michael Corradini
Co-Chairman
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A Report by
The American Nuclear Society Special Committee on Fukushima

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FOREWORD

The Tohoku earthquake, which occurred at 2:46 p.m. (Japan time) on Friday, March 11, 2011, on the east coast of northern Japan, is believed to be one of the largest earthquakes in recorded history. Following the earthquake on Friday afternoon, the nuclear power plants at the Fukushima Daiichi, Fukushima Daini, Higashidori, Onagawa, and Tokai Daini nuclear power stations (NPSs) were affected, and emergency systems were activated. The earthquake caused a tsunami, which hit the east coast of Japan and caused a loss of all on-site and off-site power at the Fukushima Daiichi NPS, leaving it without any emergency power. The resultant damage to fuel, reactor, and containment caused a release of radioactive materials to the region surrounding the NPS. Although the United States was not directly affected, our nuclear power industry will take important lessons from this accident.

The American Nuclear Society (ANS) formed a special committee, The American Nuclear Society Special Committee on Fukushima (the Committee), to examine the Fukushima Daiichi accident. The Committee was charged to provide a clear and concise explanation of the accident events, health physics, and accident cleanup, as well as safety-related issues that emerged. The Committee also evaluated actions that ANS should consider to better communicate with the public during a nuclear event.

The Committee used publically available source materials from the Japanese industry and government as well as reports from those entities to the international community, as indicated in the sections “References” and “Bibliography.” The Committee views do not reflect any major inconsistencies regarding accident events, health physics, and accident cleanup. The safety-related issues identified by the Committee are consistent with what has been noted in the reports already issued from many regulatory agencies. Finally, the Committee focused on risk communication and crisis communication as major issues that ANS as a professional society needs to address in the future.

The Committee worked from May 2011 to December 2011. Because the accident forensics, accident cleanup, and associated off-site health effects are ongoing, the Committee will continue to update the detailed accident-related information at the ANS Web site (http://fukushima.ans.org/) as new measurements, facts, insights, and regulatory developments are gained. An embedded topical meeting, International Meeting on Severe Accident Assessment and Management: Lessons Learned from Fukushima Daiichi, will be held as part of the ANS Winter Meeting in November 2012.

EXECUTIVE SUMMARY

The Tohoku earthquake of 2011 is believed to be one of the largest earthquakes in recorded history. It, along with the tsunami it triggered, is estimated to have caused nearly 20,000 deaths and economic losses approaching $500 billion (USD). Yet, despite the sheer scale of destruction in northeastern Japan, the accident at the Fukushima Daiichi nuclear power station (NPS) has come to define the tragedy for many and has become a momentous event in nuclear power technology.

In April 2011, Joe Colvin, American Nuclear Society (ANS) president at the time, formed the American Nuclear Society Special Committee on Fukushima (the Committee) to provide a clear and concise explanation of what happened during the Fukushima Daiichi accident and offer recommendations based upon both the technological and the public communications lessons learned from the event. The ANS leadership understood that sharing the lessons learned from the events of Fukushima Daiichi is important and that embracing such communications must become part of the professional culture of ANS. In this way the leadership not only serves its members' interests but also fulfills its professional obligation to advance nuclear safety.

The Committee's recommendations are generally consistent with the regulatory issues raised by national and international bodies. The Committee also focused on key technical issues that would underpin any specific set of regulatory actions.

The Committee found that no aspect of the Fukushima Daiichi accident indicates a priori that the level of safety of nuclear power plants (NPPs) in the United States is unacceptable. Indeed, the Committee agrees with the U.S. Nuclear Regulatory Commission (NRC) that the current level of safety provides adequate protection to the health and safety of the U.S. public. However, the Committee believes that elements of the accident that relate to observed vulnerabilities in the ability of NPPs to respond to such an extreme natural event must be examined with care. As importantly, the Committee believes that in responding to the accident at the Fukushima Daiichi NPS, human error and flaws in governance and regulatory oversight contributed to the severity of the accident. These errors and human factors must be understood and addressed before substantively modifying technology.

The following recommendations are consistent with this general conclusion. These recommendations are strictly motivated by the Committee's understanding of the Fukushima Daiichi accident. Its technical recommendations are largely aligned with the suggested regulatory actions proposed by the NRC Japan Near-Term Task Force, which was established to conduct a systematic and methodical review of NRC processes and regulations in light of the Fukushima Daiichi accident.

Risk-Informed Regulation

The NRC should review the scope of reactor safety design and regulation. This review should consider the adequacy of design bases for natural-phenomenon hazards and the need for extension of the design basis in a graded manner, using a risk-informed approach, into what have previously been considered beyond-design-basis accidents.

Hazards from Extreme Natural Phenomena

The tsunami design bases for the Fukushima NPPs were inadequate. If the return period for a tsunami of the magnitude experienced in Japan was as short as reported (once every 1000 years), a risk-informed regulatory approach would have identified the existing design bases as deficient. Although addressing low-probability events is very difficult, a risk-informed treatment for natural-phenomenon hazards is necessary.

Multiple-Unit-Site Considerations

Recognizing that the high cost and lengthy schedule to obtain site approval are powerful incentives for multiple-unit sites, the Committee recommends that the appropriate regulatory bodies conduct a multiple-unit risk assessment whenever a unit is added to a site. Such a risk analysis should include sensitivities to determine the extent to which multiple-unit considerations increase or decrease the risk.

Hardware Design Modifications

Analysis of the Fukushima Daiichi accident has identified a series of hardware-related modifications that may be considered by near-term regulation. Their relevance and applicability are plant specific, and thus, any generic modification should first be subjected to some form of cost-benefit analysis. Furthermore, if taken one at a time, resolution of these hardware issues may lead to unintended systems-interaction effects. Therefore, an overall systems-interaction study needs to be undertaken when looking at the combined effect of any changes to be certain that substantial safety benefits are actually realized.

Severe Accident Management Guidelines

The industry needs to develop a consensus with the NRC regarding the intent and scope of severe accident management guidelines (SAMGs), including the manner in which they interface with emergency operating procedures. Then, the SAMGs need to be revised at NPPs according to the new criteria. To the extent that the SAMGs require information regarding the status of NPP parameters, the need for additional instrumentation at operating NPPs may be warranted.

Accident Diagnostics Tool

To provide the operators with information regarding the progression of an accident, an accident diagnostics tool, which could help identify the most effective strategy to manage a prolonged station blackout or other sequence, should be developed. This information might be provided in the form of pre-prepared charts or generated for the actual conditions of the NPP by a faster-than-real-time simulator that can predict the gross behavior of the essential NPP subsystems under beyond-design-basis conditions, especially before substantial core damage occurs, so that core damage can actually be prevented.

Command and Control During a Reactor Accident

The Committee determined that the severity of the Fukushima Daiichi accident was exacerbated by an unclear chain of command. We recommend that the predefined command-and-control system currently employed in the United States for emergency situations at NPPs be reviewed to ensure that necessary accident management decisions can be taken promptly at the proper operational level. The chain of command must be able to react swiftly to an accident and thereby minimize the overall consequences for society.

Emergency Planning

The U.S. nuclear community recognizes the need for a clear approach to emergency planning in case of a serious accident. We recommend that the NRC work together with other agencies and industry to develop a more risk-informed approach to emergency planning for U.S. NPPs.

Health Physics

The Committee collected published information and data for radiation exposure, release and deposition of radioactive materials, and contamination of water and food sources. The information suggests that off-site health consequences of the Fukushima Daiichi accident may ultimately be minimal; however, the Committee believes it is too early to make any firm conclusions regarding these data and the definitive health impacts to workers or to members of the public.

Societal Risk Comparison

The Committee recommends that the federal government undertake a quantitative assessment of the societal benefits and risks—including indirect costs and externalities—relating to all energy sources. The Committee is aware of the ExternE project by the European Commission as an example of past work that could be used as a starting point for a future U.S. study.

ANS Risk Communication and Crisis Communication

The Committee focused on addressing the role and activities of a professional scientific membership society before, during, and after a nuclear event. As such, it recommends that ANS develop a Nuclear Event Communications Plan (the Plan). The Plan should include a robust, proactive, and ongoing communications program for key audiences, such as the media and Congressional policy makers. The Plan should also incorporate digital and social media tools to support the communications efforts. In particular, the Committee urges ANS to work with other professional societies to share risk communications resources in general and specifically to develop improved methods of communicating radiation facts/information and radiation risk to the public.

NOTE: Unless otherwise indicated, all dates in this report are for 2011.

I. BACKGROUND

I.A. The Tohoku Earthquake and Tsunami

Japan is located along the Pacific Ring of Fire, which is an area that rings the Pacific Ocean and is characterized by mountains, volcanoes, and faults. Of the 16 largest earthquakes in the world recorded since 1900, 15 occurred in the Pacific Ring of Fire. On Friday, March 11, 2011, at 2:46 p.m. (Japan time),[1] the largest earthquake in the recorded history of Japan (and one of the largest in the recorded history of the world) occurred on the east coast of northern Japan: the Tohoku earthquake (hereafter referred to simply as "the earthquake"). The earthquake was felt at Fukushima and in much of eastern Honshu, including the Tokyo-Yokohama area. The earthquake was felt from the island of Hokkaido to the island of Kyushu. Beyond Japan, the earthquake was felt in the Northern Mariana Islands, North Korea, Taiwan, northeastern China, and southeastern Russia (Fig. 1).

Figure 1. Epicenter of the earthquake.

The earthquake generated a major tsunami, which was the catastrophic blow of a "one-two punch." The majority of casualties and damage, which occurred in the prefectures of Iwate, Miyagi, and Fukushima, was caused by the tsunami. Along the entire east coast of Honshu from Chiba to Aomori, at least 15,700 people were killed, 4,650 went missing, 5,300 were injured, and 131,000 were displaced; moreover, at least 332,400 buildings; 2,100 roads; 56 bridges; and 26 railways were destroyed or damaged. The total economic loss in Japan is estimated to be about $500 billion (USD). Electricity, gas and water supplies, telecommunications, and railway service were disrupted. Such disruptions affected the Fukushima Daiichi nuclear power plant (NPP) reactors, which were severely damaged. This is where the nuclear story begins.

I.B. Light Water Reactors

Of the more than 400 NPPs currently operating throughout the world, accumulating ~16,000 years of reactor experience, >90% are light water reactors (LWRs), which produce heat by controlled nuclear fission and are cooled by water. In the United States, all 104 operating NPPs are LWR NPPs. There are two general LWR designs: boiling water reactors (BWRs) (Fig. 2) and pressurized water reactors (PWRs) (Fig. 3). In BWRs, the heat generated by fission turns the water into steam, which directly drives the power-generating turbines and the electrical generator connected to them. In PWRs, the heat generated by fission is transferred to a secondary loop via a heat exchanger (steam generator), where the steam is produced and drives the power-generating turbines. In both BWRs and PWRs, after flowing through the turbines, the steam turns back into water in the condenser. The water required to cool the condenser is taken from and returned to a nearby ocean, river, or water supply.

Our main focus in this report is BWRs, because the Japanese NPPs involved in the Fukushima Daiichi accident were BWR NPPs.

I.C. Boiling Water Reactors: General Description

In a BWR NPP, the nuclear reactions take place in the nuclear reactor core, which mainly consists of nuclear fuel and control elements. The nuclear fuel rods (each ~10 mm in diameter and 3.7 m in length) are grouped by the hundred into bundles called fuel assemblies

[1]All times in this report are in Japan time.

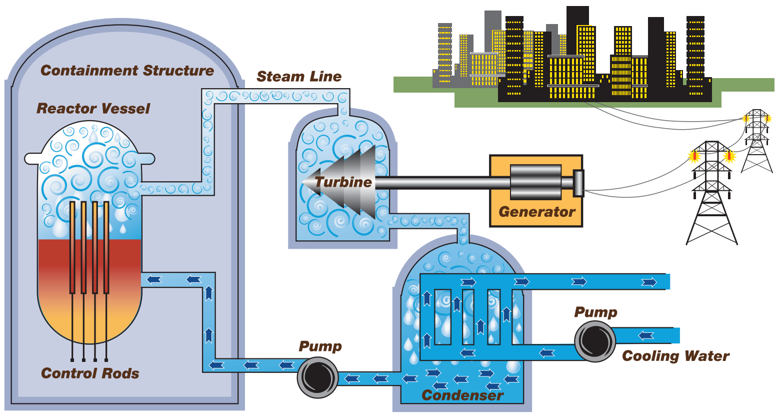


Figure 2. Simplified diagram of a BWR NPP.

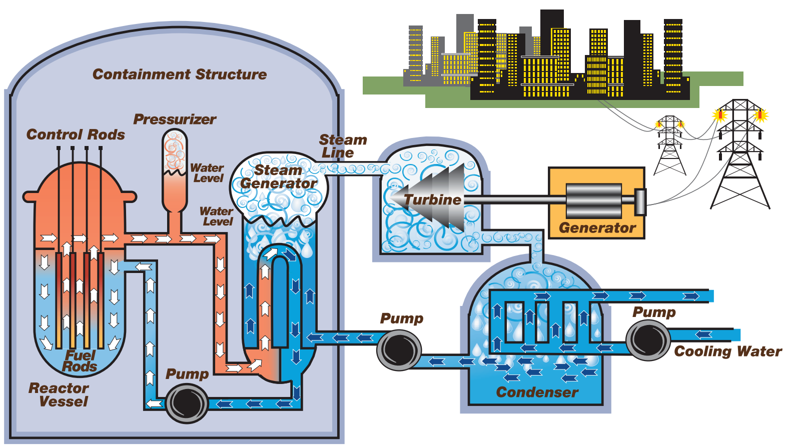


Figure 3. Simplified diagram of a PWR NPP.

(Fig. 4). Inside each fuel rod, pellets of uranium, or more commonly uranium oxide, are stacked end to end. The control elements (shown as red in cross section), called control rods, are filled with substances like boron carbide that readily capture neutrons. When the control rods are fully inserted into the core, they absorb neutrons, precluding a nuclear chain reaction. When the control rods are moved out of the core, enough neutrons are produced by fission and are absorbed by fissile uranium-235 or plutonium-239 nuclei in the fuel rods, causing further fissions, and more neutrons are produced. This chain reaction process becomes self-sustaining, and the reactor becomes critical, producing thermal energy (heat). The fuel and the control rods and the surrounding structures that make up the core are enclosed in a steel pressure vessel called the reactor pressure vessel (RPV) (Fig. 5).

When uranium (or any fissile fuel) is fissioned and energy is produced, fission products (atomic fragments left after a large atomic nuclear fission) remain radioactive even when the fission process halts, and heat is produced from their radioactive decay, i.e., decay heat. Although decay heat decreases quickly from a few percent to <1% of the rated NPP thermal power after a few hours, water must be circulated within the RPV to maintain adequate cooling. This cooling is provided by numerous systems. Some systems operate during normal conditions, and some systems, such as the emergency core cooling systems (ECCSs), respond to off-normal events. Normal reactor cooling systems maintain the RPV and temperature and a proper cooling water level, or if that is not possible, ECCSs directly flood the core with more water. More detail of BWR safety systems is provided below.

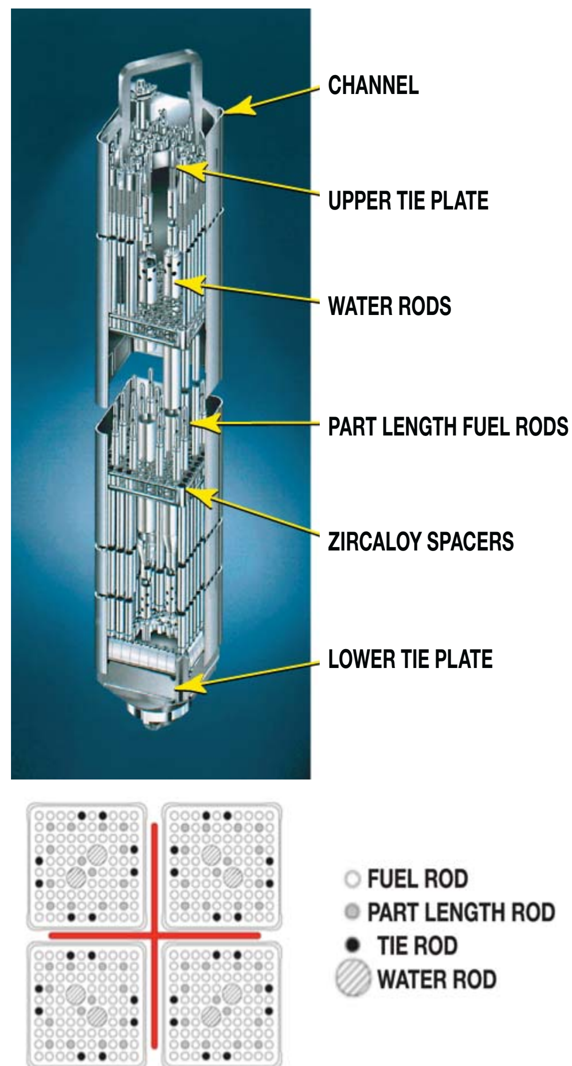
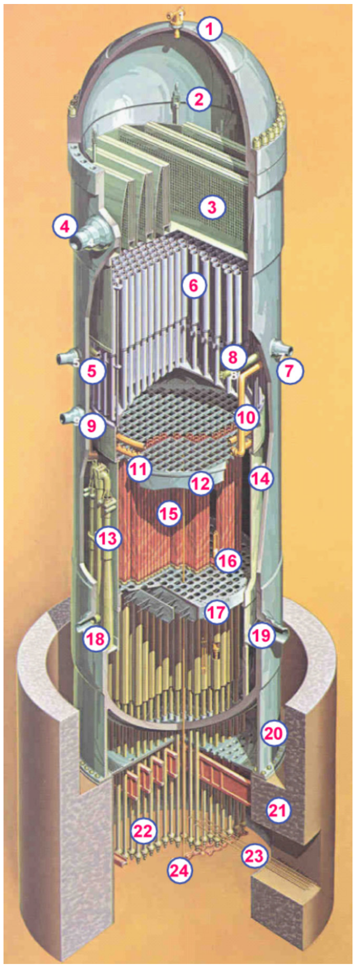


Figure 4. Nuclear fuel assembly for a BWR.

It is important to note that all of these systems require electricity for control and/or motive power for water systems to transfer the decay heat out of the fuel and reactor and into the environment. There are two particular systems in the BWR that require electricity only for control purposes: the isolation condenser system and the reactor core isolation cooling (RCIC) system. These systems play a key role in accident progression.

Because of the large amount of radioactivity that resides in the nuclear reactor core, regardless of the specific design, the defense-in-depth philosophy is used. This approach provides multiple, independent barriers to contain radioactive materials.



1 Vent and Head Spray
2 Steam Dryer Lifting Lug
3 Steam Dryer Assembly
4 Steam Outlet
5 Core Spray Inlet
6 Steam Separator Assembly
7 Feedwater Inlet
8 Feedwater Sparger
9 Low Pressure Coolant Injection Inlet
10 Core Spray Line
11 Core Spray Sparger
12 Top Guide
13 Jet Pump Assembly
14 Core Shroud
15 Fuel Assemblies
16 Control Blade
17 Core Plate
18 Jet Pump/Recirculation Water Inlet
19 Recirculation Water Outlet
20 Vessel Support Skirt
21 Shield Wall
22 Control Rod Drives
23 Control Rod Drive Hydraulic Lines
24 In-Core Flux Monitor

Figure 5. Schematic of a BWR RPV.

In the BWR, the fuel rod itself and the RPV with its primary system act as the first two barriers. The containment system is designed around the RPV and its primary system to be the final barrier to prevent accidental release of radioactive materials to the environment.

Boiling water reactors have evolved through "generations," with each generation comprising iterative BWR design evolutions in steam separation, recirculation, ECCS, and containment design. In particular, "containment" refers to the configuration of the structure and associated systems that enclose the nuclear reactor and are the final barrier to the release of radioactive materials into the environment in the case of a severe accident. Containment designs that are used in operating U.S. BWRs are designated Mark I (the oldest), Mark II, and Mark III (the most recent).

First-generation BWRs (collectively called BWR/1) used a variety of containment configurations, and none are still operating today. The BWR/2 and BWR/3 models have Mark I containments. Most BWR/4s have a Mark I containment; a few have a Mark II containment. All BWR/5s have a Mark II containment, and all BWR/6s have a Mark III containment.

The Mark I containment system design is the one that was challenged most severely at Fukushima Daiichi and is indicated in Fig. 6. It is important to note that the containment system is not only a physical boundary but also a series of systems and components that are designed to prevent the release of radioactivity. As Fig. 6 shows, the Mark I containment comprises a building (drywell) where the RPV and primary system reside. The drywell is connected to another water-filled suppression chamber (wetwell) (shown in Fig. 6 with a water pool called the suppression pool) that is designed to condense any steam that may be accidentally released in any reactor accident. Further, the wetwell can be cooled

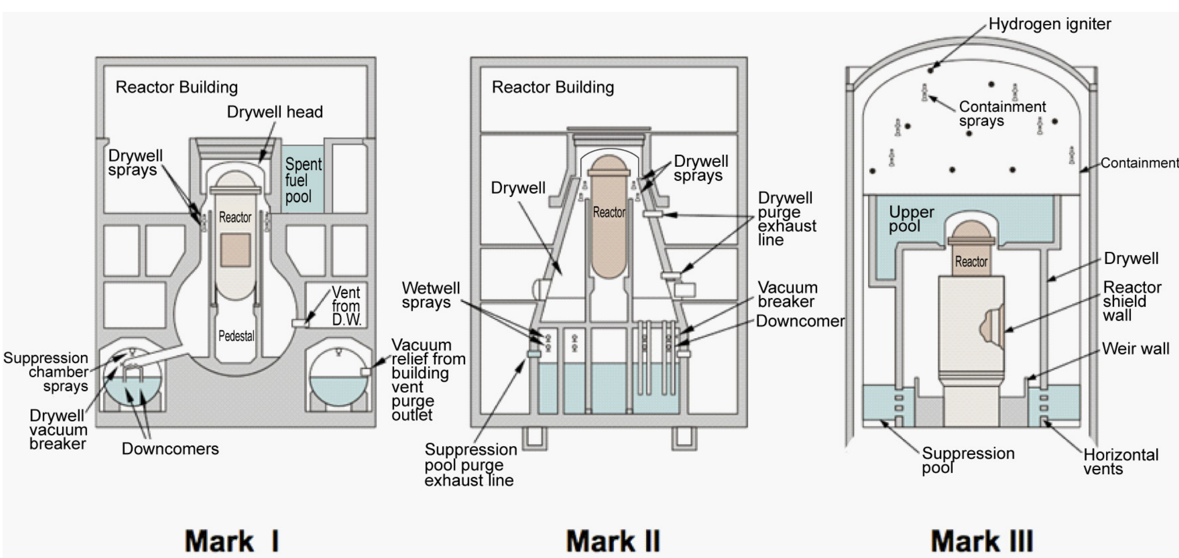


Figure 6. Generations of BWR containments.

over long periods of time to maintain lower pressures and temperatures to maintain its integrity. If this cooling is lost, the wetwell can be vented under controlled conditions by operator action to the atmosphere, where the suppression water pool filters out radioactive material before the release of gases by the vent. In the Fukushima Daiichi accident, the containments were challenged by an extended loss of emergency power for cooling and by delay in initiating the venting process, thus contributing to the failure of the containment and venting system to provide their intended function. The spent-fuel pool (SFP) is also shown and resides outside of the containment in the reactor building.

I.D. Boiling Water Reactors: Safety Systems

All BWRs have control rod drive systems that can be inserted to shut the reactor down. As a backup there is also a standby liquid control system consisting of a neutron-absorbing water solution (borated) that can be injected to shut down the fission chain reaction. After shutdown, the reactor continues to produce reductive low-level decay heat—from a few percent at shutdown, reducing to a fraction of 1% after 1 day—that must be removed in order to prevent overheating of the nuclear fuel.

In the event that the normal heat-removal pathway to the main turbine/condenser is lost, BWRs have, as the first backup, systems to provide core safety by either adding water to the RPV or by an alternate heat removal path, or by both. BWR/3s have isolation condenser systems that both remove the decay heat by condensing the generated steam in the RPV through heat exchange with a water pool outside the drywell and return condensate to the reactor over a wide range of reactor pressures. No additional water is added, however, so if there are leaks in the primary pressure circuit, additional water is required from other sources. BWR/4s and BWR/5s use an RCIC system, which is a turbine-driven pump using reactor steam that can add water to the RPV over a wide range of reactor pressures. The RCIC system draws water from either a large pool inside the containment, the suppression pool, or from a tank located outside the containment, the condensate storage tank (CST). The RCIC system has the advantage that it can provide significantly more water than needed to make up for decay heat–generated steam, but it does not remove the heat. When the reactor becomes isolated from the main turbine/condenser, that heat is transported to the suppression pool via safety and relief valves (SRVs) that open and close to maintain the primary system pressure within safety limits. There is sufficient heat capacity in the suppression pool for many hours of decay heat storage before the heat must be removed from the containment using pumps and heat exchangers requiring electrical power. If this does not occur, the pressure and temperature in the containment will rise as time progresses. If these first backup systems are not sufficient, then ECCSs are provided to both add water to the RPV and to remove decay heat either from the RPV or from the containment. With one exception, all these systems require alternating-current (AC) power that is supplied either by the NPP normal AC distribution system or by emergency diesel generators (EDGs) if the normal supply is lost. The exception is that as part of the ECCSs in BWR/3s and BWR/4s, there is a high-pressure coolant injection (HPCI) system that is a turbine-driven pump that uses reactor steam and that has about seven times the capacity of the RCIC system and can add water over a wide range of reactor pressures.

As we discuss below, because for many hours the Fukushima Daiichi nuclear power station (NPS)[2] was without electrical power and long-term cooling to remove the decay heat to the environment, the aforementioned systems were not available to keep the reactor core from overheating and the fuel from being damaged.

II. ACCIDENT ANALYSIS

II.A. The Event

The earthquake occurred at 2:46 p.m. on Friday, March 11, 2011. A tsunami, caused by the earthquake, arrived at the coastline in several waves ~30 to 45 minutes later. As indicated in Fig. 7, five NPSs, located on the northeast coast of Honshu, Japan's largest island, are in the vicinity of the earthquake/tsunami. They are, going north to south, the Higashidori NPS, the Onagawa NPS, the Fukushima Daiichi NPS, the Fukushima Daini NPS, and the Tokai Daini NPS.[3] These NPSs are the ones that were primarily affected by the earthquake/tsunami. Table 1 gives details of each NPS.

All Japanese NPPs have seismic instrumentation systems that shut down the reactors when a significant earthquake occurs, and when the earthquake occurred, these systems functioned normally for all units. Following the earthquake, all the safety systems, including on-site emergency electrical power, operated as designed. It was the subsequent tsunami that caused the major damage. Let us consider the impact at each NPS.

[2]Nuclear power stations comprise the grounds, the buildings, and the reactors that generate electricity. NPSs can have one or more reactors, which are referred to as units with numbers. For example, the Fukushima Daiichi NPS comprises six reactors, i.e., six units: Unit 1, Unit 2, Unit, 3, Unit 4, Unit 5, and Unit 6.

[3]"Daiichi" and "Daini" roughly translate as "first" and "second," respectively; hence, although not used in this report, "Fukushima 1" (Daiichi) and "Fukushima 2" (Daini) may be used elsewhere.

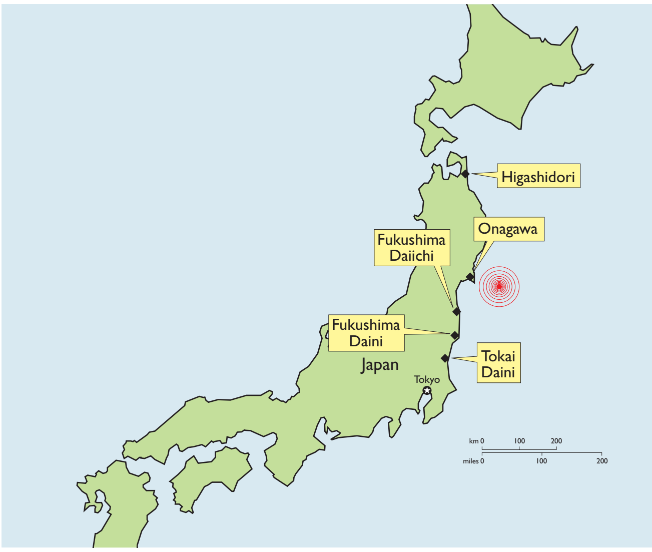


Figure 7. Japanese NPSs near the earthquake/tsunami zone.

II.A.1. Impact at Higashidori NPS

Since Unit 1 was under periodic inspection at the time of the earthquake, all the fuel in the reactor core had already been taken out and placed into the SFP. All three lines of the off-site power supply lost power because of the earthquake. One of the two EDGs was under inspection, but the other EDG started and fed power to the emergency electrical busses to provide the AC power needed for the safety systems.

II.A.2. Impact at Onagawa NPS

Units 1 and 3 were at rated thermal power operation at the time of the earthquake, and Unit 2 was under reactor start-up operation. Four out of the five lines of the off-site power supply were lost as a result of the earthquake, but the off-site power supply was maintained through the continued operation of one power line.

Table 1. Details of Japanese NPSs near earthquake/tsunami zone

Nuclear Power Station	Reactor Model	Containment	Power (MWe)	Status Before Earthquake/Tsunami[a]	Status After Earthquake/Tsunami[a]
Higashidori					
Unit 1	BWR/5	Mark II	1100	Already in cold shutdown and outage	In cold shutdown and outage
Onagawa					
Unit 1	BWR/4	Mark I	524	Operating	Reached cold shutdown March 12
Unit 2	BWR/5	Mark II	825	Start-up	Reached cold shutdown March 11
Unit 3	BWR/5	Mark II	825	Operating	Reached cold shutdown March 12
Fukushima Daiichi					
Unit 1	BWR/3	Mark I	460	Operating	Significant damage
Unit 2	BWR/4	Mark I	784	Operating	Significant damage
Unit 3	BWR/4	Mark I	784	Operating	Significant damage
Unit 4	BWR/4	Mark I	784	Already in cold shutdown and outage	Significant damage
Unit 5	BWR/4	Mark I	784	In cold shutdown and outage; conducting RPV pressure test	Reached cold shutdown March 20[b]
Unit 6	BWR/5	Mark II	1100	In cold shutdown and outage; RPV head on	Reached cold shutdown March 20[b]
Fukushima Daini					
Unit 1	BWR/5	Mark II	1100	Operating	Reached cold shutdown March 14
Unit 2	BWR/5	Mark II	1100	Operating	Reached cold shutdown March 14
Unit 3	BWR/5	Mark II	1100	Operating	Reached cold shutdown March 12
Unit 4	BWR/5	Mark II	1100	Operating	Reached cold shutdown March 15
Tokai Daini					
Unit 2[c]	BWR/5	Mark II	1100	Operating	Reached cold shutdown March 15

[a] Cold shutdown: RPV water temperature is <100°C. Outage: Cold shutdown condition and periodic inspections and/or refueling operations are being conducted; the RPV head may be on or off. Start-up: RPV head is on, reactor is critical, and primary system is being heated.

[b] Fukushima Daiichi Units 5 and 6 were in cold shutdown and outage but were conducting (or about to be conducting) RPV pressure testing when the tsunami hit. As a result, the ultimate heat sink was temporarily lost, so the reactor decay heat went into pressurizing the reactors. That is why even though the NPPs were technically in cold shutdown before the tsunami, a second date was claimed for cold shutdown after the heat sink was restored.

[c] Tokai Daini Unit 1 was closed in 1998.

Unit 1 tripped at 2:46 p.m. because of high seismic acceleration, and both EDGs started automatically. At 2:55 p.m. the start-up transformer failed because of a fault and short-circuit in the high-voltage electrical switchgear caused by the earthquake, and this led to a loss of power supply in the NPP. Both EDGs fed power to the emergency AC electrical busses that power the safety systems. Using normal systems, the reactor reached a state of cold shutdown with a reactor coolant temperature of <100°C (212°F) at ~1:00 a.m. on March 12.

Since Unit 2 was in start-up operation, it shifted promptly to cold shutdown because the reactor had shut down automatically at 2:46 p.m. as a result of high seismic acceleration. The three EDGs automatically started because of an automatic signal from the EDG at 2:47 p.m. but remained in a standby state since the off-site power source was available. Subsequently, as a result of the tsunami, one division of component cooling pumps was flooded and lost function, and two of the EDGs tripped. Since the component cooling water system pump in the remaining division was intact, there was no degradation of the reactor's cooling function.

Unit 3 tripped at 2:46 p.m. because of high seismic acceleration. The off-site power source was maintained, until the tsunami arrived, which caused the turbine component cooling seawater pump to fail. Nevertheless, cooling and depressurization operations of the reactor were able to be successfully carried out, leading the reactor to a state of cold shutdown with a reactor coolant temperature of <100°C (212°F) at ~1:00 a.m. on March 12.

II.A.3. Impact at Fukushima Daiichi NPS

At the time of the earthquake, Units 1, 2, and 3 were operating at rated power level. Unit 4 was in a periodic inspection outage, and large-scale repairs were under way. Unit 4 fuel had all been relocated to the SFP in the reactor building. Units 5 and 6 were also in a periodic inspection outage, but the fuel remained in the reactor core area of the RPV, and the reactors were in a cold shutdown condition.

The earthquake brought Units 1, 2, and 3 to an automatic shutdown because of the high seismic acceleration. The off-site power supply was also lost because of damage to the transmission towers from the earthquake. For this reason, the EDGs for each unit were automatically started up to maintain the function of cooling the reactors and the SFPs. Normal reactor cooldown and decay heat removal functions were under way.

About 45 minutes after the earthquake, the tsunami arrived with an estimated maximum wave height of ~15 m, which was much larger than the seawall at 5 m. All the EDGs (except for one air-cooled EDG at Unit 6) stopped when the tsunami arrived. Specifically, the tsunami submerged the seawater systems that cooled the EDGs and the electrical switchgear. The result was that all AC power supply was lost at Units 1 through 5.

Units 1 through 4 were significantly damaged by the tsunami and subsequent actions and are the subject of more detailed description below.

Units 5 and 6 are slightly separated from Units 1 through 4 and are at a higher elevation. The earthquake disabled the off-site power, and the tsunami caused the loss of both EDGs of Unit 5 and two of the three EDGs of Unit 6. However, one EDG of Unit 6 was air cooled (not dependent on cooling water) and was located at a higher elevation, so it was able to supply emergency AC power to both Units 5 and 6. The availability of AC power gave these units the ability to depressurize the reactors. So, it was possible to add water to the RPVs via the low-pressure condensate transfer pumps. The residual heat removal (RHR) pumps were also not lost, so when a temporary seawater pump was installed to allow transfer of heat to the ocean, it was possible to reach cold shutdown again in both Units 5 and 6. This was achieved by March 20.

II.A.4. Impact at Fukushima Daini NPS

Units 1 through 4 were all in operation and automatically shut down because of the earthquake. After the occurrence of the earthquake, the power supply needed for the NPS was maintained through one of the three external power transmission lines, and normal decay heat removal was occurring. Subsequently, the tsunami triggered by the earthquake hit, flooding the seawater cooling pumps, making them inoperable and causing a loss of normal decay heat removal function.

Units 1, 2, and 4 maintained core cooling by the use of the RCIC systems and the CST water supply. However, since there was no decay heat removal function, the suppression pool temperature continued to rise and reached 100°C (212°F) ~14 hours after the tsunami struck. During this time, because of the extraordinary efforts of the operating staff, Units 1, 2, and 4 recovered their decay heat removal functions; e.g., electrical cables were installed, and damaged pump motors were replaced. The success of this effort was aided by the fact that limited off-site power connections were maintained and key pieces of equipment were not damaged. As a result, the Unit 1 suppression pool temperature was reduced to <100°C (212°F) at 10:15 a.m. on March 14, and the reactor was brought to a cold shutdown condition at 5:00 p.m. on March 14. The Unit 2 suppression pool temperature was reduced to <100°C (212°F) at 3:52 p.m., and the reactor was brought to a cold shutdown condition at 6:00 p.m. on March 14. The Unit 4 suppression pool temperature was reduced to <100°C (212°F), and the reactor was brought to a cold shutdown condition at 7:15 a.m. on March 15. It was not necessary to vent the containments at these units because the containment pressure did not reach the containment design pressure.

At Unit 3, one RHR loop was not damaged at all, so the reactor was brought to a cold shutdown condition at 12:15 p.m. on March 12 without losing reactor cooling functions or suffering other damage.

II.A.5. Impact at Tokai Daini NPS

The Tokai Daini NPS was at rated thermal power operation at the time of the earthquake on March 11; at 2:48 p.m. that day, the reactor tripped because of a turbine trip caused by the turbine shaft bearing registering a large vibration signal as a result of the earthquake. Immediately after the earthquake, all three off-site power source systems were lost. However, the power supply to the equipment for emergency use was provided by the activation of three EDGs. Because the EDGs provided power, the ECCSs kept the water level of the reactor at a normal level, and cooling of the core and removal of decay heat were maintained.

Subsequently, one seawater pump for one EDG stopped as a consequence of the tsunami, and the EDG became inoperable. But, the remaining two EDGs provided power supply to the emergency equipment, and cooling of the suppression pool was maintained by one RHR system.

One off-site power supply system was restored at 7:37 p.m. on March 13, and the nuclear reactor reached a state of cold shutdown with a coolant temperature of <100°C (212°F) at 12:40 a.m. on March 15.

II.B. Accident Details for Fukushima Daiichi NPS: Units 1 Through 4

II.B.1. Fukushima Daiichi Unit 1

After scram[4] and loss of AC power due to the earthquake, both trains of the isolation condenser system were started because of closure of the main steam isolation valves (MSIVs) and subsequent pressurization of the RPV. Operators determined that with both trains operating, the reactor cooldown rate exceeded the technical specification rate of 55°C/hour (100°F/hour), so the isolation condensers were shut down by the operators. Subsequently, one train of the isolation condenser system was restarted and stopped several times to control the reactor pressure and cool the reactor. The HPCI system was not started during this time period as the water level in the RPV was adequate. After the tsunami struck, there was major flooding. In addition to the loss of heat removal function, the EDGs and direct-current (DC) batteries for both power and instrumentation, which were located in the basement of the turbine building, were also flooded and lost. All the instrumentation that was needed to monitor and control the emergency became unavailable; in addition, the HPCI system was not able to operate because of the loss of DC power and not yet needed because the isolation condenser system had just been shut down.

Several attempts were made to open the steam supply and condensate return valves of the previously operating train of the isolation condenser system. There is some evidence that this isolation condenser was at least partially working, because of observed steam evolution from the shell side of the heat exchanger. However, by 10:00 p.m., March 11, rising radiation levels were observed in the reactor and turbine buildings, which was an indication that core damage was occurring.

In addition, at 12:49 a.m. on March 12, local measurements confirmed that the containment pressure had exceeded the design pressure, which was further evidence of core damage and hydrogen production from the zirconium fuel cladding metal-water reaction. Therefore, processes were started to evacuate local residents and to prepare the containment for venting, in accordance with the NPP emergency procedures. Operators began preparations for primary containment vessel (PCV) venting, but the work ran into trouble because the radiation level in the reactor building was already high. At ~2:30 p.m. on March 12, a small decrease in the PCV pressure level was actually confirmed, which could have been due to leakage paths in the PCV that opened because of the PCV being at high containment pressure and temperature or because of the vent rupture disk opening. Subsequently, at 3:36 p.m., a hydrogen explosion[5] occurred in the upper part of the Unit 1 reactor building. The source of the hydrogen in the reactor building is thought to be containment leakage due to the high containment pressure and temperature that occurred, which were well in excess of the design.

The records do not show any deliberate attempt to depressurize the RPV, which would be necessary to allow emergency pumps, such as fire pumps, to add water. However, by 2:45 a.m. on March 12, the RPV pressure was found to be low, and by 5:46 a.m. on March 12, the operators began adding freshwater using fire engines. It is not clear whether the RPV depressurization occurred because of damage to the RPV by the molten core, a break in an attached low-elevation pipe, or SRVs that had stuck open. By this time, the fuel was already significantly damaged.

Longer term, the water level in the RPV did not recover to more than core midplane regardless of the makeup

[4]"Scram" is used to designate the shutdown of the nuclear reactor fission process by insertion of control rods.

[5]As used in this summary, the term "explosion" could mean either a "deflagration" or a "detonation."

water quantity being added, indicating a low-elevation leak in the RPV pressure boundary.

II.B.2. Fukushima Daiichi Unit 2

As with Unit 1, a scram occurred, and the MSIVs were closed after the earthquake. The RCIC system was manually started a couple of times and automatically tripped because of a high water level in the RPV. After the tsunami, some DC power was also lost, just as in Unit 1; therefore, the HPCI system was lost. However, the RCIC system operated for ~70 hours. In general, one should not expect the RCIC system to run much beyond 8 hours in a station blackout (SBO).

At 1:25 p.m. on March 14, it was determined that the RCIC system of Unit 2 had stopped because the reactor water level was decreasing, and operators began to reduce the RPV pressure in order to be able to inject seawater into the reactor using fire-extinguishing-system lines. There were problems depressurizing due to lack of electricity for the solenoid valves and lack of pressurized nitrogen supply to force the SRVs open. These issues caused significant time delays in achieving a low-enough reactor pressure to allow the low-pressure emergency pumps to add water to the RPV. Therefore, the fuel was uncovered while the RPV was without any water injection for ~6.5 hours. The fuel heated up, with significant damage and hydrogen production. Longer term, the water level in the RPV has not recovered to higher than core midplane, indicating a low-elevation leak in the RPV pressure boundary.

The containment pressure rise at first was much slower than should be expected if all the decay heat is delivered to the suppression pool, which is an indication of a leak in the containment boundary. The wetwell venting line configuration had been completed by 11:00 a.m. on March 13, but the containment pressure had not reached the rupture disk setpoint, so no venting occurred. After core damage, the containment pressure increased more rapidly, probably because of hydrogen production. At 6:00 a.m. on March 15, an impulsive sound that was initially attributed to a hydrogen explosion was confirmed near the suppression chamber of the containment. Later reviews suggested that sound was not due to hydrogen burn. In any case the containment pressure did sharply decrease. It is not clear whether the designed vent path was ever in service; however, longer term, the containment pressure has remained low, around the level of atmospheric pressure.

II.B.3. Fukushima Daiichi Unit 3

The situation at Unit 3 followed closely that of Unit 2, except that the RCIC system ran for only 20+ hours. However, the DC power supply for the HPCI system was not damaged, so the HPCI system started up and was run for an additional 15 hours. The operation of the HPCI system apparently also had the side benefit of reducing the RPV pressure because of the steam consumption by the HPCI turbine (seven times larger than that of the RCIC system).

After the HPCI system stopped, the RPV repressurized. Depressurization of the RPV to allow low-pressure pumps to add water was not started for 7 hours, and the RPV did not receive any water for that time. As with Unit 2, there were problems with power for the solenoid valves and the pressurized nitrogen needed for SRV operation. The water level decreased to below the fuel level, and significant core damage and hydrogen production occurred. Fire engines began alternative water injection (freshwater containing boron) into the reactor at ~9:25 a.m. on March 13. Later, the injection was changed to seawater; however, the water level in the RPV never recovered as expected, indicating a leak in the RPV or attached piping.

As with Unit 2, the containment pressure rise from decay heating was slower than expected, indicating the presence of a leak. In parallel with RPV depressurization, containment venting to decrease the PCV pressure was begun. Because of trouble with the solenoid valves and pressurized nitrogen supply, vent operations had to be done several times. Subsequently, at 11:01 a.m. on March 14, a hydrogen explosion occurred in the upper part of the reactor building. The source of the hydrogen is thought to be from leaks in the containment boundary. Longer term, the containment pressure has remained low.

II.B.4. Fukushima Daiichi Unit 4

The total AC power supply for Unit 4 also was lost because of the earthquake/tsunami; therefore, the functions of cooling and supplying water to the SFP were lost. The SFP temperature increased to 84°C (183°F) by 4:00 a.m. on March 14. At ~6:00 a.m. on March 15, an explosion that was thought to be a hydrogen explosion occurred in the reactor building, severely damaging part of the building. At first, this was thought to be from fuel uncovery, heatup, and hydrogen production. Therefore, over the next several days, several different schemes were used to add water—via helicopter, fire truck, and concrete pump truck. Both freshwater and seawater were used. Later, photographs indicated that there was no overheat damage to fuel in the SFP, and the source of hydrogen was traced to backflow through the standby gas treatment system ducting that shared a common piping at the NPP stack with Unit 3, whose containment was being vented.

II.C. Spent-Fuel Situation at Fukushima Daiichi NPS

Damage to stored used fuel resulting in the release of radioactive material can result from several mechanisms:

- a sustained loss or degradation of effective active cooling of the SFP water
- loss of SFP water inventory
- physical impact of a dropped heavy object
- a combination of the above mechanisms.

Loss of cooling could lead to boiling of the SFP water. The time before the SFP water level drops sufficiently to result in fuel overheating depends on the amount of water in the SFP as well as the heat load of the spent fuel. In the absence of a leak in the SFP, this time could range from several days to a couple of weeks depending on the details of the SFP design and the decay heat.

Conditions at the NPS during the accident suggested that these mechanisms may have existed. However, the evidence is that no damage occurred to the fuel in the Unit 5 SFP, the Unit 6 SFP, or the common SFP. The September 2011 supplemental report by the Japanese government to the International Atomic Energy Agency (IAEA) concluded that it is most likely that water levels in the Unit 1 through Unit 4 SFPs were recovered before any spent fuel was exposed and damaged [1]. No subsequent evidence has emerged to counter these conclusions.

When the off-site power and all but one of the EDGs were lost at the NPS because of the earthquake/tsunami, normal cooling of the SFPs was lost. The available EDG allowed cooling to be restored to the Unit 5 and Unit 6 SFPs before the temperature of these SFPs increased significantly. Power was also restored to the common SFP cooling system before its temperature increased significantly.

On March 12, a hydrogen explosion damaged the upper portion of the structure surrounding the refueling bay on Unit 1. While this explosion may have resulted in material falling into the SFP, there is no evidence that damage to the fuel occurred. Beginning on March 31, a concrete pumping truck was used to provide makeup inventory to the Unit 1 SFP. An alternative cooling water system has since been put in service for Unit 1. As of September, the SFP water in Unit 1 has been maintained at <35°C (95°F).

Water addition using existing Unit 2 SFP piping began on March 20 and was intermittent. A sample of the water in the Unit 2 skimmer surge tank was taken on April 16. Analysis of this sample suggests that the spent fuel was not damaged. By May 31, a dedicated system incorporating a heat exchanger was in service. An alternative cooling system is in operation, and as of September, the SFP water in Unit 2 has been maintained at <35°C (95°F).

On March 14, a hydrogen explosion damaged the structure housing the Unit 3 refueling pool. Water spray by water cannon and water drops by helicopter started March 17. By March 27, water addition to the pool was accomplished by use of a concrete pump. Use of existing SFP piping to restore SFP inventory began in late April. A video recording made in the Unit 3 SFP was released on June 16 that showed debris from the containment structure that had fallen into the SFP. It was not possible to confirm the structural integrity of the fuel racks using the video recording. It is likely that no damage has occurred to the spent fuel. As of September, the SFP water in Unit 3 has been maintained at <35°C (95°F).

Because of the relatively high decay heat associated with the fuel in the Unit 4 SFP (all fuel had been removed from the Unit 4 RPV in December 2010), special concern was focused on this SFP. When the refueling floor containment structure was severely damaged because of an apparent hydrogen explosion early in the morning of March 15, this concern was intensified. Initially, since the Unit 4 RPV was defueled, the source of the hydrogen was thought to be the stored used fuel, implying that SFP inventory had been lost early in the accident. Later, the source of the hydrogen was determined to likely be from Unit 3, via a pathway to the Unit 4 refueling floor, leaking through a shared pipe to the stack.

Unit 4 SFP temperatures were reported to be 84°C (183°F) on March 14 and 15. Water was intermittently sprayed from trucks beginning March 20. Nevertheless, the reported SFP temperature on March 24 was 100°C (212°F). Water was introduced to the SFP using concrete pumps starting March 25, which offered a more reliable method of delivering water to the SFP.

Additional evidence of the condition of the used fuel in the Unit 4 SFP was inferred from a series of assessments of specific radionuclides from samples taken of the SFP water. Evaluation of the radiochemical assessments supported the proposition that the source of the hydrogen that led to the destruction of the Unit 4 reactor bay superstructure was Unit 3. A video recording of the Unit 4 SFP was released on May 9. This video recording did not show evidence of extensive damage. In fact, the fuel racks appeared to be intact with little debris visible in the SFP.

In April, a concern developed centered around the strength of the structure supporting the Unit 4 SFP. Between May 31 and June 20, steel support pillars were installed to provide protection against damage that might result from additional seismic events.

In late September, the temperature in the Unit 4 SFP was <40°C (104°F), and a new system to provide active cooling was in operation. This is a typical SFP temperature.

II.D. What Happens When Disaster Strikes

When off-site and on-site AC power are lost, an SBO occurs. As noted above, this leaves only the following installed systems to cope with the loss of water supply to the RPV:

- the isolation condenser systems in BWR/3s, such as Fukushima Daiichi Unit 1
- the RCIC systems in BWR/4s, such as Fukushima Daiichi Units 2 through 5; in BWR/5s, such as Fukushima Daiichi Unit 6; and in BWR/6s
- the HPCI systems in BWR/3s and in BWR/4s, such as Fukushima Daiichi Units 1 through 5.

In addition to the systems themselves, DC power and compressed nitrogen (or air) are needed to open and close valves and operate the control systems, as well as provide power for instrumentation that the operator needs in order to take appropriate actions.

An isolation condenser system is capable of maintaining core cooling and removing decay heat, but if there are leaks in the pressure boundary, additional makeup water is needed for the reactor system. The RCIC and HPCI systems are capable of adding more water than is needed to make up for the steam generated by decay heat, and they can handle additional small leaks. During RCIC/HPCI system operation, reactor pressure is controlled by SRV action, but the steam is exhausted to the suppression pool inside the containment, so eventually decay heat removal from the containment must be restored or the containment must be vented.

In addition to the installed equipment discussed above, NPPs have direct diesel-driven pumps as part of the fire protection system, or the flexibility to connect fire trucks to the installed piping leading to the RPV for water makeup. In addition to the extra time it takes to utilize these additional emergency resources, the RPV must be depressurized to a low-enough pressure for these typically lower-pressure pumps to be able to inject. This also means it is necessary to be able to manually open SRVs to lower the reactor pressure. The manual opening of the SRVs still requires DC power and compressed nitrogen.

When there is no water coming into the RPV, there is a period of 1 to 2 hours (depending on how long the reactor has been shut down before the makeup stops) before the fuel becomes uncovered, and ~30 minutes after that, the fuel will start releasing hydrogen and heat from metal-water reaction and then melting. On the other hand, the large size of the suppression pool means that containment would not reach its design pressure for ~15 hours. Thus, higher priority should be given to assuring water makeup to the RPV, including assuring the capability to depressurize if it is necessary to use additional emergency pumps.

II.E. Analysis of Fukushima Daiichi Accident

In Unit 1, loss of DC power for both motive force and instrumentation due to flooding substantially increased the difficulty of controlling the accident. It is unfortunate that in addition to the design-basis tsunami[6] being too low, additional flood protection for the batteries was not provided. Only the isolation condenser system was available as a makeup system, and because of lack of instrumentation, it was not clear how well it was working. Priority was given to venting the containment when it should have been given to assuring core cooling, such as by restoring the isolation condenser system at reactor pressure or by lining up alternative water sources into the RPV and depressurizing the reactor system so that low-pressure pumps could be used. At the time of this writing, there is no record of any attempt to depressurize the RPV throughout the event.

The containment vent design, with valves that need DC power and compressed air or nitrogen to operate, plus an in-line rupture disk (with a setpoint greater than the containment design pressure) that cannot be bypassed, led to containment pressures well in excess of the design pressure because of delays. Most likely, the source of the hydrogen in the reactor building was leaks in the containment due to the high pressure, and perhaps also high containment temperatures that could have led to deterioration of the major seals (drywell head cover, and equipment and personnel airlocks). Another possible source could also have been leakage past containment isolation valves.

In Units 2 and 3, the operators should be commended for keeping the RCIC and the HPCI systems operating as long as they did. We note that many probabilistic risk assessments performed on BWRs have shown the dominant core melt scenario to be SBO with eventual failure of the RCIC/HPCI systems, thought to be in ~8 hours because of a number of potential failure mechanisms. However, in that time period, no attempt was made to prepare for depressurization of the RPV until these systems failed, and because of DC power failures and issues with providing alternative compressed nitrogen, depressurization to allow alternative water sources was delayed. Such accident management strategies need to be thought out in advance given the evolution of an accident.

[6]A design-basis tsunami is an external flooding event, which the NPP is designed to withstand without damage.

III. HEALTH PHYSICS

The American Nuclear Society Special Committee on Fukushima (the Committee) collected information that has been published in the open literature for the radiation exposure of workers, the release and deposition of radioactive materials over a wide area surrounding the Fukushima Daiichi NPS, and the contamination of water and food sources. It is important to note that data collection and analyses continue as this report is being written. It is too early to make any firm conclusions regarding these data and the definitive health impacts to workers or to members of the public. While these data do suggest that off-site health consequences may be minimal, it will take much longer to confirm the health impacts. These data do indicate that exposures to workers were significant during the first days of the emergency. Worker exposure controls were put into place, and with carefully planned worker protection practices during the recovery phase, exposures are being controlled. Measureable radioactive materials, mainly iodine-131 (^{131}I), cesium-134 (^{134}Cs), and cesium-137 (^{137}Cs), were identified in public water supplies as well as in certain land areas. After peaking in middle to late March, the concentration of these radionuclides trended significantly downward, with cesium as the main concern.

The International System of Units (SI) for radiation measurement is the official system of measurement and uses "gray" (Gy) and "sievert" (Sv) for absorbed dose and equivalent dose, respectively.

Conversions are as follows:

1 Bq = 1 distintegration/second = 2.7×10^{-11} Ci = 27 pCi

1 Gy = 100 rad, and 1 mGy = 100 mrad

1 Sv = 100 rem, and 1 mSv = 100 mrem.

With radiation counting systems, radioactive transformation events can be measured in units of "disintegrations per minute" and, because instruments are not 100% efficient, in "counts per minute." Natural background radiation levels are typically <0.1 to 1 μSv/hour, but because of differences in detector size and efficiency, the readings on fixed monitors and various handheld survey meters vary widely.

III.A. On-Site Worker Dose

The Tokyo Electric Power Company (TEPCO) has been monitoring emergency workers for external dose throughout the accident and its aftermath. TEPCO has also performed whole-body counting on each worker to derive his or her internal dose. Over the period of time from March 2011 through July 2011, approximately 14,841 TEPCO employees and contractors were monitored. Slight discrepancies in the reported number of workers monitored are due to a handful of individuals where external and internal dose results are not both available.

The standard worker dose limit for Japanese workers is 50 mSv/year and 100 mSv over 5 years. Before the accident, the emergency dose limit was set at 100 mSv/year but was raised to 250 mSv/year to allow workers to respond to this serious accident.

As of the most recent monitoring period, no observable health effects have been reported in any of the workers. It should be noted that acute health effects are not expected at these doses to workers, although all are being closely monitored. For chronic health effects above 0.1 Sv (100 mSv), the cancer risk can be approximated as increasing by 10%/Sv (using the regulatory accepted linear no-threshold dose model used in radiation protection). For example, the occupational worker who received a dose of 0.1 Sv (100 mSv) has a 1% increased risk of developing a cancer later in his or her life. Estimating cancer risks to the general public is complicated by the low dose rates outside of the NPS and significant overall cancer rates from various environmental factors [2].

The maximum external dose recorded is 199 mSv (0.19 Sv), and the maximum internal dose that has been calculated is 590 mSv (0.59 Sv). The maximum total dose recorded to one worker was 670 mSv, and six workers have received doses in excess of the emergency dose limits established. Although 408 workers have received doses above the normal annual limit of 50 mSv, the average dose for emergency workers is still relatively low and has decreased steadily during the months following the accident. For workers performing emergency work since March, the average total accumulated dose is 22.4 mSv. For the months April through July, the average dose is <4 mSv. The total collective dose for all emergency workers is estimated to be 115 person-Sv. In addition to whole-body doses, two male employees received significant skin dose while laying electric cables from standing in contaminated water that flooded their boots. Their estimated skin dose was ~2 to 3 Sv.

The actions in the immediate aftermath of the accident on March 11 resulted in doses to a handful of workers in excess of established limits and elevated doses to a larger group, as noted above. Since that time, TEPCO has been improving the working conditions and safety measures for its workers. All TEPCO workers are required to wear protective clothing, gloves, and protection masks. TEPCO has established contamination-free rest areas throughout the NPS; installed water coolers; and introduced a "cool vest," which aims to protect workers from heat exhaustion. Currently, seven designated rest areas have been created, and four additional rest areas are in preparation. Also, improvements in living conditions have been made at the gymnasium that houses these workers.

III.B. Off-Site Doses

At this time there are not enough data collected and publically reported by the Japanese government or the IAEA to reach any definitive conclusions on off-site health effects. The doses received by members of the public have come from four different pathways:

- submersion dose from airborne radioactivity
- inhalation dose from airborne radioactivity
- consumption of contaminated water and foodstuffs
- direct exposure from contaminated surface deposition.

The first two of these items cannot be measured retrospectively but can only be predicted from dispersion modeling. A few crude dispersion models have been made public, but no validated models have been made available for review to date in the United States. Airborne radioactivity is transitory, and the dose from inhalation is many times greater than the submersion dose for all but the inert gases.

Food and water contamination has been documented through extensive measurements. Most contaminated foodstuffs have been restricted, but there is no public information regarding their actual level of consumption at this time.

Conversely, the external exposure from ground contamination can be predicted with relative accuracy from the distribution of ground contamination. Using the relative mixture of ^{134}Cs and ^{137}Cs, the French Institut de Radioprotection et de Sûreté Nucléaire (IRSN) [3] has calculated the external dose for the first year after the accident at 16.6 mSv per MBq/m^2 of total cesium. This is based upon an assumption of 12 hours/day inside structures, where the average dose rate is reduced 70%. A similar estimate was provided by the U.S. Department of Energy (DOE) National Nuclear Security Agency (NNSA). This estimate, although not definitive, suggests that health effects to the public will be minimal.

Japan's Nuclear Safety Commission provides the latest evaluations of environmental radiation monitoring results [4]. The information provided below comes from the Japanese Health Monitoring Program.

By July more than 210,000 residents had been screened by experts from related organizations, universities, and local governments [5]. Two internal dose assessment surveys were started by Japan's National Institute of Radiological Sciences (NIRS) and the Japan Atomic Energy Agency (JAEA). NIRS has completed an internal exposure survey on Fukushima Prefectural residents [6]. Initial measurements were taken between June 27 and July 16. The survey focused on residents who lived in areas associated with high doses. A total of 122 participants—90 residents from Namie Town, 20 residents from Iitate Village, and 12 residents from Kawamata Town—were initially enrolled in the survey, and 109 subjects were surveyed in follow-up examinations. Whole-body counters were used to detect activity from ^{134}Cs, ^{137}Cs, and ^{131}I. Urine bioassays were used to determine a cutoff value for the whole-body counter measurements. Cesium-134 was detected in 52 out of 109 people (47.7%), with the highest value being 3,100 Bq. Cesium-137 was detected in 32 out of 109 people (29.4%), with the highest value being 3,800 Bq. Both ^{134}Cs and ^{137}Cs were detected in 26 out of 109 people (23.9%). Iodine-131 was not detected in any subject. Based on this survey, the combined internal dose from ^{134}Cs and ^{137}Cs was <1 mSv (100 mrem) for these individuals. JAEA began internal exposure surveying of 2,800 evacuees on July 11.

Appropriations were made for the "Health Fund for Children and Adults Affected by the Nuclear Accident," created by Fukushima Prefecture to ensure the health of residents through mid-term and long-term projects. Currently, a two-step plan is being considered. First, a preliminary study began in early July on a sample of about 100 residents who were located in regions of high radiation levels. Those selected will undergo thorough testing for internal radiation contamination. All Fukushima residents will be considered in the primary study. Questionnaires will be distributed to all residents in order to help experts determine the radiation dose received by the residents. The data will be stored for 30 years to conduct follow-up health checks. An estimated 2 million residents need to be monitored. The United Nations Scientific Committee on the Effects of Atomic Radiation has also announced that it will conduct a study on the health impact to Fukushima residents [7].

III.C. Off-Site Contamination

The long-term land contamination off-site is due to the deposition of ^{134}Cs and ^{137}Cs because of their comparatively long half-lives (the half-life of ^{134}Cs is 2.1 years, and the half-life of ^{137}Cs is 30.1 years). The other radionuclides identified as being released have half-lives on the order of less than days or tens of days. The other isotopes of concern from a reactor accident include strontium (strontium-90) and yttrium (yttrium-90) and the actinides, but none of these have been measured in any detectable quantities within or beyond the established evacuation zone.

The initial measurement of ground contamination was performed by the Ministry of Education, Culture, Sports, Science and Technology–Japan (MEXT), with substantial assistance from the DOE NNSA and DOE Office of Nuclear Energy, by measuring exposure levels aboveground using fixed-wing airplanes and helicopter flyovers, extrapolating to the exposure rate at ground level, and converting that value to an area concentration of cesium, given the relative proportions of ^{134}Cs and ^{137}Cs expected. One example is shown in Fig. 8. From several of these maps, isodose/isoconcentration curves are generated, and a map over the entire survey area is produced, as in Fig. 9 from the NNSA. This method has the potential to miss small hot and cold spots in the survey area but provides a reasonable distribution of the deposition of these radionuclides.

A significant number of soil samples throughout the region have been collected and measured with gamma spectroscopy to obtain cesium concentration. A summary map is shown in Fig. 10 (measurements analyzed by Yasunari et al. [9]). This careful work provides a detailed quantification of ^{137}Cs environmental contamination. Such data will be needed to better inform off-site cleanup or remediation activities.

A direct correlation between these various maps has not been completed at this time. But, the patterns observed are quite similar. Using the NNSA maps (Figs. 8 and 9), there is a total land area of ~874 km^2 contaminated with ^{134}Cs and ^{137}Cs in a concentration >600 kBq/m^2, which is the concentration that is predicted to correspond to a 10-mSv (1-rem) dose in the first year (this includes areas outside the 20-km evacuation zone). We were not able to precisely compare this to the Japanese government relocation land area, but the relocation area is larger.

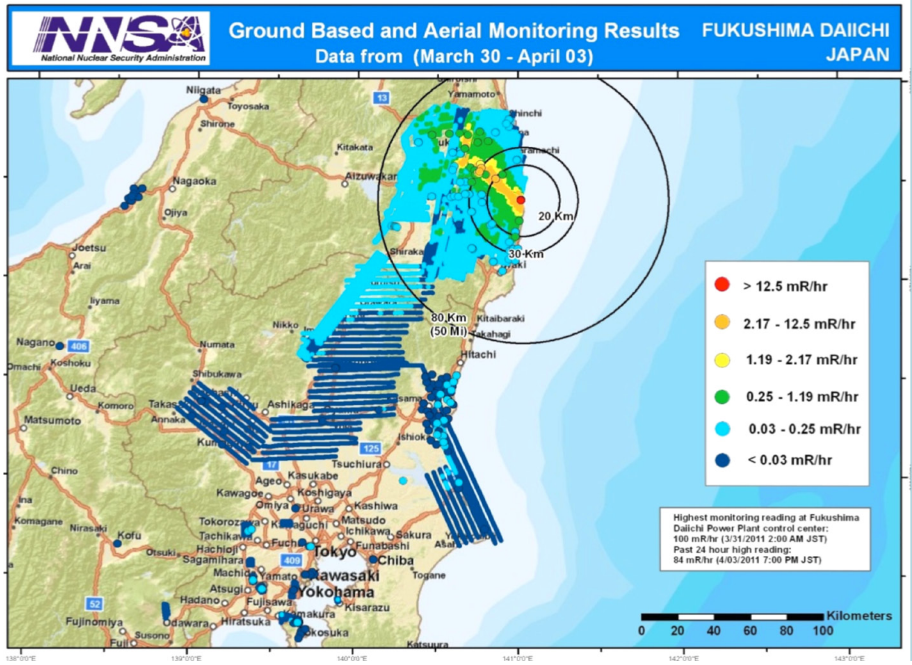


Figure 8. Monitoring results [8]. (Courtesy of NNSA.)

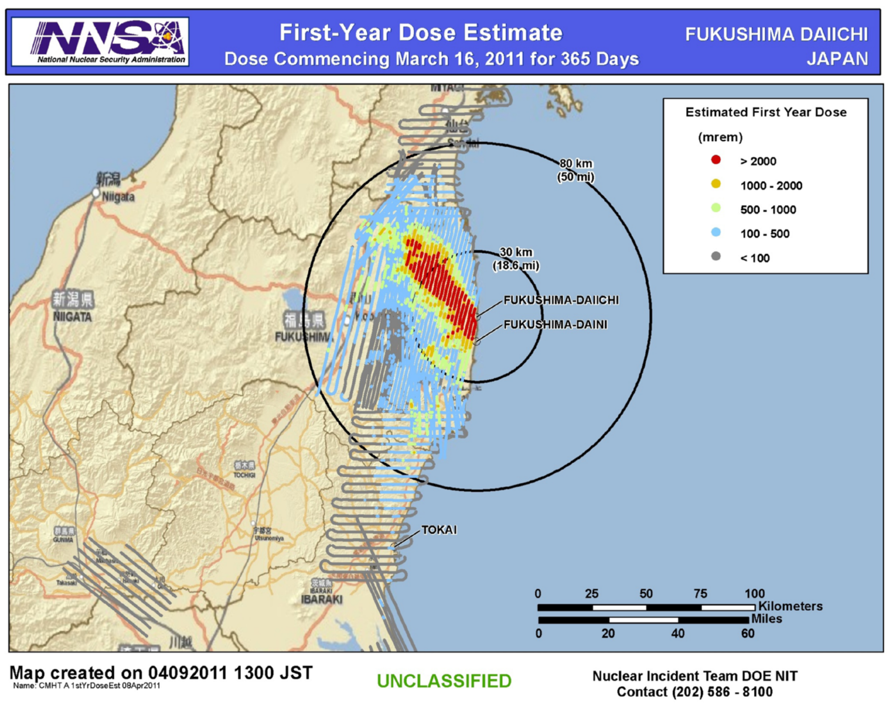


Figure 9. Map of isodose curves for Fukushima region from NNSA measurements. (Courtesy of NNSA.)

III.D. Contamination of Foodstuffs

The Committee collected and compiled data for contamination of foodstuffs by ^{134}Cs, ^{137}Cs, and ^{131}I. These detailed data, as well as detailed spreadsheets, are provided at the Japanese Ministry of Health, Labor and Welfare Web site [10]. The data for the period March 19, 2011, through September 21, 2011, indicate that typically <10% of samples were found to contain contamination levels exceeding the provisional regulation limits (regulatory action levels). Actions taken by the Japanese government to restrict consumption of contaminated meats are given in [11].

III.E. Water Monitoring

No data were available regarding the partition between public water supplies and bottled water that was used after the accident. Data do exist for some public water supplies. These data are provided in summary tables at the ANS

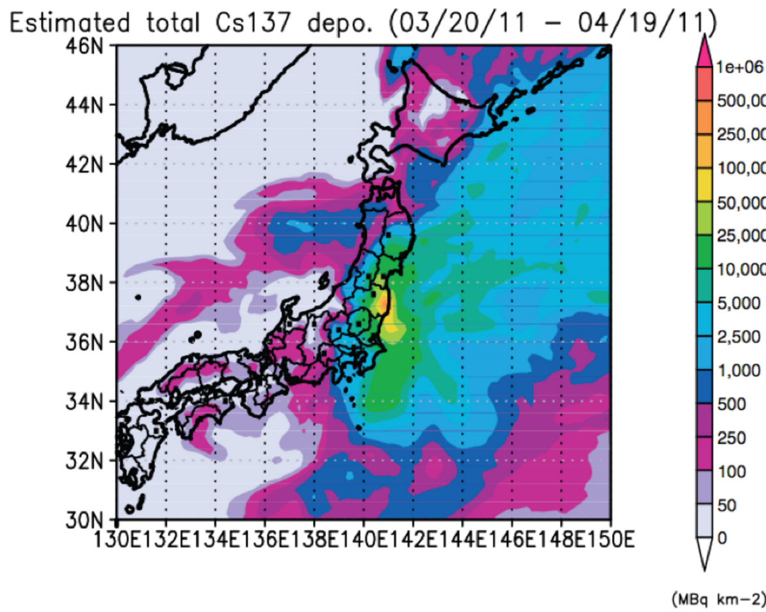


Figure 10. Overall map of total soil deposition for ^{137}Cs.

Web site (http://fukushima.ans.org/). Summary graphs of the tap water measurements taken by MEXT [12] are shown in Fig. 11.

These measured data for public water supplies indicate that radiation levels were falling after March and were trending toward levels below allowable limits.

Early in the accident, radioactive materials were released with water coolant into the sea. The measurements taken near the Fukushima Daiichi NPS indicate these releases were dispersed quite quickly. The details of the movement of these radioactive materials in the fauna and flora of the ocean's ecosystem are being monitored, and their effect will only become clear after longer-term monitoring and modeling.

IV. ACCIDENT CLEANUP

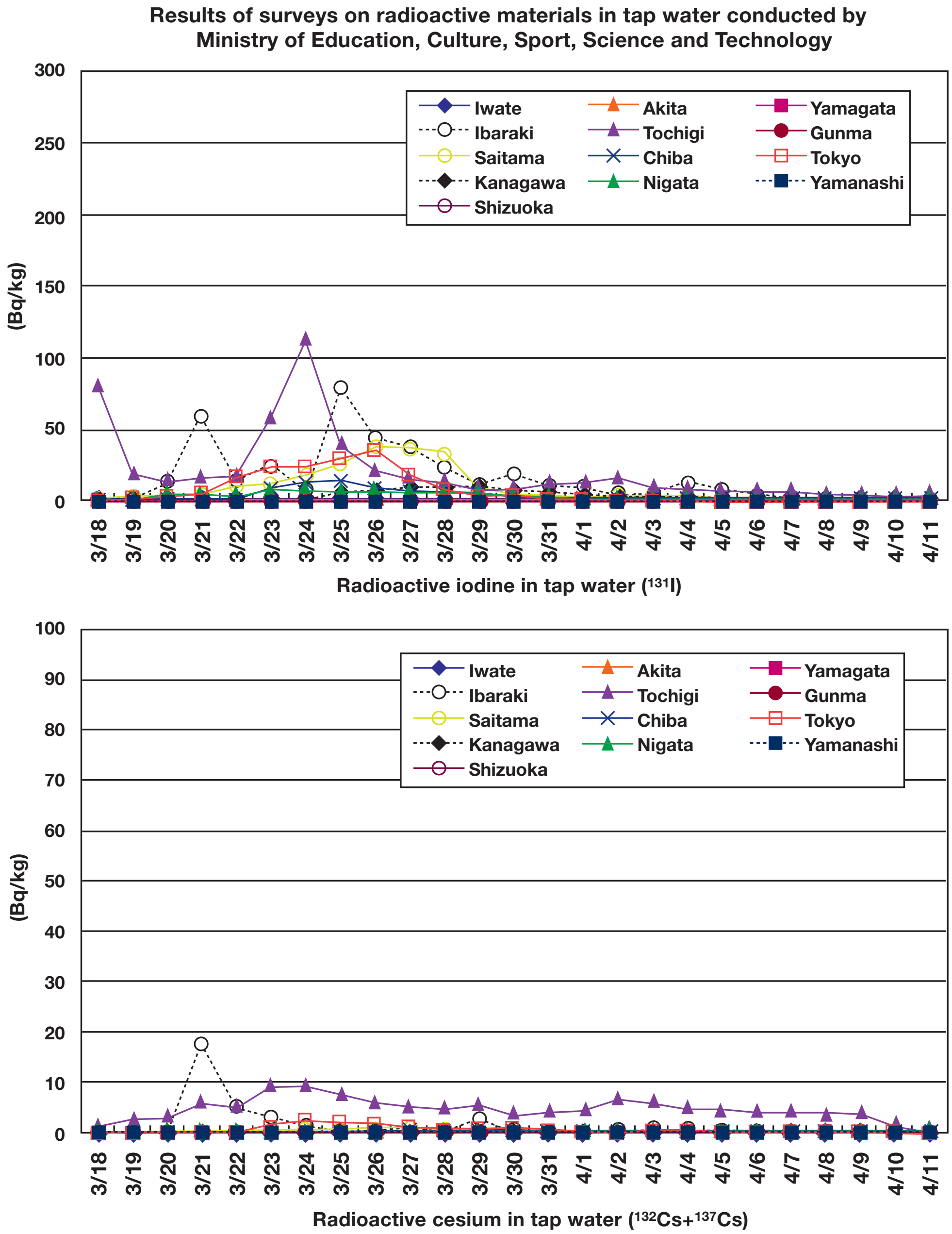
The accident at the Fukushima Daiichi NPS has resulted in significant challenges for accident cleanup and waste management. These issues include processing the large volume of contaminated water, debris, soil, secondary wastes, potentially damaged spent fuel within the reactor SFPs, and damaged fuel and fuel debris within the reactors and primary containment structures. Progress has been made in cooling of the reactors, and all the units have reached ambient pressure and temperature conditions, i.e., cold shutdown. Mid-term to long-term waste management issues will continue to be the major technical issues that must be overcome as recovery actions continue toward an acceptable end state. TEPCO (see [13] for TEPCO information on cleanup status) has established a road map that describes elements of the site cleanup and water management, and it is currently developing more detailed mid-range to long-range plans. There are also waste management challenges associated with

- treatment of contaminated water and the resulting filter and equipment wastes
- storage and disposal of secondary wastes, contaminated soils, vegetation, and debris
- decontamination to allow reinforcement of the weakened structures and installation of cooling and gas management systems
- installation of new secondary containment structures and material-handling equipment.

Resolving these challenges will be required to allow continued progress for removal of the spent fuel stored within the SFPs and ultimately the retrieval and processing of the damaged fuel within and outside of the RPVs.

As the planning for the cleanup continues to evolve, in early November, the Japanese government ordered TEPCO to draw up a road map to decommission the four damaged reactors at the Fukushima Daiichi NPS in a process that could take decades. The plan, developed by TEPCO in collaboration with the Japanese government, is based on removing fuel rods in SFPs within 2 years and damaged fuel in each of the reactors within 10 years, according to the minister in charge of the nuclear disaster response. TEPCO is developing a road map to be provided early in 2012. Decommissioning the four reactors is estimated to cost at least 1.15 trillion yen [$15 billion (USD)]. Substantial government involvement will be necessary in the decommissioning process. TEPCO must submit a road map of the utility's corporate structure and financial situation that will be viable. A committee of the Japan Atomic Energy Commission (JAEC) said it may take >30 years to dismantle the reactors. Normal decommissioning takes about half as long according to the JAEC committee. At the Three Mile Island Unit 2 (TMI-2) accident in Pennsylvania in 1979, fuel removal was started ~6½ years later and was completed in ~14 years.

The Japanese Cabinet also has approved "basic policies" to clean up off-site radioactive contamination resulting from the Fukushima Daiichi accident. Based on recommendations made in 2007 by the International Commission on Radiological Protection, areas contaminated to dose levels with a dose of 20 mSv/year (2 rem/year) above background should be cleaned up to reduce doses by 50% for adults and by 60% for children within 2 years and to bring them to a long-term level of 0.1 rem/year above background radiation levels. This dose level is approximately the same amount of radiation exposure



Out of prefectural governments conducting surveys, only prefectures in which radioactive iodine and radioactive cesium were detected are shown.

Figure 11. Japanese iodine and cesium measurement in drinking water. (Courtesy of MEXT.)

a patient would receive from a full-body CT (computed tomography) scan. The current government policy is that areas where the annual dose levels are above this level are to be given priority in scheduling decontamination activities. The current government policy may prove to be problematic for implementation.

IV.A. Cleanup Issues

The Fukushima Daiichi accident produced radioactive gaseous, liquid, and solid wastes. The gaseous emissions were released in the early days of the accident and have dispersed and decayed to small levels and are no longer a health threat. Based on measurements in November, TEPCO has already declared that significant gaseous releases have stopped and that the temperatures in all three reactors are <75°C (167°F).

Liquid waste management and the cleanup and management of the water that was injected into the reactors and SFPs had been a major concern. For many weeks following the accident, rainwater mixed with the water that had been injected into the reactors and SFPs was accumulating in NPS buildings and tanks. As the buildings and tanks filled up, additional temporary storage tanks were brought in to hold the water. In June, the first of two temporary wastewater cleanup systems was started. As of this writing at the end of 2011, two temporary wastewater processing systems are in service operating at ~90% capacity, cleaning more water than is being injected into the reactors and SFPs. Water levels in the buildings are slowly decreasing, and plans are in place to start work in 2012 on a new, more permanent long-term wastewater processing facility.

The solid wastes at the Fukushima Daiichi NPS consist of

- secondary wastes accumulating as a result of the water treatment processes (such as sludge and filter resins)
- radioactive particles that were released during the reactor building explosions and drifted away and settled across downwind areas

- contaminated rubble and materials from in and around the NPS buildings (including deforestation and other organic debris cleared to make room for storage tanks and buildings)
- radioactive nuclear fuel in the SFPs and in the damaged reactors.

Plans are being developed and implemented to monitor and, if necessary, clean up or remove radioactive contamination from surrounding areas on the Fukushima NPS site. Much of the contaminated rubble and materials around the NPS buildings and in the roadways has been removed, and work has started on rubble removal from the refueling floors of Units 3 and 4. Planning is in progress to start moving the fuel from the SFPs to interim or long-term storage or reprocessing facilities within the next couple of years. Studies are in progress or planned to determine the best methods to be used to defuel the reactors, remove the spent fuel from the SFPs, and treat and dispose of the accumulated radioactive wastes. The initial phase of the complete plan for removal of fuel from the reactor is illustrated below. A complete summary is given at the ANS Web site (http://fukushima.ans.org/), and the detailed plan and progress can be found at the TEPCO Web site [13].

IV.B. Current Status

Because of damage to the RPVs, PCVs, and reactor buildings, contaminated water injected into the reactor cores is leaking into the turbine buildings. This situation required the quick design of two water treatment systems. One was a short-time-frame installation, and the other was a mid-term installation (Fig. 12). The two water treatment systems are still being used to process wastewater to remove oil, contamination, and brine. The water is being processed at a rate of ~50 m^3/hour. Contaminated water is being generated at a rate of 25 m^3/hour from reactor core injection and 200 to 500 m^3/day from groundwater in-leakage. The processed water is being reused to inject into the RPVs to minimize the volume of new water used. The systems initially experienced equipment and operational problems caused by quick installation and operator unfamiliarity. The systems are currently operating above 90% capacity. TEPCO has been able to reduce the inventory of contaminated water creating enough margin to increase the cooling injection rates into the RPVs. The waste sludge from the oil separator, reverse osmosis membrane, and desalination units is being stored on-site in temporary tanks. In addition, Units 5 and 6 are experiencing groundwater intrusion of 200 m^3/day that is slightly contaminated but below release limits. However, TEPCO is unable to release this water because of current environmental policy issues. Therefore, TEPCO is spraying this water on the NPS site to alleviate storage concerns. Similarly, the NPS has a large volume of tritiated water at a tritium concentration of 10^3 Bq/m^3. The total amount of the accumulated water is increasing at ~200 to 720 tons/day. This volume will eventually challenge the storage capacity. Multiple tank farms containing several hundred tanks for a total volume of >111,000 m^3 and a megafloat barge to store 10,000 m^3 of water have been added to the NPP site.

A similar portable skid-mounted water treatment and desalination system is being used to reduce contamination and chlorine levels in the SFPs of Units 2, 3, and 4. These SFPs had seawater injected into them during the event. The system is being moved to the Unit 2 SFP as cleanup has been completed on Unit 4. In many ways, the Fukushima Daiichi NPS has evolved from a nuclear power electric generation site into a large water treatment facility (Fig. 13).

Site cleanup has been accomplished through the use of ten remotely controlled vehicles including backhoes, bulldozers,

Figure 12. Photographs of portable water cleanup and decontamination treatment units. (Courtesy of TEPCO.)

and dump trucks. The site has two remote vehicle control rooms that are used to control all the debris-removal construction equipment. One control room operates a backhoe, a dump truck, and a lift truck. The second control room operates two backhoes, a bulldozer, two dump trucks, and two lift trucks. All the items and materials removed from the yard area around the NPS have been stored in metal containers (4- to 8-m^3 volume). Larger and less contaminated items are stored in bulk in a new solid-waste building. Each container has an assigned number and is labeled with its container number, where the debris is from, dose rate, and type of debris. This will be used to maintain inventory control during eventual transport off-site and waste disposal.

Removal of reactor building structures damaged by the explosions will be required to allow removal of spent fuel and ultimately core material. Planning is currently in progress for removal of fuel from the SFPs (Fig. 14) to storage containers within the next few years after the structures are removed [13].

Frequent monitoring and development of plans for environmental cleanup or removal of harmful levels of radioactive contamination from areas surrounding the NPS are progressing. The magnitude of the cleanup outside of the NPS site has required the Japanese government to take ownership for these tasks. A number of demonstration projects have been initiated, and the complete road map is to be provided in early 2012. A complete summary is given at the ANS Web site (http://fukushima.ans.org/), and the detailed plan and current progress can be also found at the TEPCO Web site [13].

V. SAFETY ISSUES AND RECOMMENDATIONS

As the Committee reviewed and analyzed the information regarding aspects of the Fukushima Daiichi accident, we, the members, raised a series of questions regarding safety issues, i.e., emergency power, long-term cooling, containment performance, SFPs, emergency response, plant siting, and design-basis events. In this section we provide a summary of our safety-related recommendations that evolved from the discussion of these questions. The complete set of our questions and answers can be found at the ANS Web site (http://fukushima.ans.org/).

We want to emphasize that these recommendations are consistent with most of the regulatory issues that have been raised by national and international bodies. However, our emphasis is not to directly suggest what regulatory rules or process changes are needed; rather, we focus on the key technical issues that would be the basis for any specific set of regulatory actions.

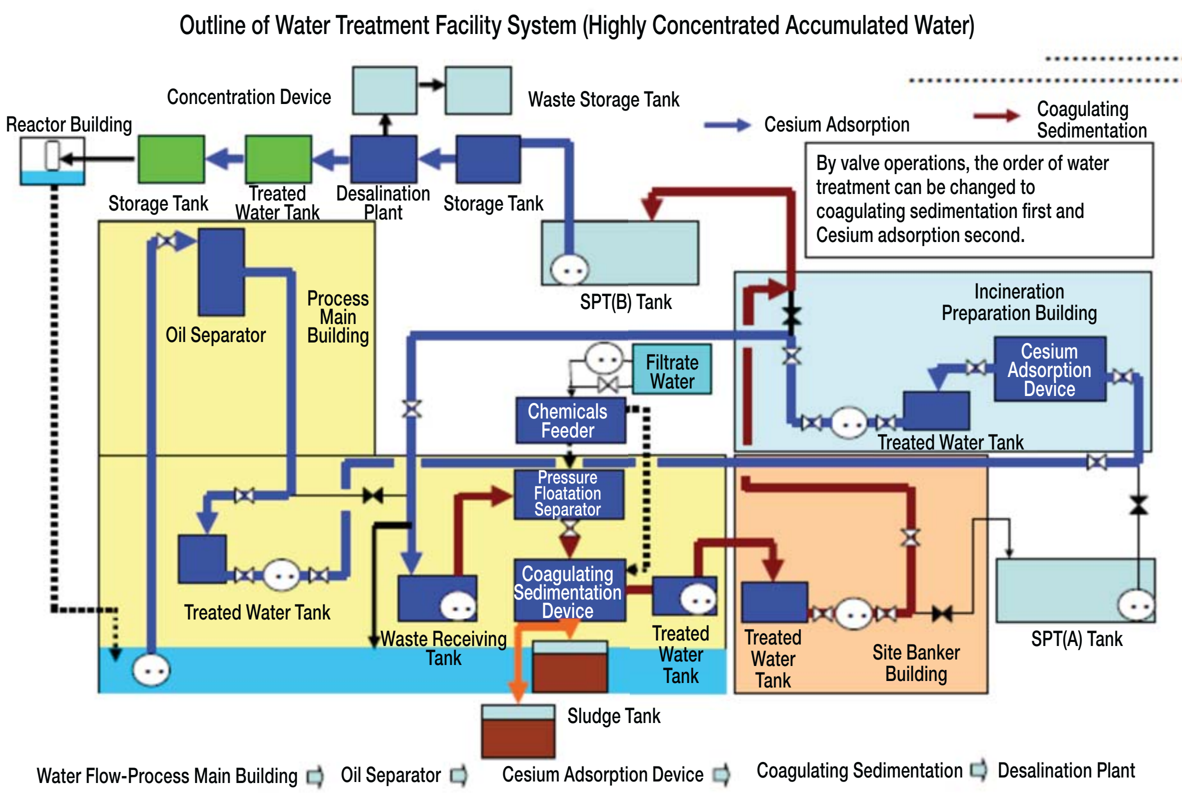


Figure 13. Overview of water treatment facility system at Fukushima Daiichi NPS. (Courtesy of TEPCO.)

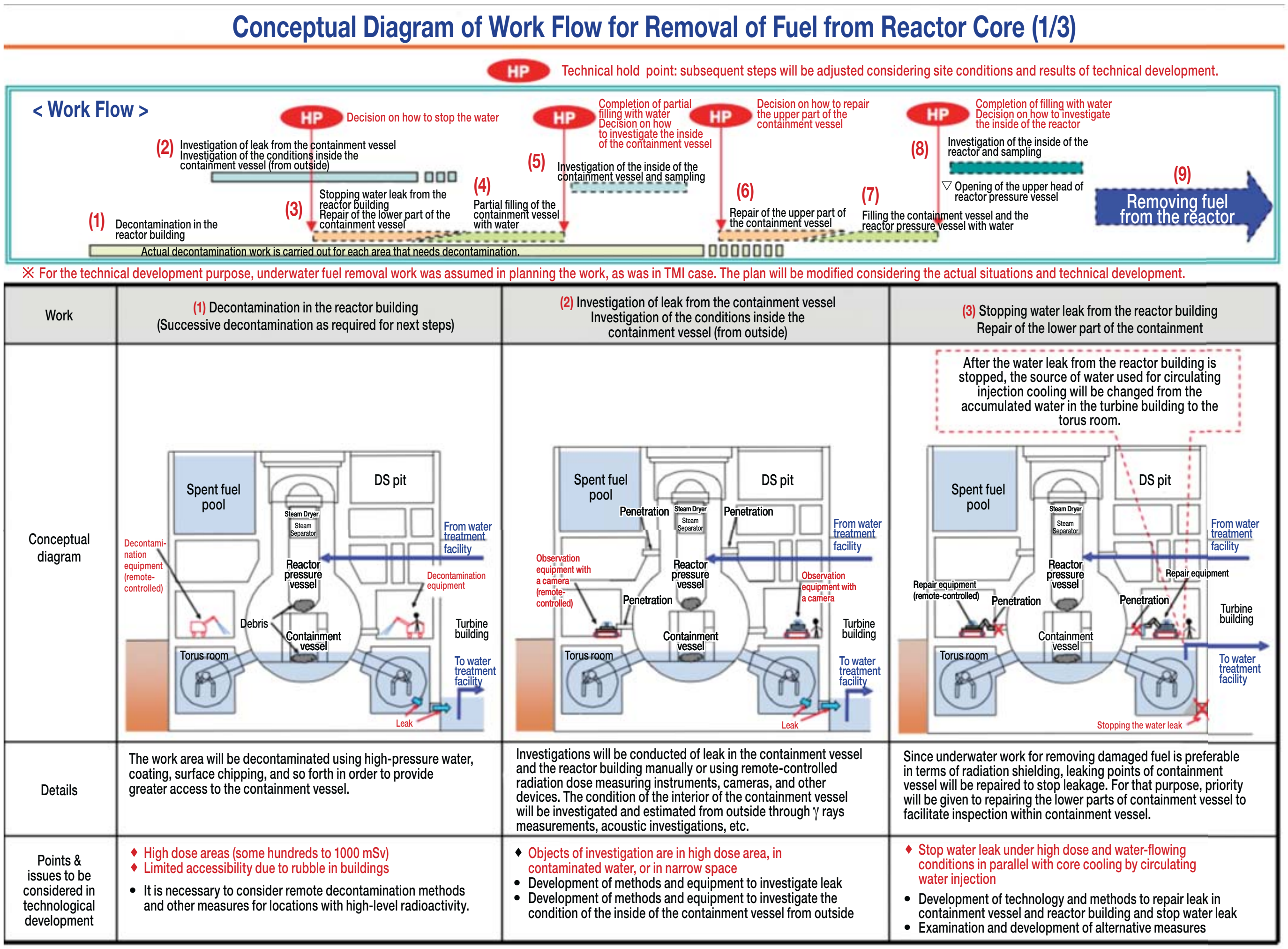


Figure 14. Conceptual diagram of plan for removal of reactor fuel with details provided for steps (1), (2), and (3). (Courtesy of TEPCO.)

There is no aspect of the Fukushima Daiichi accident that a priori indicates that the level of safety of NPPs in the United States is unacceptable. The Committee agrees with the U.S. Nuclear Regulatory Commission (NRC) Near-Term Task Force (NTTF) that the current level of safety provides adequate protection to the health and safety of the U.S. public. However, from a public confidence viewpoint, it is unacceptable to have an accident of the visibility and societal consequences of the Fukushima accident occurring somewhere in the world every 25 to 30 years.

There are some major lessons to be learned from the accident that relate to observed vulnerabilities in the design and operation of the Fukushima Daiichi NPPs and to weaknesses in the ability of the NPPs to respond to such an extreme event. We need to examine each of these observed vulnerabilities to see how they relate to U.S. NPPs and address those issues, as necessary.

The following recommendations are consistent with our general conclusion. These recommendations are strictly motivated by our understanding of the Fukushima Daiichi accident and technical shortcomings observed. These recommendations are largely embodied within the suggested regulatory actions proposed by the NTTF.

V.A. Risk-Informed Regulation

The scope of reactor safety design and regulation should be reviewed to consider the adequacy of design bases for natural-phenomenon hazards and the need for extension of the design basis in a graded manner, using risk information, into what have previously been considered beyond-design-basis accidents (BDBAs). A key NTTF recommendation was that such a "risk-informed" approach to safety be installed as the basis for regulation, and we concur.

Historically, nuclear reactor regulations have focused on providing high assurance that events within the design basis of the NPP would not result in severe fuel damage or in a substantial off-site release of radioactive material. Since the release of the NRC's "Reactor Safety Study" in 1975

(WASH-1400), it has been recognized that reactor risk for the current generation of NPPs is dominated by BDBAs involving substantial fuel melting and failure of the reactor containment. The TMI-2 accident largely confirmed the recognition of the risk dominance of these BDBAs. Some requirements have been imposed on licensees related to beyond-design-basis conditions, such as hydrogen mitigation devices in some NPP designs. In general, though, the insights from risk information and safety assessments have been used to reduce design vulnerabilities that would lead to beyond-design-basis events rather than the mitigation of the consequences of those events.

We are quite aware that a risk-informed approach is a long-term effort and is technically complex. It may lead to a change in the scope of regulatory requirements for beyond-design-basis events, including the development of deterministic acceptance criteria for risk-dominant accident sequences and end states. This could impact both existing and future NPPs. Thus, specific regulatory changes motivated by the Fukushima Daiichi accident should be carefully evaluated from a risk perspective, with input from all stakeholders, including the public, existing NPP owner/operators, and NPP designers.

V.B. Hazards from Extreme Natural Phenomena

The tsunami design bases for the Fukushima NPPs were not consistent with the level of protection required for NPPs. If the return period for a tsunami of the magnitude experienced in Japan is as short as reported (once every 1000 years), a risk-informed regulatory approach would have identified the existing design bases as inadequate.

It has long been recognized that external events, particularly seismic and external flooding events, could be substantial contributors to risk because of the potential for multiple common-cause failures. The Fukushima Daiichi accident raises the issue of whether past risk assessments have underestimated the relative importance of natural-phenomenon hazards to NPP risk. There is little question that the methods of analysis used for analyzing internal event risk are more developed and have smaller associated uncertainties than those used to assess the risk of low-frequency natural-phenomenon hazards.

The NRC is requiring that the design bases for all U.S. NPPs be reviewed for natural-phenomenon hazards to assure that they are consistent with the existing regulations. The NRC should also undertake a review of regulations for each of the natural-phenomenon hazards to determine whether they are appropriately risk-informed. For example, the current regulatory approach in the United States for establishing a design basis for floods is deterministic, based on the concept of the maximum possible rainfall. This type of concept, even though inconsistent with nature, may work effectively when dealing with common engineering concerns like assurance of a low frequency of dam failures or bridge failures. However, the criteria that we have established for NPPs are much more stringent. Although it is very difficult to deal with low-probability events, this is the perspective needed for a risk-informed treatment of natural-phenomenon hazards. Such an approach to regulating hazards from extreme natural phenomena should be undertaken.

As part of this approach, the NRC should periodically reanalyze and potentially redefine the design and licensing basis for severe natural events (earthquakes, floods, tsunamis, hurricanes, tornadoes, and fires) using the latest, accepted, best-estimate methodologies with quantified uncertainties and data available that are well vetted and have a strong consensus of technical experts. All risks to NPPs from severe natural events should be periodically (e.g., every decade) reassessed using the same methodologies and data. Based on the outcome of the assessment, the NRC may mandate improvements based on cost-benefit analyses.

V.C. Multiple-Unit-Site Considerations

Recognizing that the high cost and lengthy schedule to obtain site approval are powerful incentives for multiple-unit sites, we recommend that a multiple-unit risk assessment be performed whenever a unit is added to a site. Such a risk analysis should include sensitivities to determine the extent to which multiple-unit considerations increase or decrease the risk. Factors to consider include (1) the extent of system inter-ties between units; (2) reduction of common-cause vulnerabilities (e.g., enhance diversity of locations for EDGs to defeat floods, fires, and plane crashes; enhance physical separation of units to prevent unit-to-unit spreading of problems caused by external as well as internal events such as turbine blade missiles); (3) availability of staff and resources to address a severe accident impacting multiple units simultaneously; (4) effect of potential source terms (e.g., consideration of reactor size, i.e., small modular reactors versus large monolithic NPPs); (5) high degree of standardization among units (i.e., shared learning); (6) shared equipment (e.g., shared EDGs and venting pipes), which has implications for both economics and safety; and (7) impact of multiple-unit cooling.

V.D. Accident Diagnostics Tool

Provide the operators with information regarding the accident progression (e.g., estimates of time to fuel uncovery, time to reach suppression pool saturation, and time to reach containment design pressure), which can then allow them to identify the most effective strategy to manage a prolonged SBO or another BDBA sequence. This information might be provided in the form of pre-prepared charts or generated for the actual conditions of the NPP by a faster-than-real-time simulator that can predict the gross behavior of the essential NPP subsystems (i.e., RPV, suppression pool, and containment) under beyond-design-basis conditions, especially before substantial core damage occurs, so that core damage can actually be prevented.

V.E. NPP Hardware Design Modifications

Analysis of the Fukushima Daiichi accident has identified a series of hardware-related modifications, which may be addressed by near-term regulation. Their relevance and applicability are plant specific; i.e., these changes simply may not be needed in many NPPs, or an alternative approach may be implemented to achieve the intended safety improvements. Ultimately, some type of cost-benefit analysis would determine which improvements make sense for each NPP. Furthermore, if taken one at a time, resolution of these hardware issues may lead to unintended systems-interaction effects. For example, early venting to permit continued RCIC system operation has the potential for conflict with the desire to delay containment venting as long as possible to minimize the release of radioisotopes. Another example is the desire to depressurize the RPV in order to permit low head alternate pumps to be able to add water, which can conflict with the need to have sufficient RPV pressure to run the RCIC/HPCI systems. Therefore, an overall systems-interaction study needs to be undertaken when looking at the combined effect of these recommendations to be certain that substantial safety benefits are actually realized.

We recommend the following:

1. Reviews of current flooding protection for DC batteries should be made and additional protection provided, or independent connectable DC power should be provided. Direct-current power, especially for instrumentation, is critical for operators to know the current state of the reactor and containment and therefore be in a position to execute emergency procedures accurately. In addition, the power supplies needed for critical instrumentation and critical valve operation (including valves that actuate passive safety systems) or control functions [e.g., steam-driven auxiliary feedwater systems (AFSs)] should be sufficient for the full coping time, currently 4 to 8 hours in the United States, which is likely to be increased to the 24- to 72-hour range by the NRC and industry.

2. Reviews of the current capability to defend against floods should be done and changes made, if necessary, to ensure that adequate dike height and a minimal set of on-site AC power sources are available. This could include adequate protection of EDGs and/or diversity in power and water sources and location for an alternate AC power source as defined in 10 CFR 50 [14]. NPP equipment added to meet either aircraft crash impact (10 CFR 50.150 [15]) or loss of large area (Interim Compensatory Measures Order EA-02-026, Sec. B.5.b, now 10 CFR 50.54(hh)(2) [16]) could also address this recommendation.

3. Improve the robustness of the RCIC system in BWRs. Currently, RCIC system longevity in an SBO is limited by a number of factors:

   a. High suppression pool temperatures can lead to pump cavitation (net positive suction head problems) or problems in cooling the shaft bearings.

   b. High containment pressures may cause the turbine to trip.

   c. An inadequate DC power reserve may lead to loss of the ability to control the RCIC system.

   d. A high room temperature may make access for manual operation difficult.

   e. Current emergency procedure guidelines require emergency RPV depressurization when the suppression pool temperature becomes high.

   We note here that there is new hardware available that is capable of operating indefinitely even without AC or DC power or operator intervention, if there is the ability to vent the containment to maintain suppression pool temperatures at <120°C (248°F). The same technology is used for steam-driven AFSs in PWRs, so PWRs could also benefit from the adoption of improved steam turbine–driven pumps.

4. Improve primary coolant pump seal leakage for SBO scenarios in PWRs. With no seal cooling, significant pump seal leakage may occur. Hardware fixes are known to exist for a few pump models, but coverage of the PWR fleet does not exist at this time.

5. Improve the reliability of the ability to depressurize the RPV and maintain it depressurized in SBO conditions. The isolation condenser system or the RCIC system (HPCI system) should not be the single line of defense for fuel safety in an SBO in BWRs. Since the most likely alternate emergency pumps are low pressure, the ability to use them requires reliable depressurization. An additional consideration for NPPs that use direct-acting SRVs is the assurance that these valves can be opened and remain open with high containment back pressure. In PWRs, reviews should be made of the ability to reduce primary- and secondary-system pressures to allow alternate low-pressure makeup under extended SBO conditions, in case of failure of the AFS.

6. Improve the reliability of the containment hard-piped vents, and extend the application to all Mark I, II, and III BWR containments. In SBO or any other emergency in which the ability to remove heat from the containment is lost, these containments must be vented in <1 day to avoid containment overpressure failure.
   a. The current configurations should be reviewed for valve type, failure mode upon loss of power, or compressed nitrogen.
   b. If rupture disks are used, it should be possible to bypass them (or to burst them) in order to permit venting at low containment pressure and when the core is safe to support long-term RCIC system operation by limiting the peak suppression pool temperature.
   c. Vent exhaust should be to a dedicated release point, not to a common header that could allow backflow to other NPPs or buildings.
7. Review the current NPP instrumentation with a view of providing the operator with more knowledge about the course of a degraded core accident, for example,
   a. thermocouples in the RPV, including the lower head, that can read temperatures up to 1000°C (~1800°F)
   b. hydrogen concentrations and gross gamma radiation measurements at key locations in the reactor building in BWRs.
8. Review key instrumentation in BWR containments as well as penetrations or other seals for operability and accuracy during an extended SBO, considering that under some circumstances portions of the drywell, wetwell, and/or suppression pool may exceed the qualification temperature that has historically been based on design-basis loss-of-coolant-accident considerations.
9. As a defense-in-depth measure, system studies should be made of the efficacy of providing hydrogen mitigation in the reactor building that surrounds BWR containments. The type of technology (e.g., fail-open louvers, igniters, passive autocatalytic recombiners, or active hydrogen recombiners), number and location of devices, and expected rates of local accumulations if containment leaks occur should all be inputs to the study.
10. As a defense-in-depth measure, previous studies of the use of filters on containment vents in both PWRs and BWRs should be updated to include the effects of extended SBOs. The efficacy—considering potentially high steam/gas temperatures being processed—impact on residual risk to the local environment, etc., should be included in order to determine the benefits compared to the costs of any implementation. European experience and testing should also be included.
11. The possibility of an earthquake that damages the SFP wall and liner, causing spent-fuel containment of the water to be lost, should be evaluated. Because the SFPs are outside the reactor containment, to mitigate the consequences of such an accident, a hardened means (e.g., a strong pipe) should be provided that would allow the continued provision of water to the SFPs from the outside, without resorting to improvised approaches such as a helicopter water drop or concrete fire pump. Note that most NPPs in the United States already have hardened makeup-water paths for SFPs, as a result of the NRC-mandated post-9/11 safety and security enhancement efforts. A wide range of water-level measurements and temperature measurements for SFPs should also be made available to the operators in the control room.

V.F. Severe Accident Management Guidelines

Immediately following the Fukushima Daiichi accident, the NRC surveyed U.S. NPPs to determine how effectively severe accident management guidelines (SAMGs), a voluntary initiative of the industry, had been implemented in U.S. NPPs. The results of that review indicated inconsistencies and deficiencies, particularly with regard to the training of personnel. The approaches taken by the different owners' groups toward the development of SAMGs were found to be substantially different. The NRC needs to develop a consensus with industry regarding the intent and scope of SAMGs, including the manner in which they interface with emergency operating procedures. Then, the SAMGs need to be revised at NPPs according to the new criteria. To the extent that the SAMGs require information regarding the status of NPP parameters, additional instrumentation (appropriately qualified) may need to be installed into operating NPPs.

Examples of additional considerations include the following:

- common-mode failures at multiple-unit sites, e.g., loss of common heat sink
- proximity effects from multiple units, i.e., problems at one reactor cascading into problems at adjacent units
- specific consideration of the use of seawater, where appropriate
- shutdown accidents (e.g., SFP inventory, RPV draining, dropped fuel bundle)
- potential need for additional backups (Plan B), including managing reactor pressure while depressurizing to permit continued RCIC/HPCI system operation

- early containment venting, if no fuel failure, to support extended operation of the RCIC/HPCI systems.

V.G. Command and Control During a Reactor Accident

One serious issue that arose from the Fukushima Daiichi accident was an unclear chain of command when the site emergency was declared. The Committee recommends that the predefined command-and-control system currently employed in the United States for emergency situations at NPPs be reviewed to ensure that necessary accident management decisions can be taken promptly at the proper operational level. It is important to have a chain of command that can react swiftly to an accident and thereby minimize the overall consequences for society, i.e., where responsibility and competence are properly matched.

V.H. Emergency Planning

The need for a clear approach to emergency planning in case of a serious accident is recognized in the United States. In the case of the Fukushima Daiichi accident, the Japanese government issued notices for mandatory evacuation of residents within 12 miles of the site and voluntary evacuation within 18 miles of the site immediately following the declaration of a site emergency. Subsequently, the NRC in collaboration with other federal agencies issued an evacuation alert for U.S. citizens within 50 miles of the site. At the time, the NRC justified the alert on the basis of a loss of water inventory in the SFP of Unit 4 and the subsequent possible release of radioactive materials outside of containment. The NRC News Release [17] that provided the technical basis for the evacuation decision was puzzling, since it was based on technical calculations from a simplified computer model for upper-bound radioactive material releases from severe reactor accidents, not for the spent fuel.

Although this concern of SFP overheating and fuel damage was found to be incorrect, the technical basis for this decision was never clarified. The Committee feels that the technical basis should be clarified to better understand the source of the uncertainties. Also, a more risk-informed approach to emergency planning should be developed for U.S. NPPs. The DOE has expertise in this area, and the NRC should work together with the DOE to improve emergency planning activities.

V.I. Health Physics

The Committee collected information that has been published in the open literature for radiation exposure, release and deposition of radioactive materials, and contamination of water and food sources. It is important to note that data collection and analyses continue as this report is being written. It is too early to make any firm conclusions regarding these data and the definitive health impacts to workers or to members of the public. While these data do suggest that off-site health consequences may be minimal, it will take much longer to confirm the health impacts.

V.J. Societal Risk Comparison

We recommend that a quantitative assessment of the societal benefits and risks relating to all energy sources be performed. The assessment should take into account the following aspects: (1) risk from accidents; (2) risks from normal operation such as release of effluents; (3) reliability/continuity of supply (e.g., intermittency of renewables); (4) indirect costs to secure the fuel supply (i.e., military efforts dedicated to ensuring stable oil flow to the United States); and (5) the cost of the energy technology, including both internal costs and externalities. The Committee is aware of the ExternE project (1995) [18] by the European Commission as an example of past work that could be used as a starting point for a future study.

VI. SOCIETAL CONTEXT FOR THE FUKUSHIMA DAIICHI ACCIDENT

VI.A. Introduction

Each of the preceding sections of this report provides technical facts and analyses of what occurred at the Fukushima Daiichi NPS and what may be needed in the future technically. This section addresses the Japanese societal context within which the accident unfolded as well as communication during the crisis.

The earthquake/tsunami was a catastrophe of monumental, unanticipated proportions. That the challenges faced by the Japanese were extraordinary and profound must be recognized and respected. Given the backdrop of the situation, mistakes related to Fukushima Daiichi certainly should have been expected. However, there were serious problems with accident management and with risk communication and crisis communication that need to be examined. Poor communication engenders mistrust and anger and intensifies fear and stress, the effects of which can be long term. Indeed, there were missteps on the part of the Japanese government and TEPCO, but the behavior of others was problematic as well. However, to place blame is not productive; rather, behavior must be carefully, objectively, and critically examined so that valuable lessons are learned by mistakes. This is how meaning can be derived from tragedy.

Ideally, in a crisis, a government would communicate effectively to its people and the global community. Risks associated with the crisis and ongoing efforts to manage the crisis would be clearly articulated. Efforts would be made to provide factual reassurances to the international community. All of this would be done with timely information provided by recognized authorities in a coordinated fashion. Fundamental to such effective crisis communication would be adherence to a sound, well-researched accident management plan predicated on coordination and support among government entities and the utility (or utilities) involved and on trust among all parties, including the national and global communities.

None of the above happened with the Fukushima Daiichi accident. The reasons why are not entirely clear. Obviously, the Japanese government; safety authorities; and TEPCO, the nuclear utility, had a stake in the conduct and outcome of the accident, and they, for their own benefit at least, needed to provide reliable, timely information to their stakeholders and constituents. In addition, many other organizations across the globe had a stake in the conduct and outcome of the accident, and they too needed solid information to be provided to them so that they themselves could provide meaningful information to their decision makers, stakeholders, and constituents. What was actually executed was unfortunate for all parties involved.

The communication efforts during the Fukushima Daiichi accident will likely be studied in depth for years to come, but what we know today is that this is a complex story of mismanagement, culture, and sometimes even simple errors in translation, all amidst a voracious need for immediate information by governments and media.

VI.B. Conditions in Japan

VI.B.1. The Japanese Nuclear Industry

With more than one-third of its electricity derived from nuclear, Japan is second only to France in dependence upon nuclear power to drive the national economy. Like in France, the oil embargos of the 1970s had a severe impact on Japan's national economy, and the drive to diversify its energy supply accelerated the expansion of NPP construction. So important was the electrification of Japan, the events at TMI-2 hardly slowed this expansion.

The push to expand nuclear power was driven by what became known as "Japan Inc.," or the high degree of cooperative planning between Japan's corporate and political sectors—so, too, were the relationships between the nuclear utilities and the governmental authorities, who were charged with overseeing safety. The term *amakudari*—or "descent from heaven"—was used to describe the common practice of senior government officials retiring to take highly paid jobs in industry. This environment contributed to a weakened nuclear regulatory structure.

One of the key lessons learned by the United States after the TMI-2 accident was the need to reform and strengthen the independence and technical competence of the NRC. Many other nations followed, recognizing the prudence in changing their governance approach to nuclear power. However, Japan did not change its regulatory governance because to do so would centralize too much authority in its central government, which would upset the shared authority arrangement with the prefectural governments.

The prefectural governments were highly dependent upon the subsidies provided by the central government for hosting the NPPs and exerted influence in maintaining the regulatory status quo. Furthermore, in a strange contrast to Western practices, the prefectures actually benefit from the inefficiency of the utility. Japan's poor nuclear reactor capacity factors (percentage of actual annual electrical output compared to rated capacity) are about mid-60%, while those of the United States and Korea are near mid-90%.

The reasons for this disparity are simple: Japan's reactors are required to shut down every 13 months for routine maintenance and cannot be restarted without the approval of the prefectural government. The extended utility outages are an economic boon to the regional economies (largely because of the hundreds of outage workers and vendors who fill the local hotels and restaurants), and few incentives exist to change the existing system of governance. The prefectural government, not the national safety regulator, has final say on NPP restart operations, which is a fact that is not lost on the NPP operators.

By U.S. standards, this system of shared regulatory authority and economic benefit would be viewed as flawed. Yet, this system allowed the Japanese to develop 58 reactors at 18 sites in a country whose national psyche is still affected by the atomic bomb. The Japanese created a system that promoted and enforced the safe and peaceful use of nuclear energy, and the Japanese had an enviable safety record. Unlike the United States, where states are independent governments, the Japanese prefectures are jurisdictions of the central government with subprefectural structures down to districts, townships, and villages. The hierarchical distribution of authority suits the Japanese culture, and the effectiveness of this governance structure was demonstrated during the evacuations around the Fukushima Daiichi NPS and in response to the earthquake/tsunami.

So, why did this system, built up over many decades, fail in crisis communication during the Fukushima Daiichi accident? Many have cited the lack of a central authority; others have cited the widespread distrust of TEPCO. Both of these factors contributed to the failure in crisis management, but the simplest explanation is that the government did not use the system that was in place to address this very issue.

VI.B.2. Emergency Management

Exactly why the Japanese government chose not to follow its established process for managing a nuclear crisis is still a mystery, but we know that it revolved around personalities; a widespread distrust of TEPCO; and a general low regard of the Japanese regulatory system, which was driven more by process than by analysis.

There is little doubt that the magnitude and devastation caused by the earthquake/tsunami were enough to overwhelm any governmental emergency management system. Japan is an island affected by large and destructive earthquakes with some frequency, and the people and government have demonstrated resilience in dealing with natural disasters. The multiple-unit NPPs at the Fukushima Daiichi NPS and Fukushima Daini NPS posed unique problems for the emergency managers—problems that the emergency planners assumed would be controlled by the utility.

In the United States, the NRC expects and requires utility operators to be at the forefront of any response to an emergency. In an emergency, the role of the NRC is not to supervise but to coordinate the federal response and to ensure at all times that the operator is capable of implementing adequate protective measures—and, perhaps most importantly, to provide those assurances to the president, Congress, and the American people.

On a periodic basis the NRC, along with other organizations at the federal, state, and local levels, conducts widespread exercises at each NPP to test the regional emergency management systems. These exercises are critiqued not only by the NRC but also by the Institute of Nuclear Power Operations, a peer-review organization composed of representatives from other U.S. utilities. The goal of the critique is to gain insight and a common understanding of how the utilities and the NRC can make better decisions.

Japan, too, routinely exercises its nuclear emergency management system and has modeled much of its system after that of the United States. But, unlike the United States, Japan rarely tests the limits of the system and training of personnel by using highly unusual events or crafting scenarios that are impossible to recover from. Culturally, the Japanese do not accept failure as a learning opportunity. The Japanese system is largely designed to test the proficiency of the operators in responding to known scenarios. The problem with this approach is that if a scenario has not been incorporated into the design basis, the ability to anticipate and respond is lessened.

We have learned from documents released by the Japan Nuclear and Industrial Safety Agency that TEPCO had "no operational manual that envisioned a loss of all power sources needed to activate emergency condensers and backup water injection devices to cool down nuclear reactors" [19]. In addition, according to the *New York Times*,

> In a country that gave the world the word tsunami, the Japanese nuclear establishment largely disregarded the potentially destructive force of the walls of water. The word did not even appear in government guidelines until 2006, decades after plants … began dotting the Japanese coastline [20].

Basically, TEPCO's emergency management plans never contemplated an extended SBO or the potential devastation of a tsunami, and therefore, neither the utility nor the safety regulator ever practiced these scenarios.

VI.B.3. Tokyo Electric Power Company

Tokyo Electric Power Company, whose service area includes the capital, Tokyo, is one of the largest utilities in Japan. Its influence in politics at all levels is substantial. In Japan's regulated markets, it controls both the production and the distribution of about one-third of all the electricity in Japan. Considered by many to be an essential part of the economic engine that drove Japan Inc., it also has a long history of providing postretirement jobs to government officials and exerting influence to protect its monopoly. Embroiled in controversy since 1990 for several failures in its nuclear operations, TEPCO saw a series of senior managers resign as part of a ritual process for accepting blame for corporate misconduct, which included falsifying records and submitting false information to the regulators. While honor may have been satisfied, it is not clear that any change in corporate safety culture was achieved.

In July 2007, a major earthquake hit TEPCO's Kashiwazaki Kariwa NPPs. The subsequent investigations by regulatory bodies and external reviewers showed many fundamental weaknesses and failures by TEPCO to implement recommended safety procedures. TEPCO crisis communication and management capabilities were also of particular concern to the safety authorities, but it appears that TEPCO did little to fundamentally change its approach.

The inadequate response by TEPCO to the unfolding events at Fukushima Daiichi should not have been a surprise to anyone. TEPCO had not anticipated a severe earthquake and tsunami event, had no operational procedures to handle an extended SBO scenario, and had not practiced or learned from the Kashiwazaki Kariwa earthquake how to manage and communicate during a crisis.

VI.B.4. The Japanese Government

The prime minister of Japan entered the accident situation having a widely known distrust of TEPCO and its relationships with the Ministry of Economy, Trade and

Industry and with MEXT. The *New York Times* reported that the prime minister

> had built his career on suspicion of the collusive ties between Japan's industry and bureaucracy.… At the drama's heart was an outsider prime minister who saw the need for quick action but whose well-founded mistrust of a system of alliances between powerful plant operators, compliant bureaucrats and sympathetic politicians deprived him of resources he could have used to make better-informed decisions.… He struggled to manage the nuclear crisis because he felt he could not rely on the very mechanisms established by his predecessors to respond to such a crisis. Instead, he turned at the beginning only to a handful of close, overwhelmed advisers who knew little about nuclear plants and who barely exchanged information with the plant's operator and nuclear regulators.[21]

Japan had a system designed specifically to monitor, assess, and report on radioactive releases during emergencies. But, it was ignored during the early stages of the crisis and provided little or no help coordinating analyses and managing communication for the central government. Why it was ignored is still a question. We know the advisors put in charge by the prime minister neither were familiar with nor understood the hierarchical role of data reporting from the utility and regulatory body. The process of transforming data into useful information was likely viewed suspiciously as a filtering of information, and certainly, direct access to data from the utility would be timelier.

Ironically, in bypassing the existing nuclear emergency management system, the central government under the prime minister was solely reliant on information from TEPCO, a company he did not trust. The people he made responsible for dealing with TEPCO and the regulators had little or no experience with nuclear issues and were soon overwhelmed. Moreover, they were reluctant to challenge the views of the prime minister or accept support from others with more expertise in managing a nuclear crisis. When asked why an immediate offer of assistance from the United States was largely ignored, people close to the situation in Japan privately told members of the Committee that because of "questionable leadership of the prime minister's office," the offer was not understood. Early in the crisis—when time was of the essence—the offers of assistance from the international community were never forwarded for action but instead were assigned to lower-level bureaucrats for consideration and appropriate response.

VI.C. Progression of Events

We know that early in the crisis, the Japanese Cabinet Office was in contact with TEPCO and understood the status of the Fukushima Daiichi NPS and the problems it faced. But, information was sparse and slow in coming. The extent of the damage was not known, but it appeared that all the reactors had survived the earthquake/tsunami without any radioactive releases.

Then, troubling reports began to trickle in from TEPCO on its ability to recover from SBO and the loss of water level in Unit 1. At 7:03 p.m., a nuclear emergency was declared, and 2 hours later, an evacuation within 3 km of the NPP was announced. By 1:30 a.m. on March 12, the decision was made to vent the containment in Unit 1, which would relieve pressure and allow injection of water, but venting was not begun. By 5:44 a.m., the prime minister ordered the evacuation extended from 3 km to 10 km from the NPS boundary. The continual escalation of reports, the seeming failure of TEPCO to begin venting of Unit 1, and the inability to establish communication with senior TEPCO leaders were a source of tremendous frustration to the prime minister, so he visited the site at first light to speak directly to the NPP operators to find out why the utility had not started venting Unit 1. After a briefing at the Fukushima Daiichi NPS, the prime minister departed the site, and at 9:00 a.m., the venting started.

The failure to begin venting Unit 1 was seen by the media as a TEPCO attempt to avoid taking the unprecedented step of releasing radioactivity, which would have harmed its corporate image. It became a source of friction between the prime minister and the TEPCO operators and ultimately tainted all attempts to bring perspective to crisis communication. But, the records show that in the early morning of March 12, the pressure levels allowed the utility to begin injecting freshwater into the RPV using fire truck pumps. While venting was needed, the ability to add water was a priority. Another reason given by TEPCO was that it delayed venting until the evacuation was largely complete.

There has been much speculation that TEPCO executives hesitated in directing or authorizing the actions taken that would destroy the economic value of the reactor site. While there may have been those discussions at some level in TEPCO and perhaps the government, it is not apparent that was the case at the NPS, where managers and employees were attempting to prevent a catastrophe. While the extent of core damage was not known, they knew early on that the core had most likely been exposed and that without off-site power they would need to resort to seawater cooling.

VI.D. Cultural Perspectives

In the West, we may not be able to fully appreciate cultural differences that drive and motivate the Japanese public. The extraordinary efforts to control the disaster made by TEPCO employees and many others in the Japanese nuclear industry were widely reported as acts of desperation rather than a coordinated attack on the problem. Acts of heroism and sacrifice were symbolized by the "Fukushima Fifty," a group of employees and emergency responders who temporarily stayed behind to man the control systems and site while the bulk of NPP employees were relocated. The Fukushima Fifty remained only 50 in number for a short time, and soon hundreds of NPP workers, military, firefighters, and TEPCO employees from other reactors arrived to support recovery operations [22]. For the Japanese, the Fukushima Fifty were a symbol of national resolve and willingness to sacrifice to protect the nation. The Fukushima Fifty were a source of national pride and became a rally point for finally bringing the coordinated national and international response effort needed to bring the situation under control.

In contrast, in the Western media the Fukushima Fifty were a symbol of the desperate measures required—a shocking sign of how desperate things had become. The Fukushima Fifty illustrate the power of symbols, cultural perceptions, and interpretations in communication with the public. Effective communication across the globe is predicated on having a common understanding, with cultural differences being recognized, understood, and embraced.

VII. THE FUKUSHIMA DAIICHI ACCIDENT AND ANS

VII.A. Reaction of ANS to the Fukushima Daiichi Accident

The situation in which ANS found itself at the time of the Fukushima Daiichi accident was a microcosm of what was happening more broadly. The role of ANS as a professional society has always been as an honest information broker. When the Fukushima Daiichi accident happened, significant efforts were made to provide ANS members with current information and analysis, as well as respond to media requests for experts to provide context. However, the Fukushima Daiichi accident was an event of such magnitude and interest that ANS, like other technical societies and organizations, was unprepared for the huge onslaught of demand for information and analysis. The Fukushima Daiichi accident resulted in a serious reappraisal on the part of ANS regarding the organization's role in crisis communication.

VII.A.1. The Difference Between Risk Communication and Crisis Communication

While often used interchangeably, risk communication and crisis communication address different audiences at different times. A recent issue of the *IAEA Bulletin* presents risk communication as

> vital in the process of achieving a common risk perception. It can be defined as a two-way process of information exchange that includes multiple types of information with multiple purposes. As an important benefit, risk communication has the potential to build public trust.[23]

Meanwhile, crisis communication is used to help governments and companies respond to and recover from a crisis. A key part of crisis communication is using risk communication to build "public trust" by providing experts and reference materials to convey effectively to the public and decision makers the risks of ongoing events or proposed actions. In essence, risk communication is a continual process of public education and awareness. Crisis communication leverages risk communication programs to manage misinformation and speculation that typically occur during a crisis.

VII.A.2. Professional Society Versus Trade Association

The American Nuclear Society is a professional society with almost 12,000 individual members. When the Fukushima Daiichi accident occurred, ANS launched an effort in risk communication, providing informational material on radiation protection and nuclear operations. The ANS effort served an important function as an unbiased source of information, because ANS is not intended to be—and is not viewed by the media as—a promotional organization seeking to preserve the reputation of its members. ANS is not a trade association or an advocacy group.

In contrast, the Nuclear Energy Institute (NEI) is a trade association whose members include all U.S. nuclear utilities and major technology vendors. Almost immediately after news of the damage to the Fukushima Daiichi reactors became public, NEI launched a crisis communication program designed to reassure the public and government officials about the safety of nuclear power in general and specifically the U.S. reactor fleet. The efforts of NEI were focused not on the public, but upon those whom the public expects to provide them with knowledge and leadership. Additionally, NEI had the benefit of prior planning and practice, financial resources, and articulate leaders well trained to handle the blizzard of media questions and demands.

As a society with limited resources, ANS experienced difficulties with its Fukushima risk communication effort. There were problems with the informational materials that ANS had available. Many were largely designed as written materials for an educational setting or briefing and were not well suited for today's major sources of public information: the Internet and social media. Another barrier facing ANS was a deficit of members skilled in dealing with the media, and of those who were media savvy, many, as would be expected, were restricted by their employers from any public discussions or representations.

VII.A.3. Mobilizing ANS

At ANS headquarters, an ad hoc ANS response group was quickly formed composed of ANS executive officers, staff, members, and consultants to help to support the deluge of demands for information from the media. The group began to exchange information derived from multiple sources, several of which were in Japan; other sources were with governmental organizations involved in monitoring the crisis. This information exchange enabled ANS communications and public affairs personnel to provide the media context pertaining to ongoing events as they were happening, from an organization primarily concerned with scientific and technical accuracy, not advocacy.

VII.A.4. The Turning Point

From the first moments of the Fukushima Daiichi accident, the specter of Chernobyl drove much of the conversation and speculation. Lacking real information from the Japanese government, the media quickly focused on Chernobyl as a convenient comparison for predicting fallout deposition and radiation health effects. ANS members, NEI, and other technical and trade organizations made repeated attempts to show this was a flawed comparison. But, no amount of facts or analyses could replace the dramatic images of hydrogen explosions at three out of four units, the scenes of devastation from the earthquake/tsunami, the public confusion by Japanese officials in reporting recovery operations, and rapid-fire media appearances by nuclear opponents who seized the opportunity to advance their agendas.

Furthermore, on March 16, 5 days after the accident, the chairman of the NRC testified before the Congressional Energy and Commerce Committee that the NRC believed that the secondary containment on Unit 4 had been destroyed; that there was no water in the SFP; and that radiation levels were "extremely high," limiting the ability of responders to take corrective measures. In essence, he informed Congress that the Fukushima NPS was about to become another Chernobyl and recommended an evacuation of 80 km from the NPP site.

But, the chairman's statement was incorrect and was never substantiated by the NRC. The Japanese government immediately denied the statement, but the effect on public perceptions was done. What little confidence that the international community and media had in reports coming from the Japanese authorities evaporated, and speculation ran rampant. Several other nations followed the NRC advice to have their nationals evacuate to 80 km, and the U.S. military began relocating personnel and offering voluntary evacuations for nearly 20,000 dependents located in surrounding bases far outside of the 80-km designated area. The exodus of foreigners only confirmed in the minds of many that the Fukushima Daiichi accident would become a worse disaster than Chernobyl.

This crisis of public confidence marked a turning point for both the Japanese and ANS. Within the Japanese government, the disarray in managing the nuclear crisis could no longer be excused. An aide to the prime minister told the *New York Times,* "We found ourselves in a downward spiral, which hurt relations with the United States. We lost credibility with America, and TEPCO lost credibility with us."[21]

VII.A.5. Questions for ANS

The Fukushima Daiichi accident resulted in ANS asking itself two questions. First, should ANS act as both a resource for credible information and proactively address misinformation? Second, should ANS transition from its traditional role of risk communication to also supporting crisis communication?

ANS leaders debated these questions. They were not fully prepared; they had no established nuclear crisis communications plan; and ANS communications resources, such as social media outlets and media training programs, had been underfunded and underutilized. The TMI-2 and Chernobyl accidents were in the distant past, and the "Nuclear Renaissance" had convinced them that the public had regained confidence in nuclear power. As a society, ANS committed the ultimate error of nuclear safety culture: It had become complacent.

VII.B. Communication and Misinformation

In an age in which international media make news available in real time, failure to communicate risk effectively will inevitably lead to misinformation that can spread like an epidemic. Responding to misinformation and speculation can overcome crisis managers and distract them from addressing issues of real significance. Misinformation can occur because of ignorance, particularly with regard to technical information, and because of jumping to conclusions without substantiating facts. Misinformation can also derive from a simple mistake in translation or presentation or from a cultural issue not transparent to outsiders. Sometimes, individuals and organizations with agendas will use the crisis—and media attention—to advance their views with spurious and speculative information.

The Fukushima Daiichi accident forced ANS members to relearn lessons from the TMI-2 and Chernobyl accidents: Crisis communication and addressing misinformation are an integral part of our responsibilities under the ANS Code of Ethics. As a professional society, we understand that if people act on misinformation, the crisis not only will be exacerbated but also may lead to tragic personal outcomes. A grim legacy of the Chernobyl accident is the estimated 100,000 to 200,000 elective abortions driven by unwarranted hysteria and fear that consumed Europe and states of the former Soviet Union in the months following the accident [24, 25, 26]. The secrecy that surrounded the accident, the response by the Russian and the Ukrainian governments, and the uncoordinated international monitoring response all fueled that fear and gave rise to much of the misinformation that surrounds the accident even today. In the first few days of the Fukushima Daiichi accident, nuclear engineers and scientists feared that many of the mistakes of Chernobyl were about to be repeated.

VII.B.1. Role of ANS in Combating Misinformation

At the start of the crisis, ANS leaders debated the role ANS should play in addressing the continual stream of media misinformation. As a professional society, ANS does not routinely engage in advocacy, leaving that function to trade associations like NEI. Instead, ANS has traditionally focused efforts on risk communication and, when asked, on providing scientific experts to counsel on technical matters. As the events at Fukushima Daiichi unfolded, the credibility of the entire nuclear industry and profession was questioned.

After the March 16 announcement from the NRC, hyperbole and speculation ran rampant as news organizations painted increasingly dire scenarios and predictions of massive impacts to human health and the environment. The news reporters were not responsible for misinformation; rather, so-called experts who filled the hours of the global 24-hour news cycle spread fear, uncertainty, and doubt. Many of these "experts" had little understanding of nuclear operations or radiation protection, but they offered their opinions as scientific facts.

News producers sought people with expertise, but producers often have little experience in judging credentials and weighing the technical expertise of different people. In the crushing demand for experts, news producers naturally turned to people who had previously commented on nuclear or science matters to aid their interpretation of the news from Japan. Well-known personalities from nuclear nonproliferation policy organizations confidently predicted increased cancers in Alaska and the West Coast of the United States. A popular theoretical physicist and media personality made dozens of television appearances ridiculing the Japanese effort to cool the reactors and predicting the loss of the entirety of northern Japan unless the reactors were immediately entombed. There was no sustained counter view or strong challenge to these claims—and perhaps, none was wanted.

The misinformation was a source of tremendous frustration to ANS members, who barraged ANS headquarters and the ANS Web site with demands that ANS counteract the flow of misinformation. But, the Fukushima Daiichi accident had moved from a news event to a media circus. The global fascination with the ongoing crisis at Fukushima was an opportunity for the media to increase advertising revenues. This is not intended to be a criticism of the media, but simply to put into context the decisions that ANS was about to make.

VII.B.2. A Major Commitment

For ANS, the decision to mount a crisis communication campaign required a significant commitment of staff resources and members' time. ANS is a voluntary society, and the members who supported the response to the Fukushima Daiichi accident did so with no compensation or any expectation that their efforts would boost ANS fundraising. Putting aside their careers, many ANS members suddenly found themselves on the national stage in the midst of the media circus. To supplement the media outreach effort, ANS called upon its social media group to rapidly expand ANS's presence on the Internet. The group was a loosely knit coalition of nuclear professionals and other nuclear advocates. Committed to using digital communications to convey science-based perspectives on nuclear energy and combat misinformation, the group played a crucial role in projecting ANS's views into the volatile and demanding world of social media. Another key role the group played was quickly identifying incorrect information contained in mainstream printed and Internet-based media and providing on-the-record corrections.

As the dramatic images of explosions, terrified evacuees, and increasingly ad hoc attempts to cool the reactor played across global media, the flow of misinformation turned into a flood. The demand for information and on-air interviews by ANS experts was overwhelming. One week turned into two, then three, and still the Fukushima Daiichi accident remained the headline story. The ad hoc coalitions so ably put together by ANS staff began to break apart as members returned to their jobs and obligations. The problem was not that ANS was incapable of responding; rather, it was incapable of a sustained effort.

VII.C. ANS Risk Communication and Crisis Communication Recommendations

The Committee is focusing its recommendations to address the role and activities of a professional scientific membership society before, during, and after a nuclear event. As such, ANS must commit to an ongoing effort to build upon the lessons learned during the Fukushima Daiichi accident.

The American Nuclear Society should develop a Nuclear Event Communications Plan (the Plan):

- The Plan must include budgetary authority and mechanisms to support activation of the Plan.

- The Plan should proceed in a timely manner.
- ANS should convene a Technical Group on Nuclear Communications (the Technical Group) under the auspices of the Public Information Committee (the PI Committee). The mission of the Technical Group would include incorporating communications techniques, tools, resources, and expertise into the scientific and technical work of ANS.
- In parallel with the establishment of the Technical Group, the PI Committee should convene an Advisory Group on Nuclear Event Communications (the Advisory Group) to develop the Plan for review by the PI Committee and, eventually, endorsement by the ANS Board of Directors.
- The Advisory Group should include crisis communications and risk communications experts, including thought leaders from outside ANS.

The Committee recommends the following for the Plan:

- Focus on developing a cadre of experienced nuclear professionals who are willing to "embed" themselves with major U.S. media outlets during a nuclear crisis.
- Match experts with geographic regions, both in the United States and abroad, and develop relationships with the appropriate media in those regions.
- Incorporate social media tools and techniques into the Plan.
- Prepare focused messages specific to crisis communications.
- Make available a publicly accessible, communications-focused Web site specific to the nuclear crisis.
- Commit to an ongoing media training and risk communications training program for ANS membership as a whole (required for designated ANS crisis communicators).
- Examine methods to ensure that ANS has immediate access to the best available information from relevant governmental bodies and trade associations.

The American Nuclear Society should work with other organizations, such as the Health Physics Society and the American Physical Society, on sharing risk communications resources in general and specifically on developing improved methods of communicating radiation and radiation risk to the public.

Moreover, ANS should commit to an ongoing, sustained, and proactive Congressional and media outreach program to increase national nuclear literacy and to establish ANS as a credible resource during nuclear incidents.

Finally, ANS should develop enhanced communications methods to provide ANS members with information and updates during a nuclear event.

VII.D. Final Thoughts

Among the most important questions for ANS to face as a result of the Fukushima Daiichi accident is how we, as nuclear professionals, and ANS, as a professional society, could improve our risk communication and crisis communication and be prepared for future events, were they to occur. The efforts made by our members in responding to and supporting ANS's outreach efforts demonstrate a resolve to not remain silent as events unfold, to advance ANS's position and share information, and to be proactive in countering misinformation. The Fukushima Daiichi accident will provide lessons learned on many fronts, but for ANS, perhaps one of the most significant will be in accepting and transforming the role of ANS in risk communication and crisis communication.

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ACRONYMS, ABBREVIATIONS, AND DEFINITIONS

AC	alternating-current
(the) Advisory Group	Advisory Group on Nuclear Event Communications
AFS	auxiliary feedwater system
ANS	American Nuclear Society
BDBA	beyond-design-basis accident
Bq	becquerel
BWR	boiling water reactor
Ci	curie
cold shutdown	RPV water temperature is <100°C.
(the) Committee	The American Nuclear Society Special Committee on Fukushima
containment	refers to the configuration of the structure and associated systems that enclose the nuclear reactor and are the final barrier to the release of radioactive materials into the environment in the case of a severe accident; containment designs are designated Mark I (the oldest), Mark II, and Mark III (the most recent).
^{134}Cs	cesium-134
^{137}Cs	cesium-137
CST	condensate storage tank
DC	direct-current
DOE	U.S. Department of Energy
ECCS	emergency core cooling system
EDG	emergency diesel generator
Gy	gray; the international system unit of measure for the amount of energy deposited in any material from any form of radiation
HPCI	high-pressure coolant injection
^{131}I	iodine-131
IAEA	International Atomic Energy Agency
JAEA	Japan Atomic Energy Agency
JAEC	Japan Atomic Energy Commission
kBq	kilobecquerel
km	kilometer
km^2	kilometers squared
LWR	light water reactor
m	meter
Mark I	see "containment"
Mark II	see "containment"
Mark III	see "containment"
MBq	megabecquerel
MEXT	Ministry of Education, Culture, Sports, Science and Technology–Japan
μSv	microsievert; see "Sv"
mm	millimeter
mR	millirad; see "rad"
mrem	millirem; see "rem"
mSv	millisievert; see "Sv"

MWe	megawatt electric
m^2	meters squared
m^3	cubic meters
MSIV	main steam isolation valve
NEI	Nuclear Energy Institute
NIRS	National Institute of Radiological Sciences (Japan)
NNSA	National Nuclear Security Agency (DOE)
NPP	nuclear power plant
NPS	nuclear power station
NRC	U.S. Nuclear Regulatory Commission
NTTF	Near-Term Task Force
outage	Cold shutdown condition and periodic inspections and/or refueling operations are being conducted; the RPV head may be on or off.
PCV	primary containment vessel
person-Sv	person-sievert
(the) PI Committee	Public Information Committee
(the) Plan	Nuclear Event Communications Plan
PWR	pressurized water reactor
RCIC	reactor core isolation cooling
rad	radiation absorbed dose; the unit of measure for the amount of energy deposited in any material from any form of radiation; the related international system unit is the gray (Gy).
rem	roentgen equivalent man; the unit of measure for the amount of energy deposited in a human body that accounts for the effect of differences in radiation types (alpha, beta, gamma, etc.) on living tissue; the related international system unit is sievert (Sv).
RHR	residual heat removal
RPV	reactor pressure vessel
SAMG	severe accident management guideline
SBO	station blackout
SFP	spent-fuel pool
SRV	safety and relief valve
start-up	RPV head is on, reactor is critical, and primary system is being heated.
Sv	sievert; the international system unit of measure for the amount of energy deposited in a human body that accounts for the effect of differences in radiation types alpha, beta, gamma, etc.) on living tissue
(the) Technical Group	Technical Group on Nuclear Communications
TEPCO	Tokyo Electric Power Company
TMI-2	Three Mile Island Unit 2
Unit	refers to reactor(s) in NPS(s)

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Professor Corradini is a Wisconsin Distinguished Professor at the University of Wisconsin-Madison (UW). He is chair of UW's Energy Institute Faculty Governance Committee and Director of UW's Wisconsin Institute of Nuclear Systems. From 1978 to 1981, he was associated with Sandia National Laboratories, where he was a member of the technical staff.

Professor Corradini is a mechanical and nuclear engineer with research interests centered primarily in thermal hydraulics and multiphase flow. He especially emphasizes the areas of reactor operation, reactor safety, reprocessing, and recycle and risk assessment.

Professor Corradini has served on a variety of boards and committees, such as the U.S. Department of Energy Nuclear Energy Advisory Committee (2000–present); the Nuclear Waste Technical Review Board, Chair (2002–2004); the Institute of Nuclear Power Operations Training and Education Accreditation Board (2004–2008), and the Advisory Committee on Reactor Safeguards (2006–present).

Among Professor Corradini's numerous awards and honors are the Presidential Young Investigator (1984) from the National Science Foundation and the Young Members Achievement Award (1990) from the American Nuclear Society (ANS), of which he was also named a Fellow. In 1996, he received the UW Distinguished Teaching Award, and in 1998, he was recognized by the National Academy of Engineering.

Professor Corradini is the Vice President/President Elect of ANS.

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In April of 2010, after serving 8½ years as a presidential appointee, Dr. Klein returned to Texas from Washington, D.C., to work at The University of Texas (UT) at Austin as Associate Director of The Energy Institute, Associate Vice President for Research, and professor of mechanical engineering (Nuclear Program). Earlier in his career, Dr. Klein had served as Vice Chancellor for Special Engineering Programs at the UT System and as a professor in the Department of Mechanical Engineering (Nuclear Program) at UT Austin. During his earlier tenure at UT Austin, Dr. Klein was Director of the Nuclear Engineering Teaching Laboratory, Deputy Director of the Center for Energy Studies, and Associate Dean for Research and Administration in the College of Engineering. Dr. Klein rejoined the UT System in January 2011 as Associate Vice Chancellor for Research in the Office of Academic Affairs.

Dr. Klein was sworn in to the U.S. Nuclear Regulatory Commission (NRC) in 2006 and was appointed Chairman by President George W. Bush, serving in that role from July 2006 to May 2009. As Chairman, Dr. Klein was the principal executive officer and official spokesman for the NRC, responsible for conducting NRC's administrative, organizational, long-range-planning, and budgetary functions, as well as certain personnel functions. Additionally, he had the ultimate authority for all NRC functions pertaining to an emergency involving an NRC licensee. Dr. Klein served as Commissioner of the NRC from May 2009 to March 2010.

Before joining the NRC, Dr. Klein served as Assistant to the Secretary of Defense for Nuclear, Chemical, and Biological Defense Programs. He was appointed to this position by President George W. Bush and confirmed by the Senate in 2001. In this position, he served as the principal staff assistant and advisor to the Secretary of Defense; Deputy Secretary of Defense; and the Under Secretary of Defense for Acquisition, Technology and Logistics for all policy and planning matters related to nuclear weapons and nuclear, chemical, and biological defense programs.

Honors and awards that Dr. Klein has received include the Henry DeWolf Smyth Nuclear Statesman award in 2011, Fellow of the American Society of Mechanical Engineers and the American Nuclear Society, Engineer of the Year for the State of Texas, the University of Missouri Faculty-Alumni Award, and the University of Missouri Honor Award for Distinguished Service in Engineering.

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Professor Buongiorno is a member of the American Nuclear Society (ANS) and the American Society of Mechanical Engineers; Co-Director of the Reactor Technology Course for Nuclear Utility Executives, which has been offered jointly by MIT and the Institute of Nuclear Power Operations for the past 19 years; and a consultant for the nuclear industry (AREVA, Westinghouse, and South Texas Project) in the area of reactor thermal hydraulics.

For his work in his research areas and his teaching at MIT, Professor Buongiorno has won several awards, including the 2011 Landis Young Member Engineering Achievement Award (ANS) and the 2011 Ruth and Joel Spira Award for Distinguished Teaching (School of Engineering, MIT).

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Dr. Ryan is an independent consultant in radiological sciences and health physics. He is an adjunct faculty member at Vanderbilt University in the Department of Environmental Engineering and at Texas A&M University (TAMU) in the Department of Nuclear Engineering. In addition to his adjunct appointment at TAMU, Dr. Ryan has taught radiation protection courses on the undergraduate and graduate levels at the University of South Carolina and the College of Charleston. He was previously an associate professor in the Department of Health Administration and Policy at the Medical University of South Carolina.

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Dr. Ryan is Editor In Chief of *Health Physics Journal*. He has held numerous offices in the Health Physics Society, including President of the Environmental Section and the Savannah River Chapter. Dr. Ryan served on the Technical Advisory Radiation Control Council for the State of South Carolina for 19 years. He is a distinguished emeritus member of the National Council of Radiation Protection and Measurements (NCRP), and is a past member of the NCRP Board of Directors, and has served as NCRP's Scientific Vice President for Radioactive and Mixed Waste Management and as Chair of Scientific Committee 87. Dr. Ryan is certified in the comprehensive practice of health physics by the American Board of Health Physics.

Dr. Ryan most recently served for several years on the independent review panel for decommissioning work at Brookhaven National Laboratory. In 2007, he completed a 9-year term as Chairman of the External Advisory Board for Radiation Protection at Sandia National Laboratories. He is a member of a similar external review board for Lawrence Livermore National Laboratory. He completed 8 years of service on the Scientific Review Group appointed by the Assistant Secretary of Energy to review the ongoing research in health effects at the former weapons complex sites in the Southern Urals. He has also served on several committees of the National Academy of Sciences producing reports regarding radioactive waste management topics and served as Chairman for the U.S. Nuclear Regulatory Commission's Advisory Committee on Nuclear Waste and Materials (ACNW&M). Dr. Ryan served on ACNW&M since 2002, until it was merged with the Advisory Committee on Reactor Safeguards (ACRS) in 2008. In June 2008, Dr. Ryan became a member of ACRS.

In 1989, Dr. Ryan received Health Physics Society's Elda E. Anderson Award, for demonstrated excellence in research, discovery, and/or significant contribution to the field of health physics. He was recently inducted into the Georgia Institute of Technology's Academy of Distinguished Alumni. He is a recipient of the Francis Cabot Lowell Distinguished Alumni for Arts and Sciences Award for the University of Massachusetts Lowell.

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Since 1972, Dr. Sawyer has been involved in boiling water reactor (BWR) plant technology with exposure to virtually all aspects of plant performance. He has performed and managed advanced fuel element and core design studies to incorporate plutonium recycle and to increase the fuel performance of uranium fuel cycles. He has also performed plant system performance studies such as cost/performance studies of varying core power density, emergency core cooling system performance studies, and studies to enhance plant availability.

After the Three Mile Island Unit 2 accident, Dr. Sawyer headed a task force that performed all related studies including risk assessments and evaluations of proposed design changes. He has also managed all transient and accident analyses for BWRs under construction.

Dr. Sawyer has been associated with Advanced BWR (ABWR) development since the beginning of both the ABWR and the Simplified BWR (SBWR) designs. In this role, he managed the overall conceptual design, as well as the specification of the required overall performance of key systems and performance of the transient, accident, and severe accident safety analyses required for licensing. He was one of the key people involved in the ABWR certification effort with the U.S. Nuclear Regulatory Commission (NRC), defending the ABWR design and performance before the Advisory Committee on Reactor Safeguards as well as the NRC staff. He was instrumental in developing the severe accident design and management strategy for ABWRs. In his last assignment at General Electric, he was Manager, Advanced Reactor Programs. In this assignment, he was responsible for plant design and related technology for ABWRs and liquid metal reactors.

Since his retirement in 2000, Dr. Sawyer has stayed active in nuclear energy, participating in design reviews, design changes, and power uprate of ABWRs for Finland; licensing of the Economic SBWR (ESBWR) in the United Kingdom; ABWR and ESBWR training; and occasional lectures on BWR technology. Since 2009, he has been a consultant for Westinghouse, working on ABWR renewal of the ABWR design control document and, more recently, focusing on lessons learned from the Fukushima accidents.

Dr. Sawyer has several patents.

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Mr. Shahkarami was the recipient of the 2008 Chicago United Leadership, 2009 ANS Utility Leadership, and the 2010 World Association of Nuclear Operators Excellence awards. He has also greatly contributed to the Institute of Nuclear Power Operations principle of engineering and the technical conscience document.

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Dr. Ninokata has been a professor in the Research Laboratory for Nuclear Reactors at Tokyo Institute of Technology (TITech) since 1993. Before joining TITech, he worked on boiling water reactor (BWR) core management at the Fukushima Daiichi nuclear power station from 1977 to 1978 and on fast breeder reactor (FBR) plant design at the Tokyo Electric Power Company from 1978 to 1980. Then, from 1980 to 1993, he worked on sodium thermohydraulics and FBR safety at the Oarai Engineering Center, PNC, Japan. He held visiting positions at Argonne National Laboratory from 1982 to 1983 and at Los Alamos National Laboratory from 1986 to 1987, both in the field of numerical fluid dynamics. He serves the Japanese government including the Ministry of Economy, Trade and Industry; Ministry of Education, Culture, Sports, Science and Technology; and Fire and Disaster Management Agency, as advisor on nuclear reactor safety.

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Dr. Ninokata is currently an associate member of the Science Council of Japan. He is a member of the American Nuclear Society (ANS), Atomic Energy Society of Japan (AESJ), International Association for Hydro-Environment Engineering and Research (IAHR), and Japan Society of Mechanical Engineers. He has served ANS as a member of the Board of Directors from 2006 to 2009 and as chair of the ANS Thermal Hydraulics Division (THD) from 2010 to 2011. Also, he is a former member of the ANS Honors and Award Committee and is currently a member of the ANS International Committee. He is former chairman of the ANS Japan Section.

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