The Fukushima Daiichi Accident

Technical Volume 1/5

Description and Context of the Accident

IAEA
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THE FUKUSHIMA DAIICHI ACCIDENT

TECHNICAL VOLUME 1
DESCRIPTION AND CONTEXT OF THE ACCIDENT

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TECHNICAL VOLUME 1

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The IAEA thanks the large number of experts who were involved in this report. It is the result of the dedicated efforts of many people. All participants listed at the end of this technical volume made valuable contributions, but a particularly heavy load was borne by the Co-Chairs and coordinators of the working groups. The efforts of many expert reviewers, including members of the International Technical Advisory Group, are also gratefully acknowledged.

THE REPORT ON THE FUKUSHIMA DAIICHI ACCIDENT

At the IAEA General Conference in September 2012, the Director General announced that the IAEA would prepare a report on the Fukushima Daiichi accident. He later stated that this report would be "an authoritative, factual and balanced assessment, addressing the causes and consequences of the accident, as well as lessons learned".[1]

The report is the result of an extensive international collaborative effort involving five working groups with about 180 experts from 42 Member States (with and without nuclear power programmes) and several international bodies. This ensured a broad representation of experience and knowledge. An International Technical Advisory Group provided advice on technical and scientific issues. A Core Group, comprising IAEA senior level management, was established to give direction and to facilitate the coordination and review. Additional internal and external review mechanisms were also instituted. The organizational structure for the preparation of this publication is illustrated in Fig. 1.

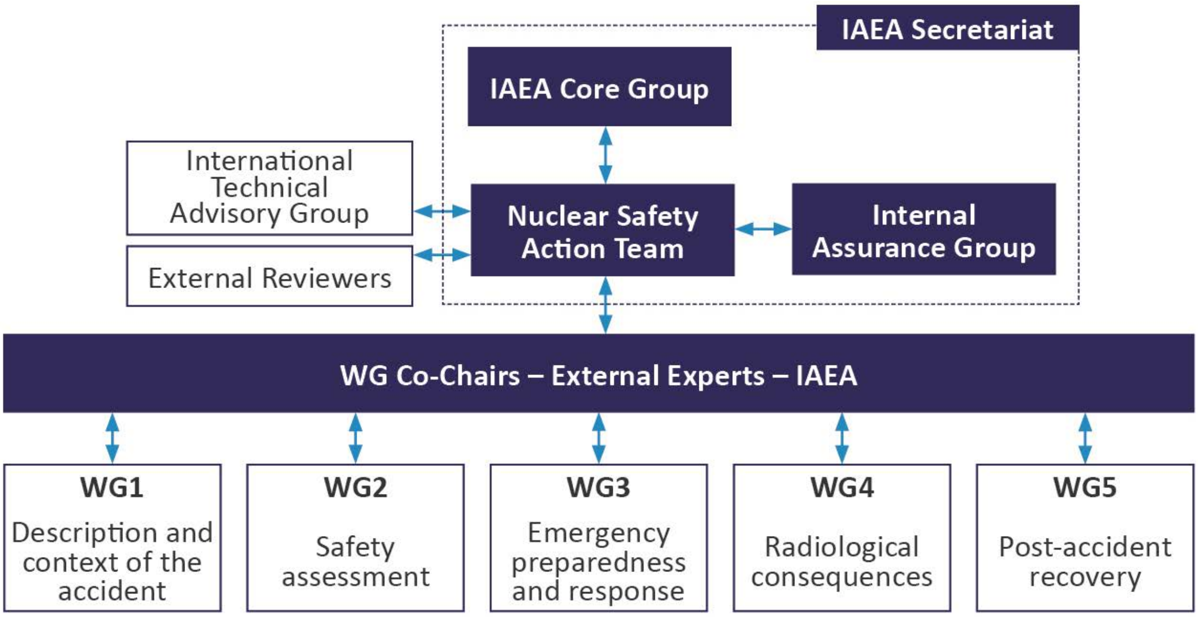

FIG. 1. IAEA organizational structure for the preparation of the report on The Fukushima Daiichi Accident.

The Report by the Director General consists of an Executive Summary and a Summary Report. It draws on five detailed technical volumes prepared by international experts and on the contributions of the many experts and international bodies involved.

The five technical volumes are for a technical audience that includes the relevant authorities in IAEA Member States, international organizations, nuclear regulatory bodies, nuclear power plant operating organizations, designers of nuclear facilities and other experts in matters relating to nuclear power.

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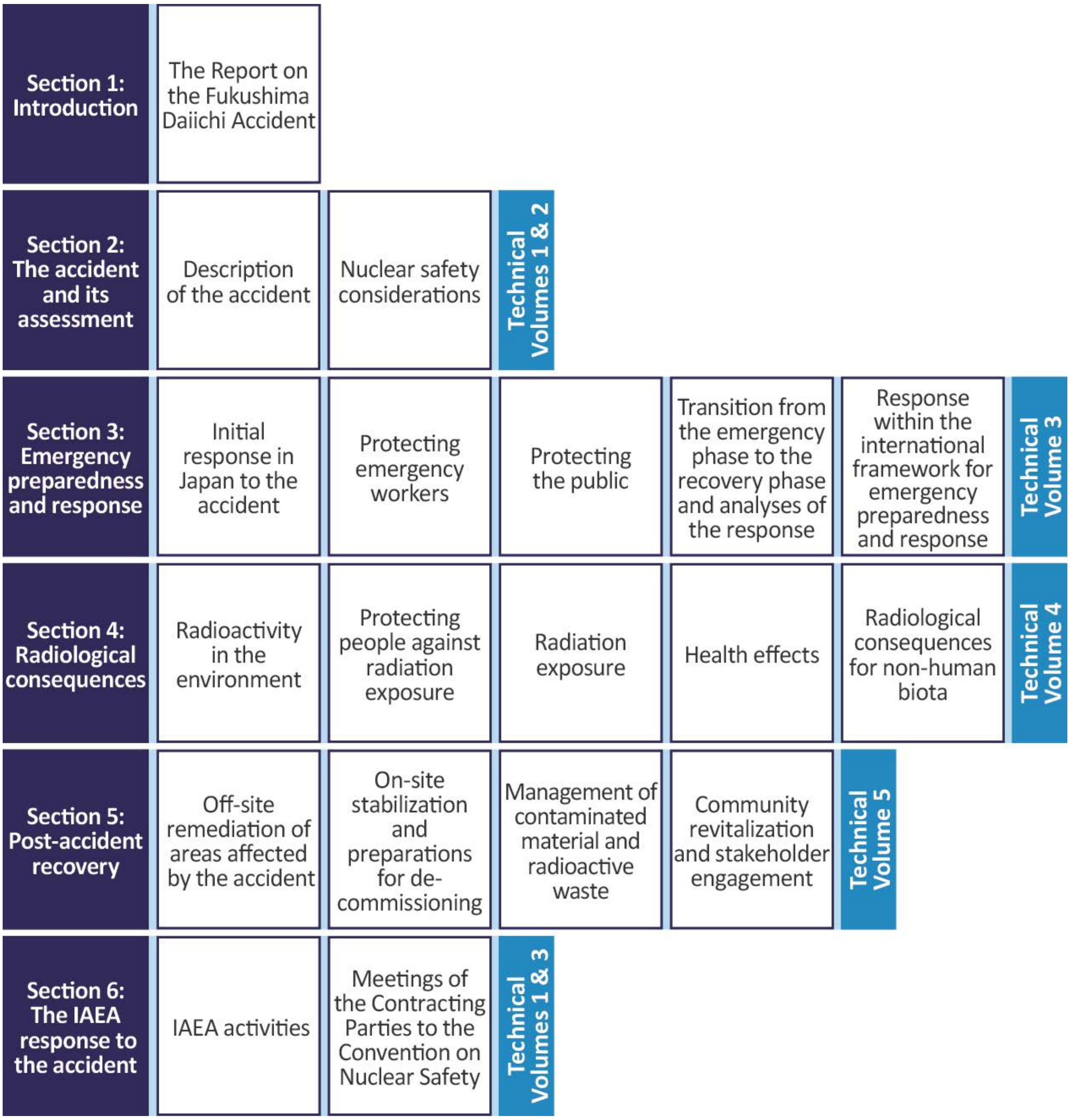
[1] INTERNATIONAL ATOMIC ENERGY AGENCY, Introductory Statement to Board of Governors (2013), https://www.iaea.org/newscenter/statements/introductory-statement-board-governors-3.

The relationship between the content of the Report by the Director General and the content of the technical volumes is illustrated in Fig. 2.



Section 1: Introduction	The Report on the Fukushima Daiichi Accident					
Section 2: The accident and its assessment	Description of the accident	Nuclear safety considerations	**Technical Volumes 1 & 2**			
Section 3: Emergency preparedness and response	Initial response in Japan to the accident	Protecting emergency workers	Protecting the public	Transition from the emergency phase to the recovery phase and analyses of the response	Response within the international framework for emergency preparedness and response	**Technical Volume 3**
Section 4: Radiological consequences	Radioactivity in the environment	Protecting people against radiation exposure	Radiation exposure	Health effects	Radiological consequences for non-human biota	**Technical Volume 4**
Section 5: Post-accident recovery	Off-site remediation of areas affected by the accident	On-site stabilization and preparations for de-commissioning	Management of contaminated material and radioactive waste	Community revitalization and stakeholder engagement	**Technical Volume 5**	
Section 6: The IAEA response to the accident	IAEA activities	Meetings of the Contracting Parties to the Convention on Nuclear Safety	**Technical Volumes 1 & 3**			

FIG. 2. Structure of the Summary Report and its relationship to the content of the technical volumes.

CONTENTS

DESCRIPTION AND CONTEXT OF THE ACCIDENT

1. INTRODUCTION

This volume presents the key events that happened before, during and after the accident at the Fukushima Daiichi nuclear power plant (NPP), operated by the Tokyo Electric Power Company (TEPCO).

The description of the event in this volume is based on objective and factual information, and is presented largely in a chronological manner. The volume also describes the Fukushima Daiichi NPP site, the reactor designs, the structure of the nuclear industry in Japan and the Japanese regulatory framework at the time of the accident. It describes in detail the earthquake, the tsunami, the events at the Fukushima Daiichi NPP and the actions taken there and elsewhere for post-accident management up to December 2014. The description of the events is largely based on information provided by the Government of Japan to the IAEA [1, 2]; reports of the investigation committees established by the Japanese Government [3, 4], the National Diet of Japan [5] and TEPCO [6], including updates and supplements by TEPCO [7, 8]; the regulatory body [9]; and the IAEA missions listed in Section 1.6.5. Information is provided without judgement and evaluation, unless it is necessary to clarify a certain occurrence assessments are contained in Technical Volumes 2 to 5.

The volume begins with a summary of the accident (Section 1.1), which presents the main events in a chronological order to provide an overview that serves to demonstrate those events that occurred in parallel or affected actions at different parts of the site. In this manner, the accident description illustrates the integrated response to a multi-unit site accident from the perspective of emergency response centres (ERCs), shared main control rooms (MCRs) and the off-site organizations. There is some necessary repetition of information that is presented later in the volume, when events are described in more detail.

The second section (Section 1.2) describes the context within which the accident occurred. It describes the Japanese nuclear power programme, its nuclear industry and the governmental/legal/regulatory framework in place at the time of the accident. It then discusses the characteristics of the Fukushima Daiichi NPP and its six nuclear reactors. Finally, this section presents the plant's resources and its capacity with respect to the qualifications and abilities of its staff as well as the tools available to them at the time of the accident.

The third section (Section 1.3) deals with the start and the development of the accident. It explains how an extreme natural event, combined with some design and operational issues, led to a severe nuclear accident in which radioactive material was released to the environment. It describes the effects of the initiating event (the Great East Japan Earthquake) and its concurrent and dependent natural event (the tsunami) on the Fukushima Daiichi NPP site, as well as the response by personnel and equipment to the dynamic events on 11 March 2011 and during the following month.

The fourth section (Section 1.4) mainly describes the initial releases of radionuclides to the environment, resulting from the failure of the fission product barriers at the time of the accident. It also presents other events afterwards that caused additional radioactive releases from the accident site.

The fifth section (Section 1.5) addresses the response to the accident, as it progressed, by off-site entities, including the actions of Japan's national, prefectural and local governments, as well as those by the IAEA and other international and regional organizations.

Finally, Section 1.6 focuses on what has happened since the accident until December 2014.[1] It covers subsequent actions taken at the Fukushima Daiichi NPP, in governmental organizations, in Japan's nuclear industry and internationally to address challenges and issues after the accident, including current activities and plans on the site decommissioning and remediation. Annexes I, II and III provide the sequence of events in Units 1–3 in tabular form. These annexes are included on the CD-ROM attached to this volume.

Overall, as the general reference account of the accident and its aftermath, this volume forms the basis for analyses of the various aspects and causal factors of the accident. The specific investigations of these facts are presented in subsequent volumes. Sections 1.2 and 1.3 provide input to Technical Volume 2 in terms of technical and regulatory aspects; Section 1.4 provides input to Technical Volume 4 with regard to the amount of radionuclides released (source term); Section 1.5 mainly supports Technical Volume 3, with additional input provided by Section 1.2 on emergency response and regulations; and Section 1.6 furnishes information on the post-accident efforts towards remediation, stabilization and decommissioning and the management of radiological waste, explored further in Technical Volume 5.

1.1. SUMMARY OF THE ACCIDENT

On 11 March 2011, the tsunami waves generated by the Great East Japan Earthquake off the Pacific coast of Japan overwhelmed the tsunami barriers of Fukushima Daiichi nuclear power plant (NPP) site. They flooded the primary and backup power systems and equipment, as well as the ultimate heat sink systems and structures, of all six units on the site. Compounding the off-site power loss that occurred before the tsunami due to the earthquake damage to the transmission system, the flooding caused the loss of on-site power sources (and/or on-site power distribution systems). Units 1–5 of the Fukushima Daiichi NPP experienced extended station blackout (SBO) events, which exceeded nine days in Units 1 and 2, and 14 days in Units 3 and 4.

The nuclear units were unable to cope with the extended loss of electrical power and plant heat removal, and the reactors of Units 1, 2 and 3 suffered damage as the fuel overheated and melted. The reactor pressure vessels (RPVs) that enclose the reactor cores were eventually breached in those units, and radioactive material escaped from the reactors. The radioactive material confined in the primary containment vessels (PCVs) was further released directly to the environment either in a controlled manner, i.e. by venting of the reactors' PCVs, or in an uncontrolled manner upon damage and failure of the confinement structures. The radioactive releases resulted in radiological exposure of the workers at the site and the general public residing in the surrounding communities and caused radiological contamination of the environment in those areas. In order to reduce radiation exposures, people within a radius of 20 km of the site, as well as other specified areas, were evacuated, and restrictions were placed on the distribution and consumption of food and drinking water.

Although no loss of life has been attributed to the radiological releases, the accident caused social and economic impacts, especially in Japan. At the time of writing[2], people who were evacuated continue to live outside the evacuated areas or are allowed to return to their homes with limitations, and post-accident management efforts towards the recovery of the affected surrounding areas are ongoing. Following the stabilization of the conditions of the affected reactors, activities to prepare these reactors for their eventual decommissioning have also been initiated. These matters are discussed in detail in the subsequent volumes.

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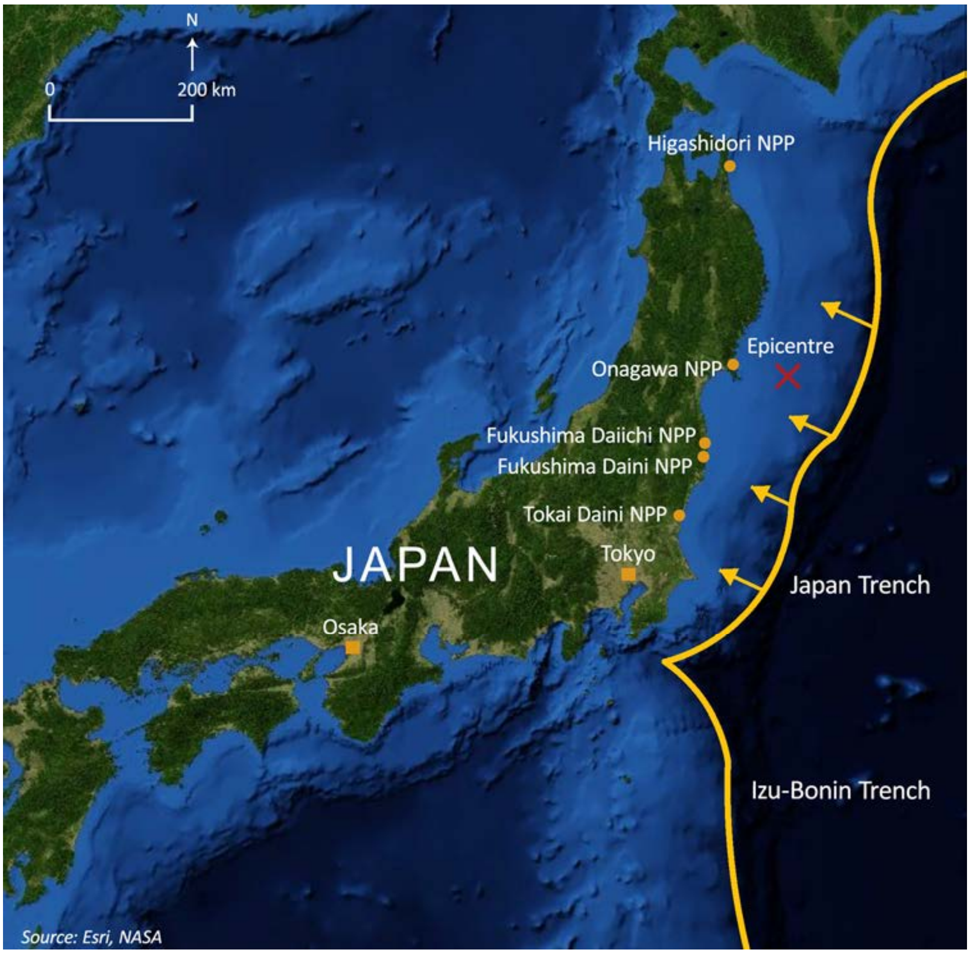
[1] In some cases information was available up until May 2015, and this was included, where possible.

[2] June 2015.

1.1.1. Main occurrences

The Great East Japan Earthquake occurred at 14:46 Japan Standard Time (JST)[3] on Friday 11 March 2011, off the eastern coast of Japan. It caused extensive damage to the infrastructure. The main shock, with a magnitude of M 9.0 [10], lasted for more than two minutes. This event was among the largest recorded earthquakes, most of which have also occurred in areas along the Pacific tectonic plate: the earthquakes of 1960 and 2010 in Chile, with a magnitude of M 9.5 and M 8.8, respectively, and those in Alaska (1964) and Sumatra (2004), both with a magnitude of M 9.2.

The large movement in the seabed also caused a series of tsunami waves that affected a wide coastal area of Japan. The earthquake and consequent tsunami caused widespread devastation and the loss of many lives. More than 15 000 people were killed, over 6000 were injured and, at the time of writing, around 2500 people were still reported to be missing [11]. These events also impacted residential and industrial establishments, including five NPP sites along Japan's north-eastern coast: Higashidori, Onagawa, Fukushima Daiichi, Fukushima Daini and Tokai Daini. As shown in Fig. 1.1–1, the epicentre was approximately 180 km north-east of the Fukushima Daiichi NPP and the Fukushima Daini NPP, and 130 km east of the Onagawa NPP.



Source: Esri, NASA

FIG. 1.1–1. The Great East Japan Earthquake and the NPPs nearby.

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[3] All times in this narrative are in Japan Standard Time (JST) and all pressure values in units of bar absolute and megapascal (MPa). The times of events and values of plant parameters such as pressures, temperatures and water levels mentioned in this section are approximate. Though not explicitly mentioned individually, these values could have some uncertainty.

At one of these plants, the Fukushima Daiichi NPP, with six nuclear units, the effects of the earthquake and tsunami initiated a series of events, shown in Fig. 1.1-2, that led to a severe nuclear accident resulting in radioactive releases. Radionuclides were released to the atmosphere from the Fukushima Daiichi NPP and were deposited on land and on the ocean. There were also direct releases into the sea.

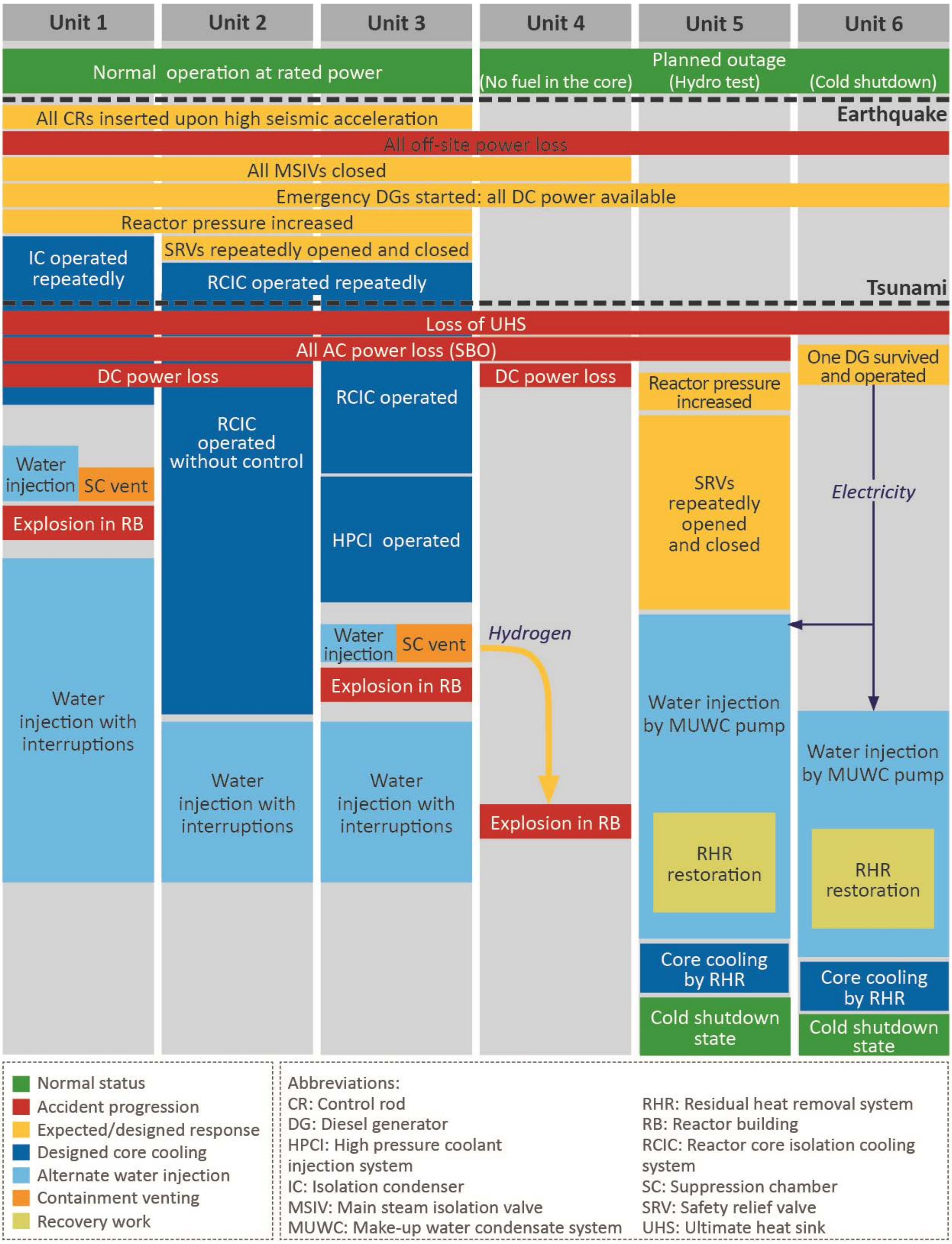


FIG. 1.1–2. Overview of the main event sequence at the Fukushima Daiichi NPP.

1.1.2. Accident initiation and response

1.1.2.1. Initiating event: The earthquake

The Great East Japan Earthquake occurred in the subduction zone off the north-east coast of Japan where the Pacific tectonic plate forces its way under the North American tectonic plate. It was caused by a sudden release of energy, as a section of the Earth's crust at the interface of these plates was ruptured and impacted an area in the fault zone estimated to be about 500 km long and 200 km wide.

The main shock, with a magnitude of M 9.0 [10], lasted for more than two minutes, with several significant pulses and aftershocks. The ground motion caused extensive damage to the infrastructure including the power transmission and transportation systems in Japan. Following the earthquake, local, regional and national 'general earthquake' emergency response organizations were activated to assess and coordinate the earthquake damage assessment and recovery. An ERC at TEPCO Headquarters in Tokyo was established for coordinating, overseeing and managing the response to the earthquake damage at all of the company's assets and the recovery from electric outages in the service area.

1.1.2.2. Plant status at the time of the earthquake

The Fukushima Daiichi NPP (Fig. 1.1–3), which comprises six units [12] with boiling water reactors (BWRs) (see Box 1.1–1), was located 180 km from the epicentre. When the earthquake occurred, the three reactors of Units 1, 2 and 3 were in normal operation at rated power, while Units 4, 5 and 6 were in various stages of periodic planned refuelling and inspection outage, as follows:

- Unit 1 was generating 460 MW electricity.
- Unit 2 was generating 784 MW electricity.
- Unit 3 was generating 784 MW electricity.
- Unit 4 had its fuel off-loaded from the reactor core to the fuel storage pool, the spent fuel pool (SFP), and no fuel assemblies were in the RPV, the vessel that houses the reactor. Both the SFP and RPV were filled with water.
- Unit 5 had fuel assemblies loaded in the reactor core. The fuel had relatively low decay heat due to the period elapsed since power operations. The RPV was filled completely with water and isolated (bottled up) and was being pressurized by a pump in preparation for the RPV pressure (leak) test. Its confinement structure, the PCV, was open, with its lid removed.
- Unit 6, which was under the cold shutdown state of the outage, also had fuel assemblies with relatively low decay heat loaded in the reactor core, and the RPV was filled with water to a prescribed height, sufficiently covering the reactor core. The main steam isolation valves (MSIVs) that, when closed, disconnect the RPV from rest of the power plant, were open, and the RPV was nearly at atmospheric pressure and ambient temperature.

There were approximately 6400 personnel at the site, among whom approximately 2400 TEPCO and contractor employees (750 TEPCO, 1650 contractors) were working in the controlled area. The majority (approximately 2000) of those were carrying out activities in support of the periodic planned refuelling and inspection outages.

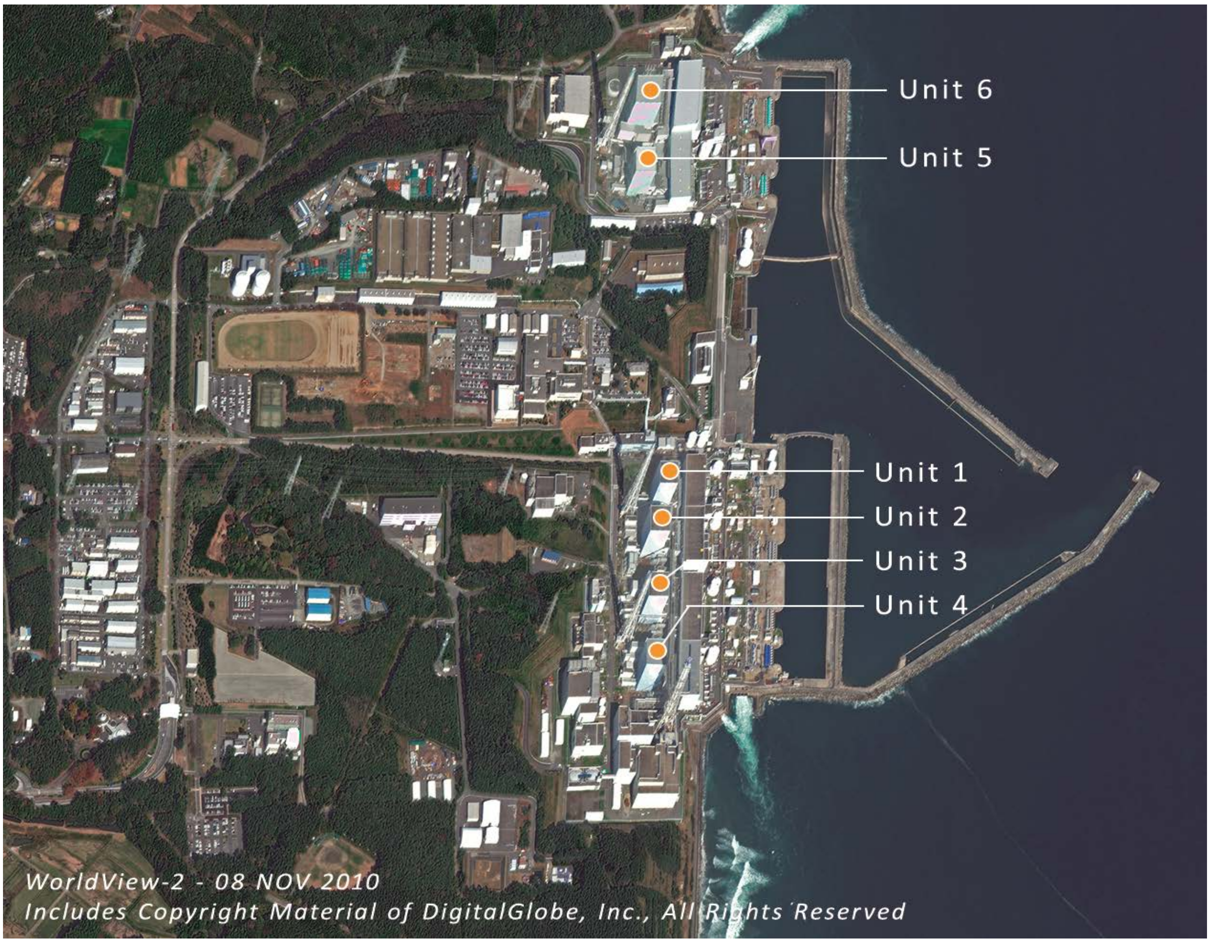


FIG. 1.1–3. An aerial view of the Fukushima Daiichi NPP site. The complex containing Units 1–4 is located at the south of the site and the complex of Units 5 and 6 is situated at the north.

1.1.2.3. Earthquake response and loss of off-site power

The operating reactors of Units 1–3 were shut down automatically when sensors at the plant detected the ground motion and triggered reactor protection systems in accordance with the design. As the ground motion exceeded the value that was set to activate the reactor seismic protection, the insertion of control rods (blades) was automatically initiated, which stopped the nuclear reaction.

After shutdown, the nuclear fuel continued to generate heat (decay heat). To prevent the nuclear fuel from overheating, this heat had to be removed by cooling systems that were mainly run or controlled by electrical power. However, the earthquake caused damage to on-site switchyard equipment, off-site substation equipment and the power lines supplying off-site AC power to the plant, leading to the loss of all off-site electrical power for every unit at the Fukushima Daiichi NPP site. This is referred to as a loss of off-site power (LOOP) event and was within the design basis of the Fukushima Daiichi NPP.

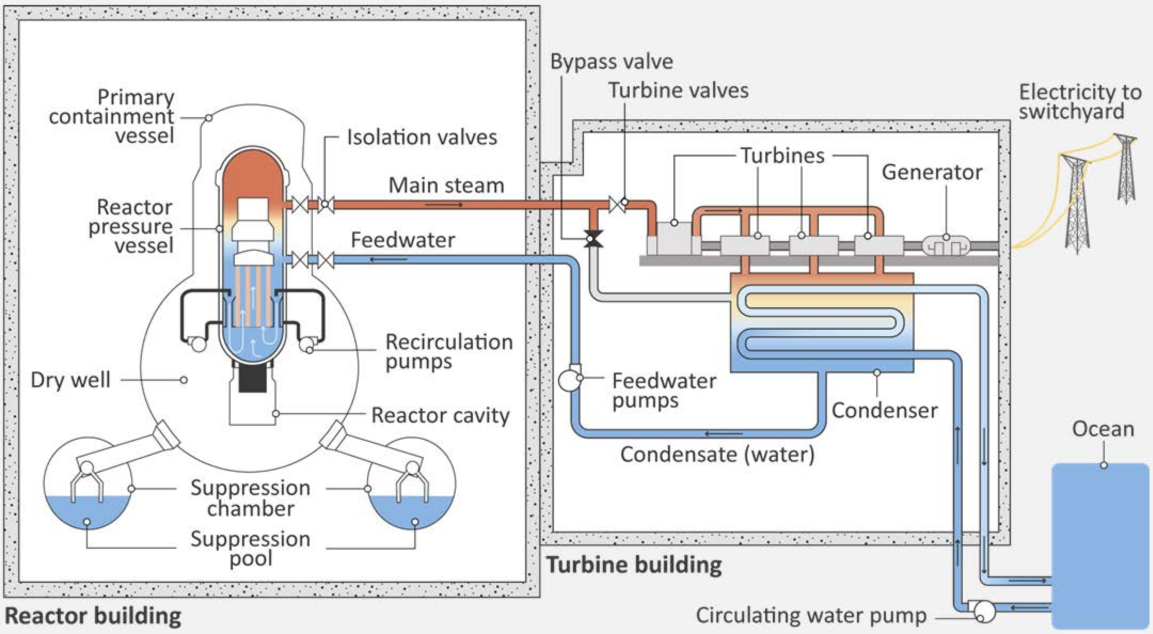
1.1.2.4. Plant response to loss of off-site power

In response to the LOOP, the on-site replacement power facilities — emergency diesel generators (EDGs) — which were designed for such LOOP situations, automatically started in order to restore

AC power in all six units.[4] The EDGs restored AC power to the emergency busses and to the direct current (DC) power battery chargers, as designed.

Box 1.1–1. Boiling water reactors

Boiling water reactors use a closed, direct steam cycle loop, as shown schematically below. The working fluid is water that is used both as the coolant to remove heat and the moderator for controlling reactivity. Coolant water boils in the reactor core at a pressure of approximately 7 MPa (70 bar), and the steam that is generated is used to drive turbines to generate electricity. After passing through the turbines, the steam is condensed back to water by being cooled by the condenser tubes that are filled with cold water taken from a heat sink, e.g. the ocean. The water resulting from condensation is then pumped back to the reactor as feed water.



As a result of the power interruption, the reactors of Units 1–3 were automatically isolated from their turbine systems by the closure of all MSIVs. This resulted in increases in the temperature and pressure of the reactors due to the decay heat. The cooling of these reactors after the reactor shutdown and isolation from their turbine systems was accomplished by means of the following design and operational provisions for heat removal at high reactor pressure (Box 1.1–2):

- In Unit 1, as the reactor pressure increased, both loops of the isolation condenser (IC) system started automatically and continued to cool the reactor. The operation of both IC loops lowered the reactor pressure and temperature so rapidly that the operators manually stopped them, in accordance with procedures, in order to prevent thermal stress on the RPV that would be caused by the excessive cooling rate[5]. Afterwards, only one of the loops was used by the operators to control the reactor pressure in a range prescribed by the procedures.[6]

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[4] One EDG of Unit 4 was under periodic maintenance, hence it was out of service.

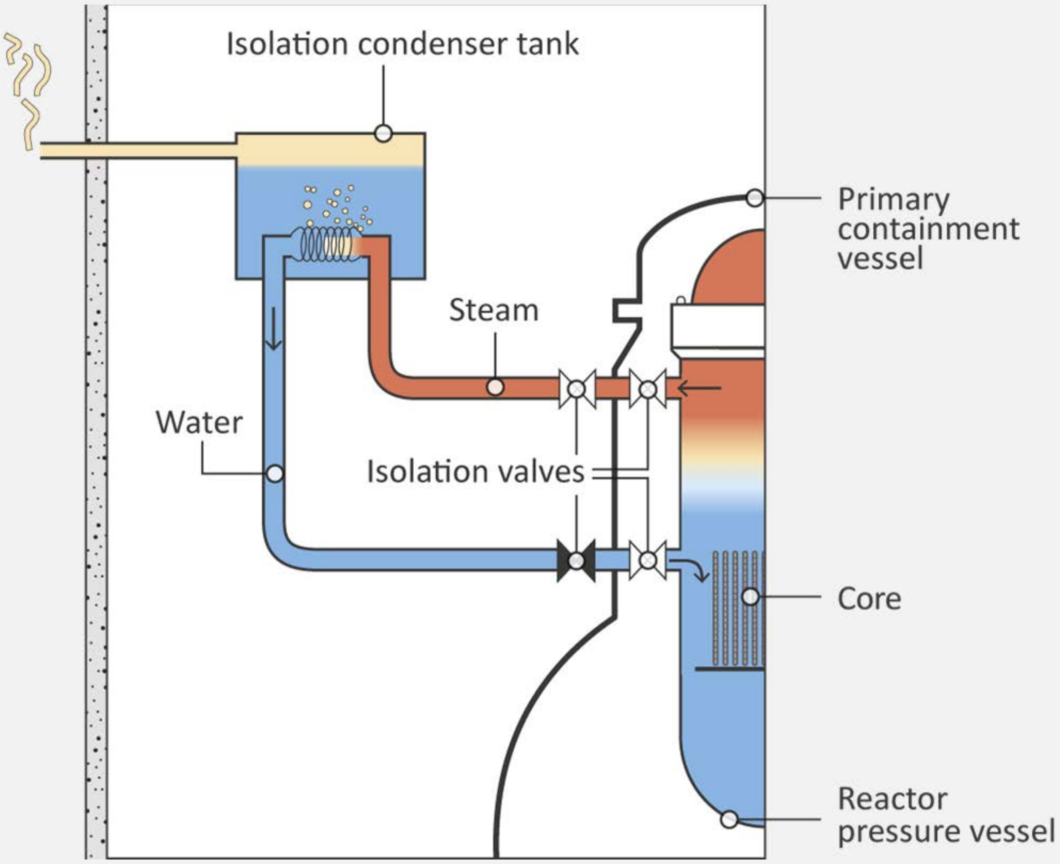
[5] In BWRs, the cooling rate is monitored and controlled by the reduction in reactor pressure, which, in turn, corresponds to the decrease in reactor temperature.

[6] In order to prevent opening of a safety relief valve (SRV) that would, in turn, result in loss of water in the reactor.

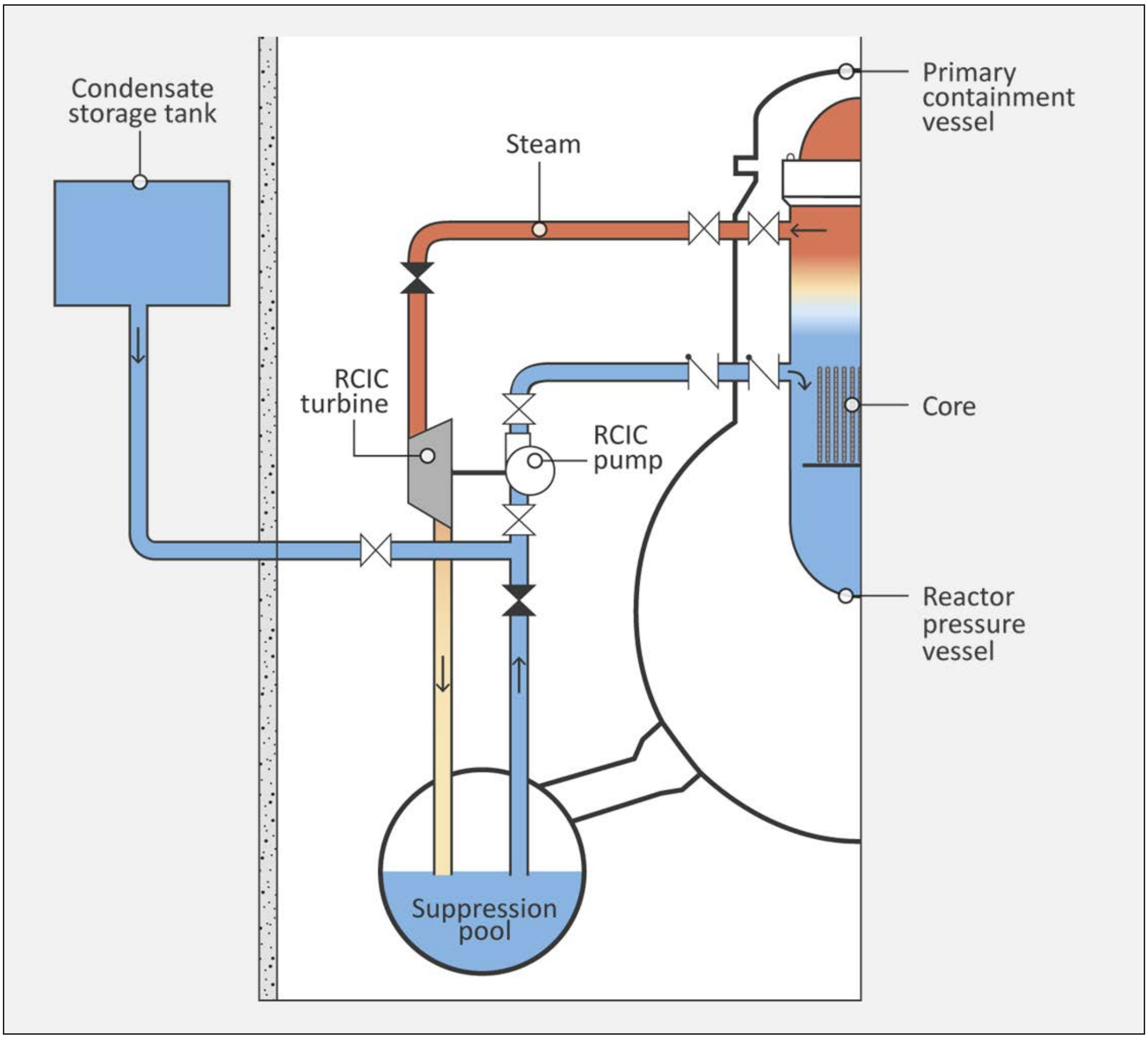
Box 1.1–2. Systems for cooling the core when the reactor is isolated from the turbines

Normal shutdown cooling of boiling water reactors at high reactor pressure is accomplished by directing the steam from the reactor to the main condenser, bypassing the turbines (see Box 1.1–1). However, when the reactor is isolated, this path is not available, and core cooling is provided by the systems designed for an isolated reactor under high pressure conditions which exist after reactor shutdown. In the design of the Fukushima Daiichi NPP, those were: the isolation condenser system for Unit 1 (the earlier design) and the reactor core isolation cooling system for Units 2–6.

Isolation condenser. In the Unit 1 design, there were two separate and redundant isolation condenser loops. In these closed loops, the primary side of the isolation condenser received steam generated in the reactor and condensed it by cooling inside the heat exchanger tubes that were submerged in colder water tanks (isolation condenser pools) located outside the primary containment vessel. Condensed steam was then sent as cold water back to the reactor by gravity (see the diagram below). Without mixing with the radioactive primary side water, the secondary side water in the isolation condenser pools boiled, and the evaporated steam was vented to the atmosphere, which served as the heat sink. The secondary side water volume of the isolation condenser (both trains together) was sufficient for eight hours of cooling before requiring replenishment from a dedicated water source.



Reactor core isolation cooling. In the design of Units 2–6, there were open cycle cooling systems that needed a source for adding water to the reactor system. In the reactor core isolation cooling systems, the steam from the reactor drove a small turbine which, in turn, ran a pump that injected water into the reactor at high pressure. The steam that ran the turbine was discharged and accumulated in the suppression pool section of the primary containment vessel, which served as the heat sink for absorbing waste heat. The water lost from the reactor was replenished by taking fresh water from the condensate storage tank (see the diagram below). When the tank emptied or the suppression pool became full, the water that accumulated in the suppression pool could be used, making the system essentially a closed loop cycle. The reactor core isolation cooling was designed to operate for at least four hours.



- In Unit 2, the operators manually activated the reactor core isolation cooling (RCIC) system in accordance with procedure. However, the RCIC automatically stopped almost immediately, since the reactor water level was higher than the pre-set water level point for RCIC operation. Increasing reactor vessel pressure eventually activated a safety relief valve (SRV), which was designed to protect the RPV from overpressurization by discharging steam into the water (suppression) pool in the suppression chamber (SC), or commonly referred as torus, section of the PCV. This resulted in a decrease in the reactor water levels. In response, the operators manually activated the RCIC system in accordance with procedures.
- In Unit 3, the reactor pressure increase first activated an SRV automatically, and the operators then manually activated the RCIC, in accordance with their procedure, upon decreasing reactor water level.

In Units 5 and 6, the decay heat from the fuel assemblies, which were loaded in the cores inside the RPVs, also had to be removed:

- In Unit 5, the reactor pressure, which was kept at an elevated level by the use of a pump for pressure testing at the time of the earthquake, initially dropped when the pump stopped as it lost power as a result of the LOOP. The pressure started to rise in the water filled RPV, as a result of the decay heat, but, unlike in Units 2 and 3, it remained for some time well below the levels that would activate the SRVs[7].

- In Unit 6, the decay heat was also low, and the reactor was near atmospheric pressure and ambient temperature. Therefore, the increase in reactor pressure and temperature and the decrease of the reactor water level was slow, with less need for immediate heat removal after the LOOP.

The heat had to be removed not only from the reactor cores but also from the following systems and structures:

- In Unit 4, where the fuel assemblies had recently been moved from core to the spent fuel pool (SFP), the equipment for cooling and refilling of spent fuel pool water[8] stopped working as a result of the LOOP. The Unit 4 SFP, containing more than 1300 spent fuel assemblies, had the largest amount of decay heat to be removed among the SFPs of all the units.
- In the SFPs of the individual units and in the common SFP[9], all of which lost cooling and refilling capabilities upon the LOOP, the temperatures of the pool water started to increase due to decay heat.
- Since the normal containment cooling system stopped as a result of the LOOP, operators (in Units 1 and 2) also manually initiated emergency containment cooling systems to remove the residual heat discharged and dissipated from the RPV to ensure control of the confinement function.

In response to the earthquake and the LOOP, the operators activated the ‘event based’ abnormal operating procedures (AOPs) for a ‘Natural Event’ and a ‘Turbine and Electrical Incident’ in all three main control rooms (MCRs)[10] in keeping with post-earthquake and post-LOOP instructions, respectively. In line with the procedures, post-earthquake inspection and off-site power restoration activities were initiated. However, their implementation was continuously interrupted by the ongoing aftershocks.

An earthquake emergency response team was activated at the on-site emergency response centre (ERC) located within the seismically isolated building[11]. The Site Superintendent, as the designated on-site emergency manager, was responsible for directing the site response and for coordination with on-site and off-site organizations. Under the Site Superintendent’s command, three shift superintendents, who were the licensed operators in each of the three common MCRs, were responsible for directing the actions of the shift teams in their units.

Therefore, the units at the Fukushima Daiichi NPP responded to the initiating event — the earthquake and the concurrent loss of off-site power — as intended by the designers and as stipulated in the operating procedures (Fig. 1.1–4).

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[7] Although the pressure relief and reduction function of the SRVs were disabled (locked) as a prerequisite of the pressure testing, their automatic overpressure protection function was still available for one set of safety valves that consisted of three SRVs.

[8] The SFPs, which store the used and new fuel assemblies, are filled with water, providing radiation shielding and removal of heat from the nuclear fuel located there. However, without cooling, the pool water would heat up and eventually start evaporating. If this situation continues without refilling, the cooling of the fuel stops when the water level falls and exposes the fuel. Overheating and exposure causes damage to the fuel and the release of radionuclides.

[9] As a shared auxiliary facility among the units, the common spent fuel pool, located in a separate building near Unit 4, stored over 6000 spent fuel assemblies, all of which needed to have their decay heat removed.

[10] Each pair of units shared a control room, i.e. Units 1 and 2, Units 3 and 4, and Units 5 and 6.

[11] The seismically isolated building was built as a result of experience gained from the effects of the Niigata-Chuetsu-Oki earthquake at the Kashiwazaki-Kariwa NPP in 2007, and put into operation in July 2010. It was designed to withstand earthquakes and was equipped with backup power. Filtered ventilation and shielding were provided for protection from radioactivity.

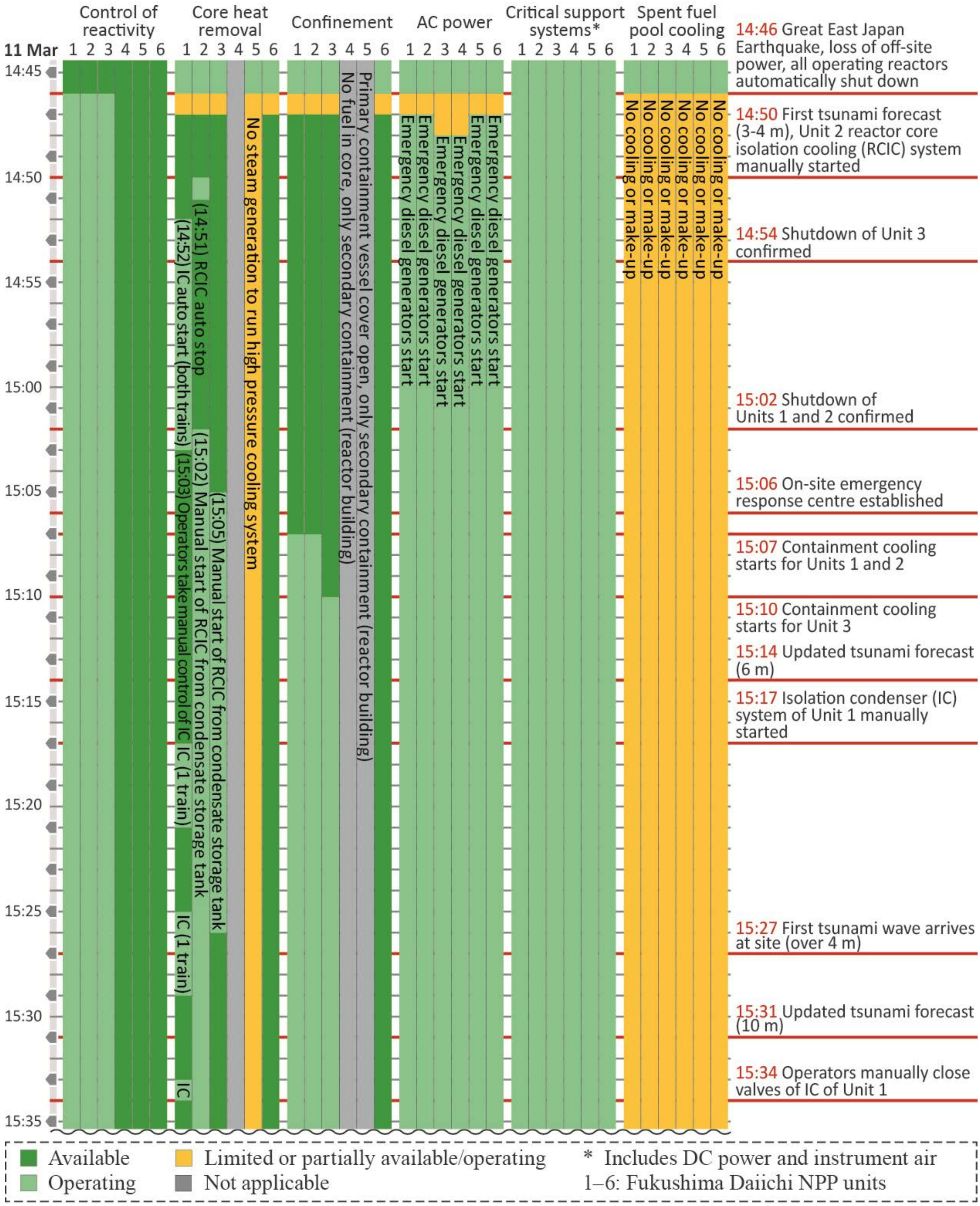

FIG. 1.1–4. Response of the Fukushima Daiichi NPP to the earthquake and the loss of off-site power.

1.1.2.5. Tsunami and station blackout

In addition to causing strong ground motion and infrastructure damage, the earthquake displaced a massive amount of water, giving rise to a series of large tsunami waves. When these tsunami waves reached the coast, they had a devastating effect over a wide area (Fig. 1.1–5).

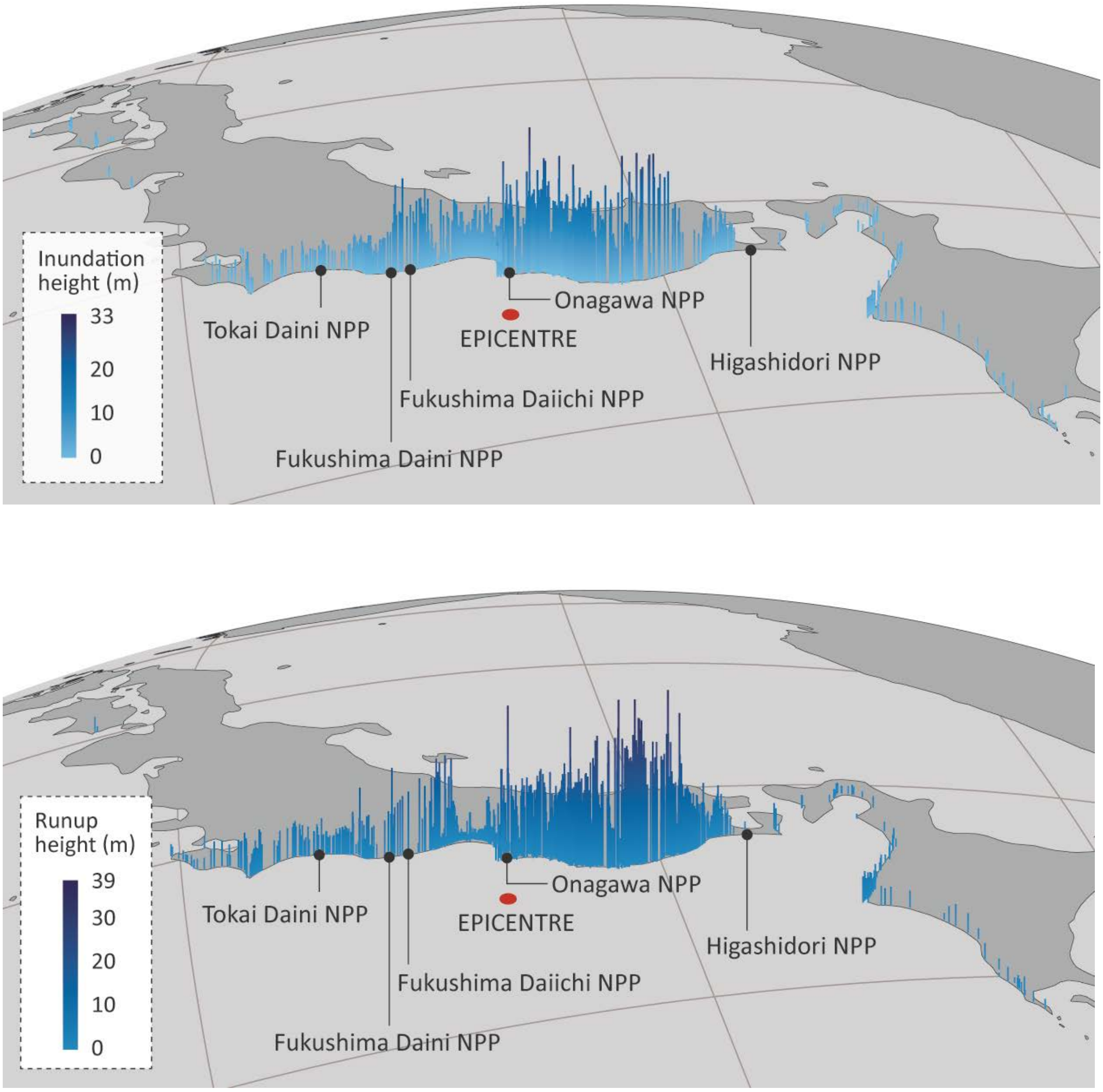

FIG. 1.1–5. The variation of tsunami wave impact, inundation (top) and runup (bottom), based on the coastal geography and topography [13].[12]

Shortly after the main earthquake shock, the Japan Meteorological Agency (JMA) issued tsunami warnings [14], initially forecasting a wave of 3–4 m high for Japan's east coast, on which the Fukushima Daiichi NPP site was located. This forecast was updated at 15:14 to 6 m and later, at 15:31, to 10 m. Upon this tsunami warning, an announcement was made from the MCRs via the PA system to the personnel to evacuate from the lower site elevations to higher positions.

The tsunami waves started reaching the Fukushima Daiichi NPP site about 40 minutes after the earthquake, at 15:27. The site was protected from the first wave, which had a 4–5 m runup height, by the tsunami barrier seawalls, the breakwater, that were designed to protect against a maximum

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[12] Runup height is the height of the wave at the furthest inland point, and inundation height is the crest height of a wave compared to the sea level.

tsunami height of 5.5 m [15]. However, about 10 minutes after the first wave (between 15:36 and 15:37), the second and largest tsunami wave, with a run-up height of 14–15 m, reached the plant. The wave overwhelmed the seawalls and inundated the site. It engulfed all structures and equipment located at the seafront, as well as the main buildings (including the reactor, turbine and service buildings) at higher elevations[13] (Fig. 1.1–6), causing the following sequence of events:

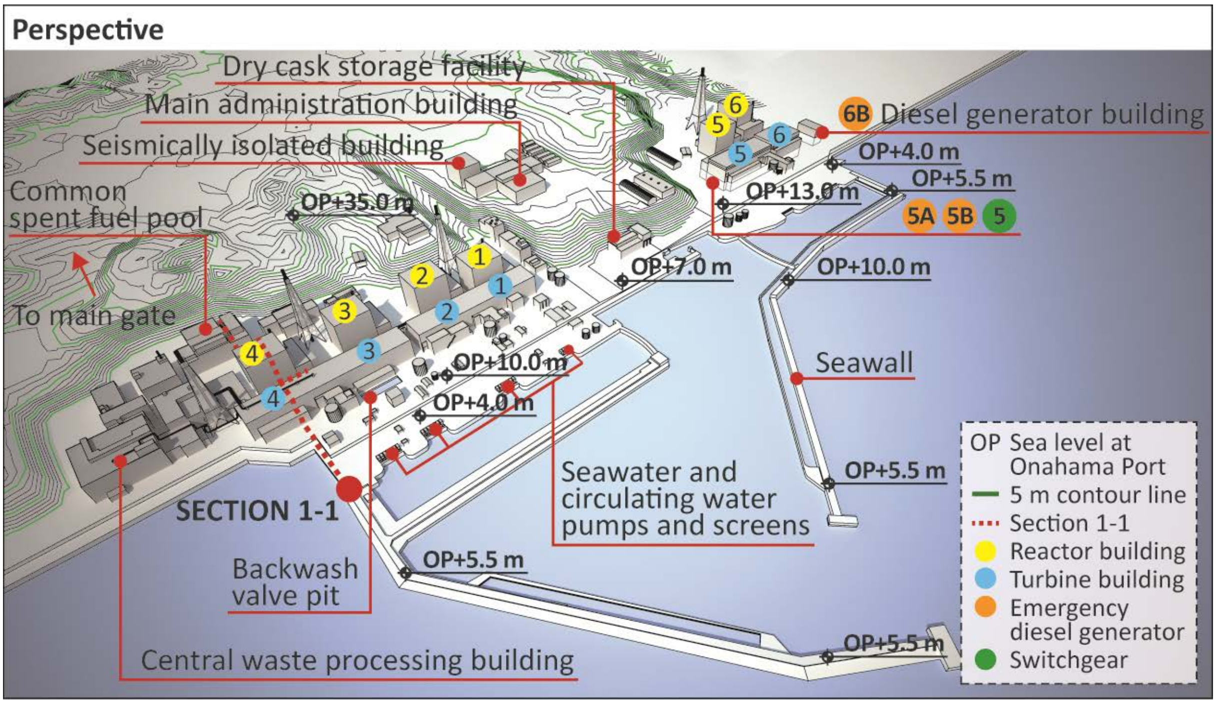

FIG. 1.1–6. The elevations and locations of structures and components at the Fukushima Daiichi NPP [16].

- The wave flooded and damaged the unhoused seawater pumps and motors of all six units at the seawater intake locations on the shoreline, resulting in loss of ultimate heat sink events for all units. This meant that essential plant systems and components, including the water cooled EDGs[14], could not be cooled to ensure their continuous operation.
- The wave flooded and damaged the dry cask storage building located near the seashore between the Units 1–4 and Units 5–6 complexes. There were no significant impacts on the casks and the fuel stored in them, as was later confirmed [17].
- Water entered and flooded buildings, including all the reactor and turbine buildings, the common spent fuel storage building and diesel generator building. It damaged the buildings and the electrical and mechanical equipment inside at ground level and on the lower floors. The damaged equipment included the EDGs or their associated power connections, power distribution panels and switchgear equipment (Fig. 1.1–7), which resulted in the loss of emergency AC power. Only

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[13] The administration buildings and the seismically isolated building that contained the on-site ERC were on a cliff at an elevation of approximately 35 m (which was the original topographical site elevation before the site area was excavated for placing the units during construction).

[14] Each unit had a pair of EDGs, and Unit 6 had an additional generator. Of those 13 EDGs, Units 2, 4 and 6 each had one that was air cooled. Since they were air cooled, operability of these generators was not directly affected by the loss of cooling water caused by the damage to the seawater pumps.

one of the air cooled EDGs — that of Unit 6 — was unaffected by the flooding[15]. It remained in operation, continuing to supply emergency AC power to the Unit 6 safety systems and allowing cooling of the reactor.

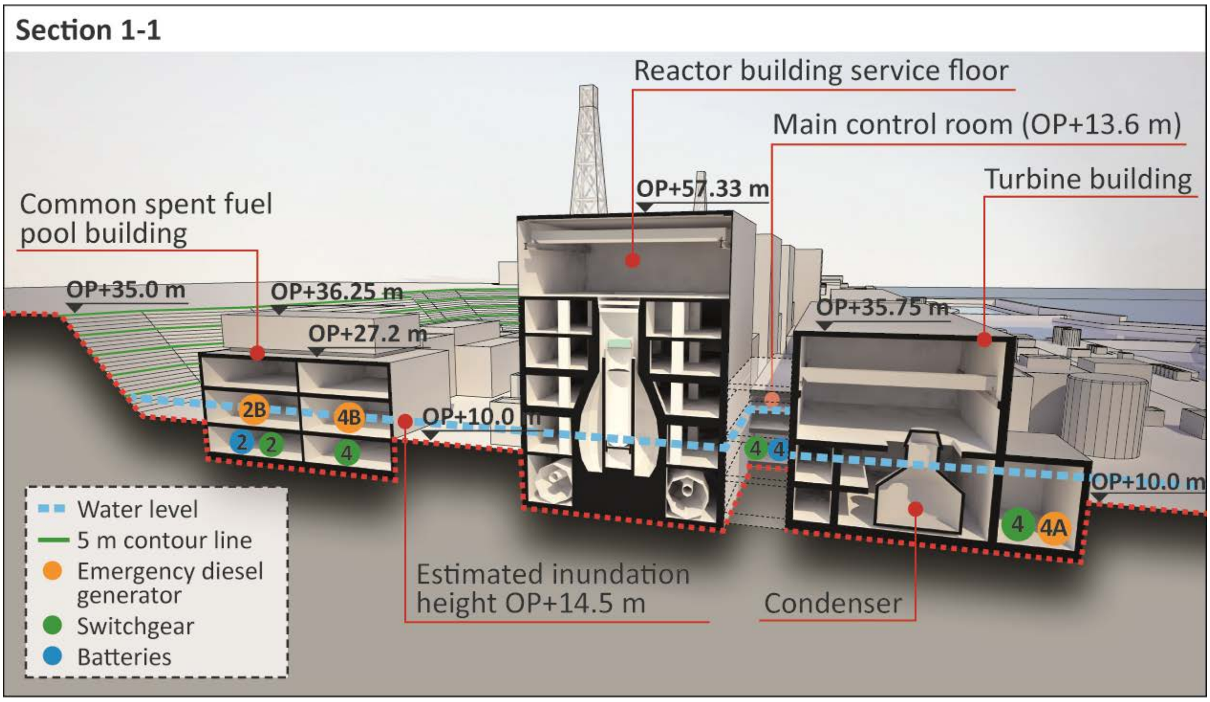

FIG. 1.1–7. The elevations and locations of structures and components at the Fukushima Daiichi NPP [16].

As a result of these events, Units 1–5 lost all AC power, a situation referred to as a station blackout (SBO). Only Unit 6, with its one remaining air cooled EDG supplying emergency AC power, did not. A 'specific event', as defined in the regulations[16] [18] associated with the Act on Special Measures Concerning Nuclear Emergency Preparedness (hereafter referred to as Nuclear Emergency Act)[17] [19] based on a 'station blackout'[18], was declared by the Site Superintendent, who was the head of the on-site ERC of the operating organization, TEPCO. Consequently, the relevant off-site agencies were informed, in accordance with the requirements of the Nuclear Emergency Act, within five minutes of the loss of all AC power, i.e. an SBO.

The Fukushima Daiichi NPP units, similar to other plants of the same age, had design provisions to withstand an SBO for eight hours, with response procedures for operators.[19] In Units 1–5, the event

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[15] The air cooled EDGs of Units 2, 4 (located in ground floor of the common spent fuel building) and 6 (located on the first floor of a separate diesel generator building at higher elevation) appeared to be not affected by the flooding. However, the components (i.e. switchgears, power centres, panels, etc.) of the air cooled EDGs of Units 2 and 4, which were located in the basement of the common spent fuel building, suffered water damage.

[16] Cabinet order in reference of the Nuclear Emergency Act.

[17] Act No. 156, adopted on 17 December 1999.

[18] Due to the loss of all AC power supplies for longer than 5 minutes.

[19] Nuclear power plants are generally equipped with on-site DC and additional backup AC power sources (i.e. gas turbine generators or diesel engines) to withstand an SBO for a limited period of time, varying between 4 and 72 hours. The determination of the coping period is based mainly on the time that it would take to restore AC power sources to the NPP and the capacity of the available measures. During that time, equipment such as DC batteries, DC/AC inverters and other secondary backup AC sources (e.g. gas turbines or diesel generators) is used.

based emergency operating procedures (EOPs) for 'loss of all AC power' [20] were initiated. As the emergency shifted from an earthquake situation to a nuclear situation, the ERC at TEPCO Headquarters and the Nuclear Emergency Headquarters of the Ministry of Economy, Trade and Industry (METI) were activated in Tokyo, along with METI's Local Emergency Headquarters at the Off-site Centre (OFC) in Okuma Town, located approximately 5 km away from the Fukushima Daiichi NPP site.[20]

1.1.2.6. Loss of DC power in Units 1, 2 and 4

All units at the Fukushima Daiichi NPP were equipped with on-site DC sources as an emergency power supply in an SBO situation, but the flooding also affected this equipment in Units 1, 2 and 4, inundating the DC batteries, power panels or connections. Consequently, DC power was gradually lost in Units 1, 2 and 4 during the first 10–15 minutes of the flooding, making it difficult to cope with the SBO.

Due to the loss of all electrical (AC and DC) power, the operators of Units 1 and 2 could no longer monitor essential plant parameters, such as reactor pressure and reactor water level, or the status of key systems and components used for core cooling. As mentioned earlier, the heat removal capability for the SFPs in all units was already lost following the LOOP. The additional loss of DC power in Units 1, 2 and 4 meant that operators could no longer monitor the water temperature and levels in the SFPs of these units.

In the absence of procedures addressing the loss of all (AC and DC) power, the operators of Units 1, 2 and 4 did not have specific instructions on how to deal with an SBO under these conditions. The operators and ERC staff started reviewing available options and establishing possible ways to restore power and thereby regain the ability to monitor and control the plant.

1.1.2.7. Response in Units 3, 5 and 6

Although Units 3 and 5 were experiencing SBO, DC power was available in these units, and Unit 6 maintained its AC power supplied by the on-site emergency source, the EDG. Power availability enabled the operators to observe the plant status as the MCR indications and controls were functioning. This allowed the operators to continue with their applicable procedures in response to the events:

- In Unit 3, DC power was available from the DC batteries. The SRVs automatically opened and continued cycling to protect the RPV from overpressurization and, as a result, the reactor water level decreased. The operators manually restarted the RCIC system, controlling and monitoring the reactor water injection with the available DC power. They also shut off other non-critical equipment to maximize the availability of the DC batteries in order to extend the period of time for coping with the SBO in accordance with their event response EOP.
- DC power was also available in Unit 5. The residual heat removal by a high pressure cooling systems — the RCIC or high pressure coolant injection (HPCI) — was not possible, since the reactor was not generating steam to drive dedicated turbines to run the pumps. The reactor had to be depressurized to enable coolant injection by low pressure injection systems, such as the make-up water condensate (MUWC) and residual heat removal (RHR) systems. However, depressurization using the SRVs was not possible, since the depressurization function of the SRVs (except for three SRVs with the highest opening pressure) was disabled. Alternative

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[20] The OFC at Okuma Town was later relocated to the Fukushima Prefecture Government office because of insufficient provisions by this office for an emergency situation caused by an earthquake and its inadequate arrangements for radiation protection for the radiation levels occurring during the accident.

options, such as discharging water from the RCIC and HPCI lines, were tried unsuccessfully, and the RPV, which was pressurized and filled with water, continued to heat up and pressurize.

- Unit 6 did not experience an SBO, since AC power was available from one operating EDG. Here, the efforts focused on maintaining fundamental safety functions[21] in response to the LOOP event as prescribed in the AOPs. The reactor was at atmospheric pressure, making it possible to utilize the low pressure systems to inject cooling water; however, some of the necessary components of those systems were damaged by the flooding and required restoration in order to provide water to the reactor. It was decided to inject water into the reactor via the MUWC system until the RHR system could be restored, since the air cooled EDG was operating and supplying AC power to the MUWC pump.

1.1.3. Progression of the accident

1.1.3.1. Presumed severe accident conditions in Units 1 and 2

As all electrical power was lost in Units 1 and 2, there were no indications available to the operators on the status of key systems and components to determine whether the safety systems were operating properly, or operating at all, in order to maintain the fundamental safety functions[22] and SFP cooling in Units 1 and 2.

Since the monitoring of the reactor water level status could not be recovered in the MCR and the status of water injection for core cooling remained undetermined, an emergency on the basis of the ‘inability of water injection of the emergency core cooling system’, as defined in regulations [18], was declared for Units 1 and 2 within one hour of AC and DC power loss, in accordance with the Nuclear Emergency Act’s ‘degrading nuclear emergency conditions’ clause (Article 15). Consequently, at 16:45, the on-site ERC reported to the off-site organizations, TEPCO Headquarters and relevant government authorities, that the nuclear emergency conditions for Units 1 and 2 existed.[23] The Severe Accident Operating Procedures (SOPs) in the Unit 1 and 2 MCR and the severe Accident Management Guidelines (AMGs) in the on-site ERC were implemented, and the staff in the ERC and MCR began to establish a strategy for coping with the potential degradation of the fission product barriers.

1.1.3.2. Establishing the severe accident management strategy

Since the core cooling appeared to be compromised, the accident management strategy focused on injecting water into the reactors in order to prevent, or mitigate, potential damage to the nuclear fuel, in accordance with the AMGs and SOPs. Two options for injecting water into the reactors were identified:

- The use of systems that could inject water directly into the reactors even at high pressures, such as the standby liquid control (SLC) system and the control rod drive (CRD) system, which required the restoration of AC power.

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[21] The control of reactivity, core cooling and confinement.

[22] The fundamental safety function of reactivity control had been confirmed before the SBO by indications showing that the control rods were inserted and the fission reaction had stopped.

[23] METI then reported Article 15 notification to the Prime Minister’s Office, and, at 19:03, the Prime Minister declared a nuclear emergency situation. The Nuclear Emergency Response Headquarters (NERHQ) was established at the Prime Minister’s Office, with the Prime Minister assuming responsibilities as the Director General, directing the national nuclear emergency response.

— The use of alternative equipment, such as mobile fire engines and the stationary diesel driven fire pump (DDFP) that could inject water at low pressures, which required depressurization of the reactors and alignment of the fire protection (FP)[24] lines to inject water into the core.

The on-site ERC adopted a core cooling strategy that used the stationary DDFP and the fire engines via the fire protection system to inject water into the reactors, in addition to obtaining and connecting temporary AC power sources. Teams were dispatched to survey and assess the power equipment and the DDFP, to prepare the FP line arrangements and to dispatch the fire engines. This strategy considered not only Units 1 and 2, but all units, in anticipation of any further degradation of the fundamental safety function of core cooling in the other reactors.

This accident response strategy was given the highest priority for Units 1 and 2 and was applicable to all other units with some variations. For example, in Unit 5, the accident management (AM) action was to restore AC power using the available interconnecting line[25] to the operating EDG in Unit 6.

1.1.3.3. Confirmation of Unit 1 core cooling loss

Just before the tsunami struck, the Unit 1 IC was stopped by the operators in accordance with established operating procedures to control the reactor pressure. This was accomplished by closing the control valves (located outside the PCV and DC-operated, as shown in Box 1.1–2). About 2.5 hours after the loss of indications in the MCR, at 18:18 on 11 March, some of the status lamps for those control valves were found to be functioning, confirming that the control valves were closed and implying that the IC was not operating. The operators attempted to start the IC by opening those valves from the MCR (i.e. remote-manually), expecting that the isolation valves, located inside the containment on each line of IC loops, were in the open position, since their status was unclear[26]. After opening the outside containment valves of one IC loop, release of steam was observed above the Unit 1 reactor building (RB), which was thought to be coming from the IC system and would have indicated that the IC was operational; however, this assumption was short lived, as the steam release stopped, raising concerns about the integrity of the IC system. Since the system was not operating as expected, the valves that had just been opened were manually closed again to ensure that the IC was not operating. A team that was later dispatched to the RB confirmed that the IC was not operating, as indicated by the local readings of high reactor pressure. The ‘non-operational’ status of the IC was communicated to the MCR and relayed to the ERC. Thus, the fundamental safety function of core cooling at Unit 1 was lost when the IC was stopped by the operators just before the tsunami, and the Unit 1 core heated up from that time onward.

The team dispatched to the RB also confirmed that the DDFP was functioning and proceeded with establishing the core spray line-up for an alternative water injection via the FP system, as envisioned in the strategy. Additionally, local measurements (in the RB) at 20:07 indicated that the reactor was still near the operating pressure of 7 MPa (70 bar), which prevented water injection by alternative methods that would only be possible below 0.8 MPa (8 bar).

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[24] The fire protection system was designed primarily for fire suppression and flooding of the containment vessel, not for injection of water into the reactor.

[25] Cross-tie lines had been installed at the Fukushima Daiichi NPP nearly a decade earlier as a design enhancement for accident management. Sharing the functioning emergency power of Unit 6 was only possible for Unit 5, since these interconnections had been installed only between pairs of units, i.e. Units 1 and 2, Units 3 and 4, and Units 5 and 6.

[26] The valve positions were not clear to the operators owing to the uncertain timing and sequence of each type of power loss that would determine the operation of isolation condenser status of isolation valves. All the inside containment isolation condenser valves (AC operated) would keep their position when the AC power was lost, but they would close, by design, if the control power (i.e. DC power) was lost to the protection system — for the line break situation — that would have sent ‘close signal’ signals to those valves. The position of AC-powered isolation valves has not yet been confirmed by post-accident investigations.

After several notifications from the on-site ERC on the status of Unit 1 and the other units and discussions among the Prime Minister's Office, METI, the Nuclear and Industrial Safety Agency (NISA) and TEPCO, a national nuclear emergency was declared by the Japanese Government at 19:03 on 11 March 2011.

In Unit 2, which was also without any indications of operation of the core cooling system and core pressure and temperature, the operators assumed the worst case scenario that the RCIC system was not operating, and the Unit 2 core was heating up. At 21:01, the on-site ERC informed government authorities that the Unit 2 core, without any cooling, was predicted to become uncovered at around 21:40. Following this prediction, the Prime Minister, as the Director General of the Nuclear Emergency Response Headquarters, issued an order at 21:23 on 11 March for the evacuation of the public within 3 km and for sheltering within 3–10 km of the site.[27]

The uncovering of the Unit 1 core was indicated when high radiation levels[28] encountered on the first floor of the Unit 1 RB by a team that was dispatched at 21:51 to confirm the status of the operation of the IC. This was an indication of the severity of the conditions at the Unit 1 reactor and the occurrence of possible core damage.

At 21:30, nearly six hours after the SBO, the operators tried to start the IC again. Although the water level in the Unit 1 reactor appeared to be increasing briefly, the IC did not function.[29]

At around 23:00 on 11 March, the radiation readings in the turbine building (TB), just outside the entry doors of the RB, were elevated (as high as 1.2 mSv/h at the north entry door). Shortly thereafter, an order that restricted entry to the Unit 1 RB was issued, and a report to the Government of Japan reporting the dose rates of 1.2 mSv/h in the RB and 1 mSv/h in the TB was sent at 23:49.

1.1.3.4. Deterioration in conditions at Unit 1 confinement

Following the confirmation of the loss of core cooling in Unit 1, further challenges to the other fundamental safety function — the confinement — became evident when the first reading of the PCV pressure became possible at 23:50 on 11 March. It showed that the Unit 1 containment pressure was 0.6 MPa (6 bar), exceeding the maximum containment design pressure of 0.528 MPa (5.28 bar). The pressures in the containments of other units were less adverse and were below the respective design pressures (local readings were 0.141 MPa (1.41 bar) in Unit 2 and 0.2 MPa (2 bar) in Unit 3).

The elevated Unit 1 PCV pressure prompted the declaration of an emergency based on 'abnormal rise in PCV pressure' for Unit 1 within one hour of the pressure measurements. The Site Superintendent also ordered preparations for Unit 1 PCV venting to relieve pressure in a controlled manner.

By 02:30 on 12 March, approximately 11 hours after the SBO, Unit 1 PCV pressure reached its highest value of 0.84 MPa (8.4 bar) before quickly decreasing to 0.8 MPa (8 bar) and stabilizing.

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[27] Earlier, at 20:50, the local Government of Fukushima Prefecture had issued an evacuation order for residents within 2 km of the plant after evaluating the national nuclear emergency declaration and discussing the uncertainty concerning the status of the NPPs with TEPCO officials.

[28] The personal dosimeters of the team dispatched to the RB to confirm the status of the IC in Unit 1 recorded levels as high as 0.8 mSv in about ten seconds of their entry in the building.

[29] The reliability of level measurements was questionable at this point, since the water levels may have erroneously been caused by the evaporation of the water in the reference leg of the water level measurement.

1.1.3.5. Heating up of Unit 5 and restoration of AC power

During the time when core cooling and confinement functions in Unit 1 were the primary concern, the Unit 5 reactor had continued to heat up in the absence of heat removal measures. An SRV in Unit 5 automatically opened for the first time approximately 10 hours after the SBO, because the reactor pressure reached its opening set value, at 01:40 on 12 March. The valve automatically opened and closed several times to maintain the pressure in a range determined by the design.

The SRVs were operating automatically to limit pressure but could not be used to reduce pressure, since most of them had their depressurization function disabled for the test carried out before the accident. Reducing pressure by opening a small valve (the head vent nozzle) on the RPV was considered as an alternative because DC power was available for this purpose.

1.1.3.6. Confirmation of Unit 2's status and focus on recovery of Unit 1's safety functions

At 02:55 on 12 March, the local observations by the team dispatched to enter the Unit 2 RCIC room confirmed that the Unit 2 RCIC system was still operating, clarifying the previously unknown status of Unit 2 core cooling. Based on this information and the acute challenge to the confinement function of Unit 1, the Site Superintendent decided to give priority to the venting efforts of Unit 1.[30]

While the venting plans were being developed, the Unit 1 reactor pressure became low enough to allow alternative water injection.[31] The AM strategy to restore Unit 1's core cooling using the DDFP for water injection proved to be impossible to implement, because the pump was discovered to be inoperable at 01:48 on 12 March. The alternative, using fire trucks connected to the FP water injection port outside the TB, which had been installed in the previous year as a fire protection measure based on the experience of the Niigata-Chuetsu-Oki earthquake, was put into action.

After a four hour effort of searching for and locating the FP water injection port among the debris, establishing the connection and getting the fire truck to the connection, the alternative water injection from the freshwater tank to the Unit 1 reactor via the FP system by using fire engine started about 12.5 hours after the SBO, at 04:00 on 12 March. Water injection from a single one-tonne truck continued intermittently, with the truck having to return to the freshwater tank periodically to be refilled. The water transport efforts were also interrupted by changing radiation conditions at the site.

1.1.3.7. Degrading on-site radiological conditions

Meanwhile, an attempt to enter the Unit 1 RB to conduct radiation measurements at 03:45 on 12 March was abandoned, when the team encountered white fog-like steam upon opening the airlock door, although the measurements at the radiation monitoring post near the site's main gate did not show any anomaly to indicate a release from RPV or PCV at 04:00. However, shortly afterwards, at 04:19, a drop in the Unit 1 PCV pressure was recorded, and an approximately ten-fold increase in the main gate radiation levels was observed (0.000 069 mSv/h measured at 04:00 versus 0.000 59 mSv/h at 04:23). Also, in the MCR, the radiation levels showed an increase requiring that the Unit 1 crew move to the Unit 2 side of the MCR, away from the entry door which was not completely closed to allow the laying of temporary cables.

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[30] The plans for Unit 1 PCV venting were announced to the public by METI and TEPCO at a joint press conference at 03:06 on 12 March.

[31] Reactor depressurization had occurred without any operator or plant systems actions, indicating that an unknown path provided pressure relief.

In response to increased dose rates at the site and the contamination detected on the workers returning from outside area activities at the site, the ERC issued a brief evacuation of site personnel conducting outside activities, and subsequently a recommendation to resume the work with protective gear. Following up on the ERC's recommendation, the shift superintendent of Units 1 and 2 issued a mandatory order for the outside workers of these units to wear full-face masks with charcoal respirators and full-body suits. He also ordered that full-face masks with charcoal respirators be worn by the operators in the Unit 1 and 2 MCR.

TEPCO also notified the government agencies about increasing radiation readings at the site. This information, combined with the elevated containment pressure in Unit 1 necessitating PCV venting, prompted the Government to expand the evacuation zone to 10 km early in the morning, at 05:44 on 12 March 2011. The activities to configure venting of Unit 1's containment were set to start at 09:00 on 12 March.

1.1.3.8. Starting continuous freshwater injection into Unit 1

As the intermittent freshwater injection by fire engines continued, the work on establishing a direct line from the freshwater tank to the Unit 1 reactor, via the FP system for continuous injection, took approximately 5.5 hours. The work on the direct injection line was interrupted by changing radiation conditions at the site. At around 09:15 on 12 March, slightly over 17.5 hours after the SBO, continuous water injection to the Unit 1 RPV started directly from the FP tank through a connection between a fire truck pump and the FP system.

1.1.3.9. Depletion of freshwater source in Unit 2

Meanwhile, in Unit 2, the contents of the freshwater source to RCIC system, the condensate storage tank (CST), for reactor water injection was being depleted. At the same time, the water level in the suppression chamber (SC) was rising to necessitate action to prevent overfill of the SC. Thus, a crew was dispatched to the RCIC room to manually manipulate the valves, in order to switch the RCIC pump water supply from the CST to the SC pool, in accordance with procedures. The valve alignment was completed at 05:00, and Unit 2 reactor water injection from the SC via the RCIC continued afterwards. This closed-loop RCIC operation resulted in a faster increase in SC temperature than a once-through line, as anticipated.

1.1.3.10. Depressurization of Unit 5 and restoration of AC power

After four hours of SRV cycling (repeated opening and closing) to limit pressure, at 06:06 on 12 March, approximately 14.5 hours after the SBO, the head vent nozzle on Unit 5's RPV was remotely opened from the MCR and left open to relieve pressure from the water-filled RPV afterwards.

In addition, the power connection between Unit 5 and the operating EDG in Unit 6 was completed nearly 16.5 hours after the SBO, utilizing the interconnecting 'accident management bus tie'. This AC connection enabled the powering of some Unit 5 equipment, such as the pumps and valves needed for reactor heat removal. Power supply to operate the MUWC pump and valves continued to be available through the rest of 12 March. Also, the MUWC-RHR interconnecting pipe valves were to be opened, to establish a reactor water injection line to Unit 5's reactor via the RHR system.

1.1.3.11. Trip of Unit 3 RCIC and switch to HPCI

While the containment venting and core cooling of Unit 1 was being established, the SBO response in Unit 3 had to be modified when the RCIC system ceased to operate at 11:36 on 12 March, after nearly 20.5 hours of continuous operation. The operators tried unsuccessfully to restart the system several times in the following hour as the water in the reactor continued to boil and evaporate, and therefore the reactor water level continued to decrease. When the water level reached the set point at which the HPCI system — an emergency core cooling system — to activate, this system automatically started at 12:35 to maintain the reactor water level in the predetermined range. However, the operators took manual control to avoid repeated automatic starts and stops of the system in order to preserve DC power for a longer period, in accordance with the SBO response procedures.

As the SC pressure and temperature had increased as a result of more than 20 hours of RCIC operation, the Unit 3 DDFP was also started at 12:06, to spray the SC via the FP line in order to suppress the pressure and temperature increase in the SC.

1.1.3.12. Venting of Unit 1 containment for protection of confinement safety function

As soon as confirmation was received from the Fukushima Prefecture authorities, at 09:02 on 12 March, of the completion of evacuation of Okuma Town, the teams were activated to start manipulation of the valves in order to arrange the path for venting the PCV of Unit 1.[32] After 5.5 hours of efforts, the venting path (Box 1.1-3) was established when the final valve on the path was opened at around 14:00 on 12 March.

The success of the venting operation was confirmed by a decrease in containment pressure, as measured at 14:30, and was reported to the relevant government authorities. Although there was no significant immediate change in the radiation measurements within the site boundaries, about one hour later, a radiation dose rate reading of approximately 1 mSv/h was recorded at 15:29 by one of the monitoring posts located near the site boundary to the north-west of Unit 1.[33] Overall, it took 14.5 hours from the Site Superintendent's order around midnight to implementation owing to high radiation levels in the torus room, which houses the SC, where valves had to be manually manipulated, and the lack of compressed air supply to manipulate the valves.

1.1.3.13. Establishment of temporary seawater injection and power provisions in Unit 1

After approximately 11 hours of water injection into the Unit 1 core via fire truck and FP system, the fresh water in the FP water tank was almost depleted. As a result, freshwater injection to Unit 1 stopped at 14:53 on 12 March. The Site Superintendent then decided to inject sea water into the Unit 1 reactor from the Unit 3 backwash valve pit, where seawater had pooled after the tsunami, as it was the only available source of water at that time. In just over half of an hour, this arrangement for seawater injection was completed. Around the same time, work to connect the mobile voltage power supplies[34] to Units 1 and 2 using an undamaged power panel in Unit 2 as a transformer was completed, and a low voltage grid for supply of AC power to Unit 1 was re-energized at 15:30 on 12 March.

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[32] Completion of evacuation to start the venting was agreed with the Fukushima Prefecture authorities.

[33] At 16:17, it was noted by the ERC that radiation measurement taken at 15:31 near the main gate was 0.569 mSv/h, and the authorities were notified at 16:27, since this value exceeded the legal reporting criterion of 0.5 mSv/h. The notification was corrected at 16:53, when it was realized that the radiation level measured at 15:29 was 1.015 mSv/h, i.e. after venting of Unit 1 (but before the explosion at Unit 1).

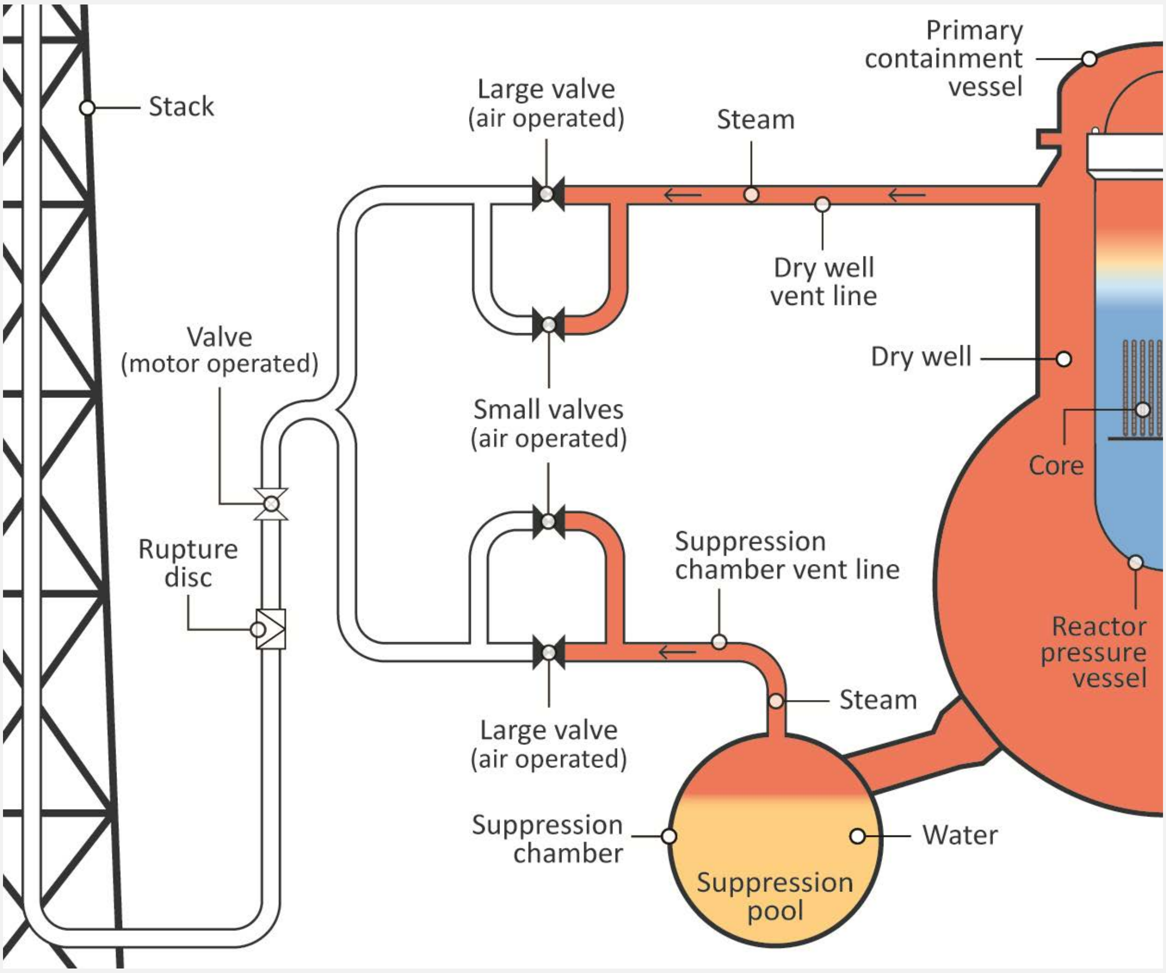
[34] Almost one hour after the SBO on 11 March, mobile power equipment (low and high voltage power supply vehicles) was dispatched to the Fukushima Daiichi and Fukushima Daini NPP sites. The first vehicle, from Tohoku Electric, arrived at around 22:00 on 11 March, i.e. nearly six hours after the SBO. More vehicles from other TEPCO and Tohoku Electric facilities and the Japan Self-Defense Forces arrived at the sites throughout the night. By 10:15 on 12 March, a total of 23 vehicles were at the Fukushima Daiichi NPP site.

Box 1.1–3. Containment venting

As a measure to improve the ability to cope with severe accidents, ‘hardened vents’ (i.e. pressure relief devices with relatively thick walled discharge piping) were installed in the units at the Fukushima Daiichi NPP in the 1990s following a regulatory decision [21, 22]. The aim was to prevent overpressurization of the PCV by allowing venting (see the figure below) in order not to challenge the integrity of containment structure that maintains the confinement safety function.

Although the preferred path of venting was from the suppression chamber, in order to benefit from the removal of radioisotopes by the water pool, the vent path included another route from the drywell. Either path could be aligned by manipulating valves from the MCR, controlling the amount and duration of the release through a stack shared between the pair of units.

In the Fukushima Daiichi NPP, the vent line also contained a rupture disc that was set to burst when the containment pressure exceeded a pre-set pressure, thereby preventing premature venting. The underlying philosophy in Japan was not to vent until it was inevitable, and as a last resort for maintaining the integrity of the primary containment in order to delay or prevent the direct release of radioactive material to the environment.



Nearly 24 hours after the SBO, temporary seawater injection and AC power supply were connected to Unit 1. However, within minutes of connection, an explosion in the Unit 1 RB damaged both of these arrangements before they could be put in use.

1.1.3.14. Explosion in Unit 1 and destruction of alternative water and power provisions

At 15:36 on 12 March 2011, an explosion occurred on the service floor of the Unit 1 RB, causing extensive damage to the upper building structure. Although the explosion did not seem to have directly affected the primary containment (PCV), it damaged the secondary containment, the reactor building (RB) by destroying its steel framework and cover plates. The cause of the explosion was unknown to the plant staff, but it was suspected that hydrogen had been released from the core and had escaped from the primary containment via an unknown path. Consequently, the on-site ERC requested evacuation of staff from the areas in and around Units 1–4, including the crews of two MCRs except for the three most senior level MCR staff.

The explosion and the ejected debris also caused serious damage to the alternative seawater injection line assemblies and to the cables laid for the mobile high voltage power supply. It worsened the already challenging field conditions for emergency operations throughout the site, injuring workers and causing locally high dose rates around the site due to scattered contaminated rubble.

Shortly after the explosion, it was recognized that the radiation dose rates at the site boundary measured 1.015 mSv/h[35], and an emergency for 'abnormal rise in the site boundary radiation dose rate' was declared 40 minutes later. Approximately three hours after the explosion in Unit 1 (four hours after venting of the Unit 1 containment), at 18:25 on 12 March, the Government extended the evacuation zone to 20 km.

Although the relatively stable pressure inside the Unit 2 and 3 containments made venting of those units not an immediate necessity, the Site Superintendent ordered preparations for Unit 2 and 3 PCV venting to be started, benefiting from the relatively less adverse radiological conditions in those buildings, as the radiation conditions across the site were deteriorating quickly after the explosion in Unit 1.

1.1.3.15. Repair and restoration of water injection lines and seawater injection to Unit 1

Following the explosion in Unit 1, the area around the Units 1–4 had to be temporarily evacuated, delaying the repair of damaged temporary water and power equipment. The crew returned to repair or replace damaged equipment about 1.5 hours later.

After the replacement of damaged hoses and the start-up of the fire engine pumps, the injection of sea water into the Unit 1 RPV via fire engines from the Unit 3 backwash valve pit through the core spray line started at 19:04 on 12 March and continued afterwards.[36] Boric acid was added later to address recriticality concerns to ensure the fundamental safety function of reactivity control. Overall, between the end of freshwater injection and the start of seawater injection, the Unit 1 core was without cooling for nearly four hours.

1.1.3.16. Unit 3 HPCI manual shut-off and loss of core cooling

While Unit 1 was assigned the highest priority with respect to the maintenance of the fundamental safety functions during the first day and a half of the accident, the core cooling situation in Unit 3 became another cause of concern at 02:42 on the morning of Sunday 13 March.

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[35] Later, this measurement was determined to have been taken at 15:29.

[36] On one occasion, according to the investigations [5], a TEPCO executive who was representing the company at the Prime Minister's Office asked the Site Superintendent on the telephone to stop the seawater injection to Unit 1. That directive was not followed, and seawater injection was not interrupted.

After 14 hours of continued operation of the HPCI system, the Unit 3 operators became concerned about the reliability and possible failure of the system's turbine powering the injection pump, which was by then already operating at low reactor steam pressure. The concern was related to the possibility of turbine damage and creation of a release path from the RPV. This would result in an uncontrollable release of radioactively contaminated steam, directly outside the PCV. This concern was heightened when the HPCI turbine did not automatically stop, as it was designed to, when the reactor pressure decreased below the automatic shutoff pressure.

Consequently, the operators decided to manually stop the HPCI system and instead use the alternative means of injection at low pressure (the DDFP). The operators thought this could be achieved without interruption of core cooling, since the reactor pressure was already below the DDFP injection pressure and could be kept low by the use of SRVs. The Unit 3 HPCI was therefore turned off by the operators, who then proceeded to open the SRVs.

However, all attempts to open the SRVs failed, and reactor pressure quickly increased above the level at which the DDFP could inject, stopping the cooling of the Unit 3 core about 35 hours after the SBO. Faced with this setback, the operators unsuccessfully tried both from the MCR and local-manually, for nearly 45 minutes, to revert to injection via the HPCI system. Without any capability to cool the reactor, an emergency report for 'loss of reactor cooling function' as defined in the regulations [18] associated with the Nuclear Emergency Act [19] was issued for Unit 3, at 05:10 on 13 March. The Unit 3 core remained without cooling for the hours that followed, and Unit 3 became the next unit after Unit 1 to lose core cooling.

The overall effects of the HPCI shut-off and actions to recover the interrupted water injection were that the Unit 3 core was without cooling for seven hours. This interruption of core cooling was an adverse turning point for the Unit 3 conditions.

During this time, neutrons were detected between 05:30 and 10:50 on 13 March by a mobile radiation monitor near the main gate, which is around 1 km away from the RBs of Units 1–3.[37]

1.1.3.17. Unit 3 alternative core cooling and containment venting

After the loss of cooling of the Unit 3 core, an alternative water injection method utilizing the fire engines was ordered by the Site Superintendent at 05:15 on 13 March. In view of the deteriorating conditions, he also ordered the Unit 3 containment venting path, up to the rupture disc, to be lined up.

In order to establish Unit 3 core cooling by an alternative method, a fire engine from the Unit 5–6 complex was immediately dispatched to Unit 3 together with an additional fire engine that arrived from the Kashiwazaki-Kariwa NPP at 06:30. Also, the work to establish a temporary line for injecting seawater from the Unit 3 backwash valve pit to the Unit 3 core was immediately started. The water injection line was completed and connected to the FP line within one hour. However, its use was postponed by the Site Superintendent in accordance with a directive[38] from TEPCO Headquarters to continue injecting fresh water, not sea water, as long as fresh water was available. As a result, the injection line was changed back to the freshwater source. However, as the reactor pressure increased above the pump pressure of the fire engines, the injection did not occur.

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[37] It has been estimated by TEPCO analyses after the accident that the neutrons came from spontaneous fission of actinides that had been released due to core damage in one of the three reactors, most probably from Unit 3.

[38] A TEPCO division director who attended a meeting in the Prime Minister's Office (PMO), asked the Site Superintendent on the telephone whether there was any fresh water available. The division director only informed the Site Superintendent of the views participants had expressed at their meeting. The Site Superintendent, however, took the discussions as directives.

The Unit 3 venting line arrangement was completed in a little more than three hours, at 08:41 on 13 March, but the containment pressure remained below the containment design pressure, and was not high enough to cause the rupture disc to burst.

The operators, meanwhile, continued their efforts to activate the SRVs in order to reduce the Unit 3 reactor pressure, using the DC batteries that were gathered from cars and collected in the common MCR of Units 3 and 4. As the opening of an SRV with those batteries was being tried, the operators in the MCR observed a drop in the reactor pressure in the Unit 3 reactor at 09:08, although the valve status indicators did not conclusively show whether or not the valves were in the open position.

Following the reactor depressurization, the reactor pressure fell below the fire engine pump pressure and injection of borated fresh water into the Unit 3 reactor, through the FP line using fire engines, started at 09:25, after more than four hours without core cooling.

Along with this depressurization of the RPV, there was a pressure surge in the SC section of the PCV, indicating a discharge from the RPV to the PCV. At 09:20 on 13 March, the containment pressure exceeded the maximum design pressure of the containment and, subsequently, the containment pressure dropped rapidly, indicating that the venting of the Unit 3 containment had occurred as a result of the bursting of the rupture disc. The venting of the Unit 3 containment, however, was short lived, when a valve on the vent line closed[39] because of the lack of sufficient air supply to keep it open. After 6.5 hours of effort, the valve was reopened by using a mobile compressor.

1.1.3.18. Unit 2 precautionary measures for fundamental safety functions

At approximately 10:15 on 13 March, as the conditions for maintaining the relevant fundamental safety functions in Units 1 and 3 became more difficult, the Site Superintendent ordered the containment vent path for Unit 2 to be pre-emptively established. This order was intended to take advantage of favourable radiological conditions by manually operating valves in the Unit 2 RB before any deterioration in line with the site wide trend.[40] The work was accomplished in 45 minutes, but venting did not occur because the pressure inside the Unit 2 containment was not high enough to cause the bursting of the rupture disc.

At around 12:05, the Site Superintendent also ordered precautionary preparations for seawater injection into Unit 2 in case the unit's operating normal cooling system, the RCIC, failed, as it was the case in Unit 3. For this purpose, fire engines were to be connected to the fire protection lines of Unit 2 to inject water from the backwash valve pit of Unit 3, if needed.

1.1.3.19. Seawater injection and increase in radiation levels in Unit 3

As the fresh water from the FP tanks was depleted at around 12:20 on 13 March, the Site Superintendent decided to inject sea water into the Unit 3 reactor. The fire engines were repositioned, and seawater injection from the backwash valve pit of Unit 3 started about one hour later, at 13:12.

At 14:15 on 13 March, a radiation dose rate of 0.905 mSv/h was measured near the site boundary. This measurement exceeded the reporting criterion of 0.5 mSv/h as defined in the regulations [18] and the relevant government agencies were notified at 14:23 of an 'abnormal rise in the site boundary radiation dose rate' in accordance with the regulations associated with the Nuclear Emergency

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[39] As discovered two hours later.

[40] Between 05:30 and 10:50 on 13 March, neutrons were detected about 1 km from the reactor buildings of Units 1–4 near the main gate, indicating a possible breach of the containment vessel, although the source of the neutrons was unknown.

Act [19]. Fifteen minutes later, the radiation dose rate exceeded 100–300 mSv/h at the entry doors of the Unit 3 RB. Also, the dose rates on the Unit 3 side of the Unit 3–4 MCR exceeded 12 mSv/h by 15:28, and the shift team moved to the Unit 4 side. The on-site ERC inferred from these increasing dose levels that radioactive gases had escaped from the Unit 3 reactor, which in turn meant that hydrogen had also escaped. Mindful of the possibility of a hydrogen explosion similar to the one at Unit 1, the Site Superintendent decided, at 14:45, to temporarily evacuate the workers from the common MCR of Units 3 and 4 and from the areas in the vicinity of Unit 3. The evacuated areas also included the Unit 3 backwash valve pit area, halting the activities for water injection. The evacuation order was lifted at 17:00, and workers returned to the Unit 3 backwash valve pit area to continue the activities for water injection and venting.

1.1.3.20. Establishing core cooling and confinement functions of Unit 5

At around 20:48 on 13 March, the power from the Unit 6 EDG was connected to the pump of Unit 5's normal, low pressure, non-safety heat removal system, the MUWC, and the pump was started at 20:54. The MUWC–RHR interconnecting pipe valves were remotely opened, completing a reactor water injection line to Unit 5's reactor via a train of the RHR system at 21:00, approximately 53 hours after the SBO. However, the reactor pressure had gradually risen and exceeded the RHR pump discharge pressure, which prevented water injection to the reactor. In response, the shift team, acknowledging that the pressure reduction by the head vent nozzle was not sufficient, decided to use the SRV set that was not locked, for additional RPV pressure relief. An SRV was opened, making use of available DC power and nitrogen supplies, reducing RPV pressure and allowing the water injection into the reactor at 05:30 on 14 March. This bleed (by SRV) and feed (by MUWC pump) operation continued afterwards.

In addition, the AC power to operate the standby gas treatment system (SGTS) for controlling RB pressure was supplied from Unit 6's EDG. The system was started up a little over two days after the SBO and kept the pressure inside the RB below the atmospheric pressure, ensuring secondary confinement.

1.1.3.21. Loss of seawater cooling in Units 1 and 3

As the injection of sea water into Units 1 and 3 from the Unit 3 backwash valve pit continued into Monday 14 March, the water in the pit fell to such a low level that injection to both units had to be halted at 01:10. After the intake hose was lowered deeper into the pit, the remaining pit water was reserved for injection into Unit 3, which resumed two hours later. Unit 1 core cooling was postponed until the pit could be refilled.

In the following hours, the Unit 3 containment pressure was found to be increasing, and the reactor water level indication continued to decrease. The reactor water level in Unit 3 went off-scale at 06:20 on 14 March, indicating to the operators that the core was uncovered. The Site Superintendent ordered an evacuation of all workers because of concern about a possible hydrogen explosion in Unit 3, halting the pit refilling activities.

The containment pressure in the drywell (DW) (see Box 1.1–1) in Unit 3 reached a maximum value of 0.52 MPa (5.2 bar) at 07:00, but was found to be slightly lower (0.5 MPa (5 bar)) at 07:20. It subsequently remained stable around 0.5 MPa (5 bar), which was below the maximum design pressure. The Site Superintendent then decided to resume the work to establish a line to refill the backwash valve pit from the ocean. In the next two to four hours, the seawater injection lines for all units were re-established, and refilling of the pit commenced, utilizing two fire engines pumping water from the ocean and seven tanker trucks from the Japan Self-Defense Forces (SDF), which arrived at the site at 10:26, to carry water to the pit.

Seawater injection into Unit 1 was ready to be resumed upon the refilling of the backwash valve pit, but all activities, including the ongoing seawater injection into the Unit 3 reactor, had to stop because of an explosion in Unit 3.

1.1.3.22. Explosion in Unit 3 reactor building

At 11:01 on 14 March, an explosion occurred in the upper part of the Unit 3 RB, destroying the building structure above the service floor and injuring workers. It also damaged the hoses and fire engines around the Unit 3 backwash valve pit. The cause of the explosion was unknown to the plant staff, but a hydrogen explosion was suspected.[41]

The explosion happened about one hour after the Unit 3 backwash valve pit levels had been restored and at a time when Unit 1 seawater injection was getting ready to be restarted. It necessitated a temporary evacuation of the workers from the outside areas, and hence interrupted the injection of water into Unit 3 and further delayed the injection into Unit 1.

In addition to the destruction of the alternative water injection arrangement, the ability of containment venting in Unit 2 was also lost as a result of the explosion, which affected the previously set up Unit 2 containment venting path. After the explosion, the isolation valve on the Unit 2 vent line was discovered to be closed and could not be reopened.

1.1.3.23. Restart of seawater cooling of Unit 1 and 3 cores

The work to re-establish the seawater injection line, this time directly from the ocean, was started again after a break of two hours. After the restoration of the injection lines, seawater injection was recommenced first for Unit 3 in the afternoon of 14 March and later in the evening for Unit 1. The cores had been without cooling water injection, for nearly 5 hours in Unit 3 and for 18 hours in Unit 1.

1.1.3.24. Loss of Unit 2 core cooling

At around 13:00 on 14 March, Unit 2 became the next unit to experience loss of core cooling, with measurements showing that the reactor water level had decreased and that the reactor pressure had increased since the previous measurements. This pointed to the possible failure of the Unit 2 RCIC system, as inferred by the MCR and the ERC. As a result, a ‘loss of reactor cooling function’ emergency was declared, now for Unit 2.

After the failure of the RCIC system, it was decided to apply seawater injection through the FP system via fire engines at 13:05. However, the reactor pressure was too high for the fire engine pumps and the RPV had to be depressurized first. It seemed likely that, without water injection, the core would be uncovered very soon. It was therefore decided to use the SRVs to depressurize the reactor in order to enable water injection at low pressure, while recognizing the potential adverse impact on the confinement function since this operation would have increased the pressure and temperature in the PCV, as a result of the release of steam from the reactor into the containment.[42]

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[41] A team that was dispatched to check the status of the Unit 4 SFP at 10:30 on 14 March, just before the explosion, encountered high radiation levels, at the door of the Unit 4 RB and could not enter the building.

[42] The SC section of the PCV was already nearly filled and saturated.

After RPV depressurization through the SRVs and refuelling of the fire engines (which had meanwhile run out of fuel), seawater injection into Unit 2 through the FP system began shortly before 20:00 on 14 March, first by one fire engine, and soon thereafter by two fire engines.

1.1.3.25. Degradation of the Unit 2 confinement

At around 21:55 on 14 March, the recently restored containment atmospheric monitoring system (CAMS) — the radiation monitoring equipment inside the Unit 2 RPV — indicated that the radiation levels inside the containment had increased substantially since the previous measurements taken about eight hours earlier, prior to the CAMS going off-line: a 5000-fold increase in the DW (from 1.08 mSv/h to 5360 mSv/h) and an almost 40-fold increase in the SC (from 10.3 mSv/h to 383 mSv/h). Additionally, neutrons were detected after 21:00 on 14 March (until 01:40 on 15 March) near the main gate.[43]

Also, both the reactor and containment pressures showed an increasing trend after 22:30. The containment pressure measurement of 0.54 MPa (5.4 bar) at 22:50 exceeded the containment design pressure, prompting an emergency declaration of an ‘abnormal rise in containment pressure’ for Unit 2 in accordance with the regulations [18]. This condition was reported to the relevant government authorities at 23:39, in accordance with the Nuclear Emergency Act [19].

At the same time, the Unit 2 reactor pressure was 1.923 MPa (19.23 bar), and over the next three to four hours, more SRVs were opened to decrease the RPV pressure in order to allow water injection. As a consequence of these discharges from the RPV to the PCV through the SRVs, the containment pressure increased further while the unit operations team tasked with establishing the venting line to relieve containment pressure was unable to open the vent valves. In order to protect the confinement function and accomplish venting as soon as possible, TEPCO staff at the on-site and off-site ERCs agreed to vent directly from the DW, recognizing that this would substantially increase radioactive releases to the environment compared to venting from the SC. However, it was not possible to open the valves on the DW vent path either, and consequently, Unit 2 venting could not be accomplished.

At 04:17 on Tuesday 15 March, the relevant government agencies were notified that depressurization by venting of the Unit 2 containment and of the reactor had not been effective and that containment pressure continued to increase.

1.1.3.26. Blasts in Unit 2 and Unit 4 and site evacuation

At 06:14 on 15 March, an explosion was heard on the site, and tremors were felt in the common MCR of Units 1 and 2. This was followed by a drop in the pressure reading of the SC section of the Unit 2 containment. The staff in the MCR initially reported to the on-site ERC that the Unit 2 SC pressure had dropped to nearly atmospheric pressure, as zero bar was displayed in the MCR indicator, inferring a potential loss of the confinement function. After re-checking the readings, it was confirmed that the Unit 2 SC pressure went off the scale, but the Unit 2 DW pressure had not decreased significantly.

This information indicated a possible PCV failure and the possibility of uncontrolled releases from Unit 2. On this basis, the on-site ERC ordered all personnel in all the units to temporarily evacuate to the seismically isolated building where the on-site ERC was located.

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[43] It was explained by TEPCO that the neutrons came from the spontaneous fission of actinides that were released following core damage in one of the three reactors.

Following the events in Units 2, all personnel, except those required for monitoring and for essential emergency response, were instructed by the Site Superintendent to go to a radiologically safe location. Approximately 650 people understood this order to mean a site evacuation, and they evacuated to the Fukushima Daini NPP site. An estimated 50–70 staff[44], including the Site Superintendent, remained at the Fukushima Daiichi ERC. The relevant government agencies were informed by the on-site ERC of the evacuation at 07:00 on 15 March.

At about the same time as the event associated with the Unit 2 SC, an explosion in the upper part of the Unit 4 RB was observed by the evacuating personnel.[45]

About two hours later, at 08:25, white smoke (or steam) was observed being released from the Unit 2 RB near the fifth floor. A radiation dose rate measurement of 11.93 mSv/h was recorded at the main gate at 09:00 on 15 March, the highest measurement since the beginning of the accident. Because of the high radiation levels, an order was issued by government authorities two hours later, at 11:00, requiring all residents within a 20–30 km radius of the Fukushima Daiichi NPP to take shelter indoors.

During this sequence of events, fundamental safety functions of Units 1–3 were lost or severely degraded (Fig. 1.1–8), and efforts focused on damage assessment and the restoration and stabilization of safety functions, starting with the SFPs of those units where explosions in the RBs had occurred.

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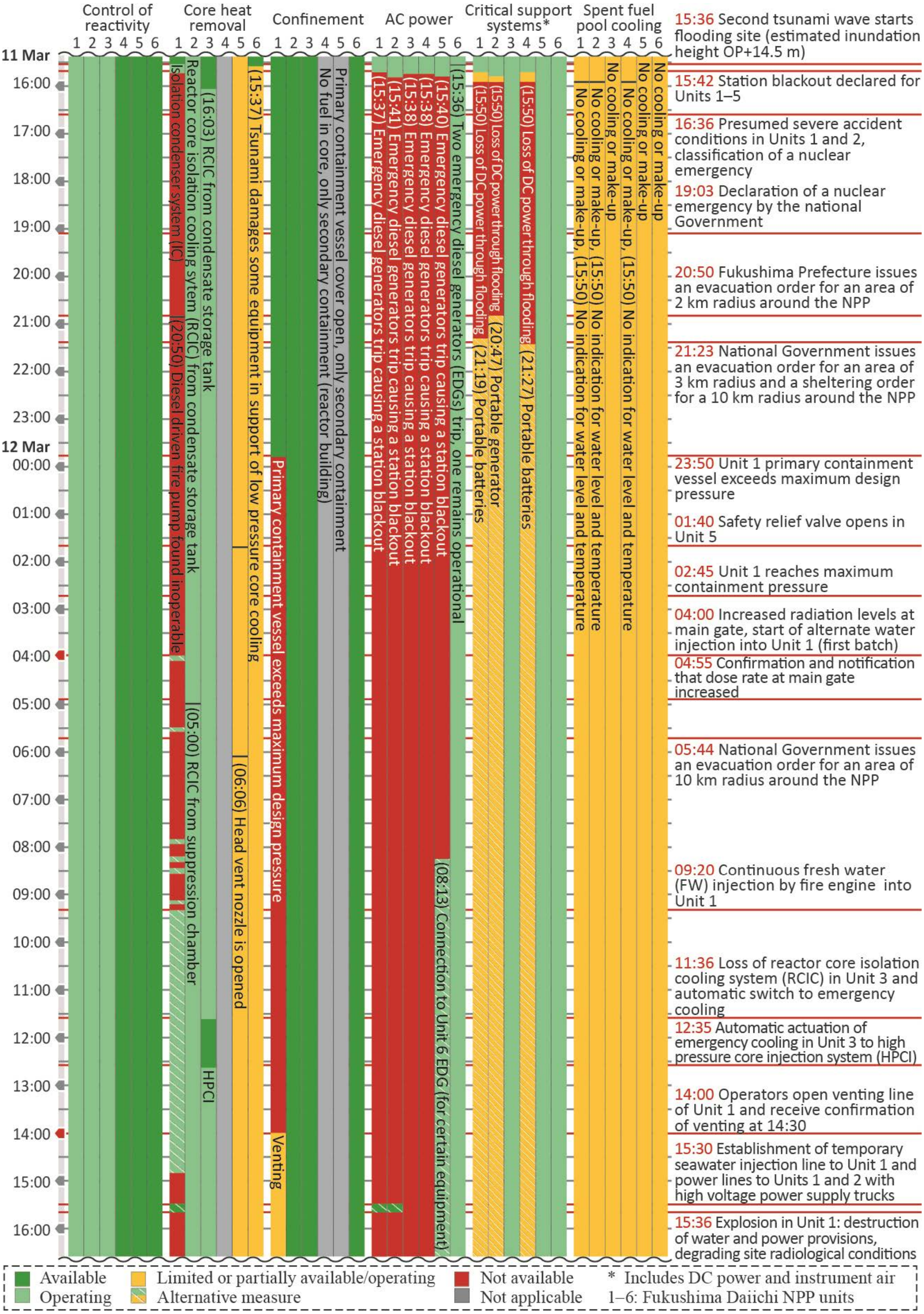
[44] As noted by different investigation reports, the exact number of staff is not certain [4, 6]. It is also noted that the staff who evacuated to the Fukushima Daini NPP started to return to the Fukushima Daiichi site later on the same day.

[45] The personnel reported the Unit 4 explosion to the ERC after they arrived at the seismically isolated building, at around 08:11.



15:36 Second tsunami wave starts flooding site (estimated inundation height OP+14.5 m)

15:42 Station blackout declared for Units 1–5

16:36 Presumed severe accident conditions in Units 1 and 2, classification of a nuclear emergency

19:03 Declaration of a nuclear emergency by the national Government

20:50 Fukushima Prefecture issues an evacuation order for an area of 2 km radius around the NPP

21:23 National Government issues an evacuation order for an area of 3 km radius and a sheltering order for a 10 km radius around the NPP

23:50 Unit 1 primary containment vessel exceeds maximum design pressure

01:40 Safety relief valve opens in Unit 5

02:45 Unit 1 reaches maximum containment pressure

04:00 Increased radiation levels at main gate, start of alternate water injection into Unit 1 (first batch)

04:55 Confirmation and notification that dose rate at main gate increased

05:44 National Government issues an evacuation order for an area of 10 km radius around the NPP

09:20 Continuous fresh water (FW) injection by fire engine into Unit 1

11:36 Loss of reactor core isolation cooling system (RCIC) in Unit 3 and automatic switch to emergency cooling

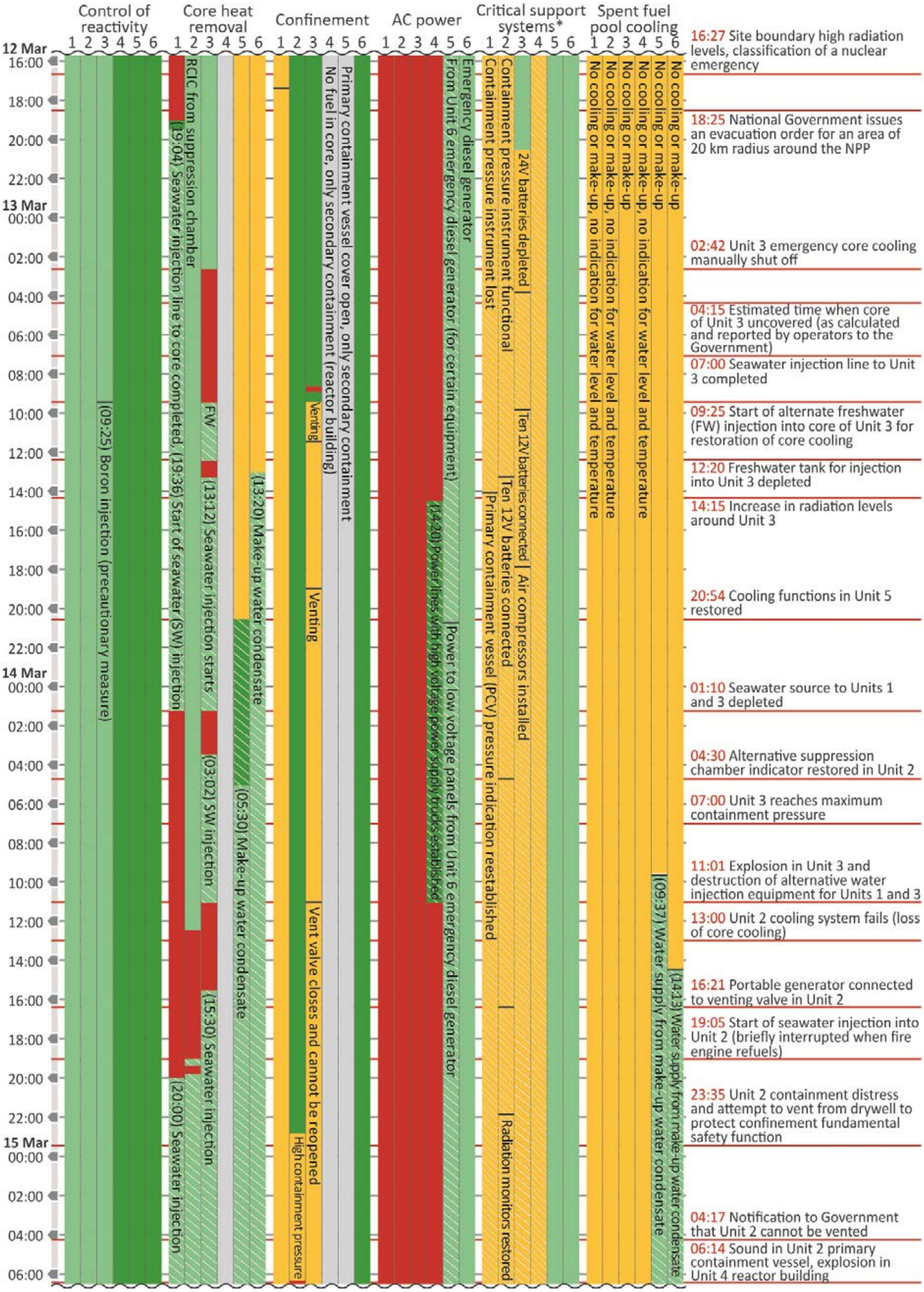
12:35 Automatic actuation of emergency cooling in Unit 3 to high pressure core injection system (HPCI)

14:00 Operators open venting line of Unit 1 and receive confirmation of venting at 14:30

15:30 Establishment of temporary seawater injection line to Unit 1 and power lines to Units 1 and 2 with high voltage power supply trucks

15:36 Explosion in Unit 1: destruction of water and power provisions, degrading site radiological conditions

FIG. 1.1–8. Fundamental and supporting safety functions in the accident response at the Fukushima Daiichi NPP (11-15 March 2011).



16:27 Site boundary high radiation levels, classification of a nuclear emergency

18:25 National Government issues an evacuation order for an area of 20 km radius around the NPP

02:42 Unit 3 emergency core cooling manually shut off

04:15 Estimated time when core of Unit 3 uncovered (as calculated and reported by operators to the Government)

07:00 Seawater injection line to Unit 3 completed

09:25 Start of alternate freshwater (FW) injection into core of Unit 3 for restoration of core cooling

12:20 Freshwater tank for injection into Unit 3 depleted

14:15 Increase in radiation levels around Unit 3

20:54 Cooling functions in Unit 5 restored

01:10 Seawater source to Units 1 and 3 depleted

04:30 Alternative suppression chamber indicator restored in Unit 2

07:00 Unit 3 reaches maximum containment pressure

11:01 Explosion in Unit 3 and destruction of alternative water injection equipment for Units 1 and 3

13:00 Unit 2 cooling system fails (loss of core cooling)

16:21 Portable generator connected to venting valve in Unit 2

19:05 Start of seawater injection into Unit 2 (briefly interrupted when fire engine refuels)

23:35 Unit 2 containment distress and attempt to vent from drywell to protect confinement fundamental safety function

04:17 Notification to Government that Unit 2 cannot be vented

06:14 Sound in Unit 2 primary containment vessel, explosion in Unit 4 reactor building

FIG. 1.1–8. Fundamental and supporting safety functions in the accident response at the Fukushima Daiichi NPP (11–15 March 2011) (cont.).

1.1.4. Stabilization

1.1.4.1. Replenishment of the spent fuel pools of Units 3 and 4

In order to perform an assessment of the reported Unit 4 fire, and to confirm the integrity of the SFP, a team attempted to enter the Unit 4 RB between 10:30 and 11:00 on 15 March, just over four hours after the explosion. The team encountered high radiation levels, in excess of 1000 mSv/h (the dosimeters hit the maximum scale of 1000 mSv/h).

A remote visual inspection from a helicopter to address concerns about the status of the Unit 3 and 4 SFPs was conducted in the afternoon of Wednesday 16 March. The inspection confirmed that there was sufficient water in the Unit 4 SFP to cover the fuel assemblies; however, observations were not conclusive for Unit 3's SFP, making its replenishment a high priority.

The first supply of water to the Unit 3 SFP was accomplished on the next day, 17 March, between 09:30 and 10:00, when helicopters dropped approximately 30 t of sea water on the Unit 3 RB. Freshwater was sprayed onto the Unit 3 SFP later on the same day, in five missions between 19:05 and 20:07, by the high pressure water cannon trucks from the Tokyo Metropolitan Police Department (44 t) and the fire engines of the SDF (30 t).

Seawater or freshwater spray into the Unit 4 SFP started on 20 March.[46] Later, on 22 March, a concrete pump truck with a boom was utilized for spraying the SFPs.

Spraying into the SFPs using water cannon and fire engine trucks or concrete pump vehicles continued intermittently in March to ensure that the spent fuel was not exposed. The fuel pool cooling (FPC) system — an SFP cooling and cleanup system — was also utilized in April and well into May 2011.

1.1.4.2. Restoration of power

In Unit 6, power was restored to the cooling system of the second, water cooled, EDG by connecting a power line to the operating air cooled EDG. The water cooled EDG started to operate again at 04:22 on 19 March, supplying AC power to Units 5 and 6.

Between 17 and 20 March, work was carried out on laying temporary power cables to Units 1 and 2, and, on 20 March, an auxiliary transformer was connected to the external grid. At 15:46 on Sunday 20 March, almost exactly nine days after the SBO, off-site power was restored to Units 1 and 2 through this temporary AC power system, ending the SBO in Units 1 and 2.

Lighting was restored in the MCR of Units 3 and 4 at 10:45 on 22 March, while the lighting for the MCR of Units 1 and 2 was re-established two days later, on 24 March.

The SBO at Units 3 and 4 ended, after more than 14 days, when temporary off-site power to these two units was restored on 26 March 2011.

Also during 23–25 March 2011, the water injection to the reactors was switched from sea water to borated fresh water. On 26 March, the fire pump was replaced by a stationary motor driven pump. On 3 April, the power supply to the pumps providing water to Units 1–3 was switched to off-site power.

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[46] The same approach was followed for adding water to the SFP of Unit 1 later. Since the Unit 2 RB was still covering the Unit 2 SFP, the spray method could not be used for Unit 2.

1.1.4.3. Achieving safe or stable conditions

Unit 5 was the first unit to reach cold shutdown mode. Its shutdown heat removal system was put into service as the RHR system was aligned to the shutdown cooling (SHC) operation at 12:25 on 20 March. The reactor temperature decreased to below 100°C in approximately two hours, placing Unit 5 in the cold shutdown mode at 14:30 on 20 March 2011, nearly nine days after the earthquake.

The normal residual heat removal system of Unit 6 was put back in service, in a manner similar to that at Unit 5, at 18:48 on the same day. The reactor temperature decreased to below 100°C in less than one hour, placing Unit 6 in the cold shutdown mode at 19:27 on 20 March (Fig. 1.1–9).

For Units 1–3, TEPCO issued an action plan on 17 April 2011, the Roadmap towards Restoration from the Accident at Fukushima Daiichi Nuclear Power Station [23]. The roadmap included measures to be taken for: the establishment of stable cooling of the reactors and spent fuel; reduction and monitoring of radioactive releases; control of hydrogen accumulation; and prevention of return to criticality. These actions were implemented in the nine months following the accident.

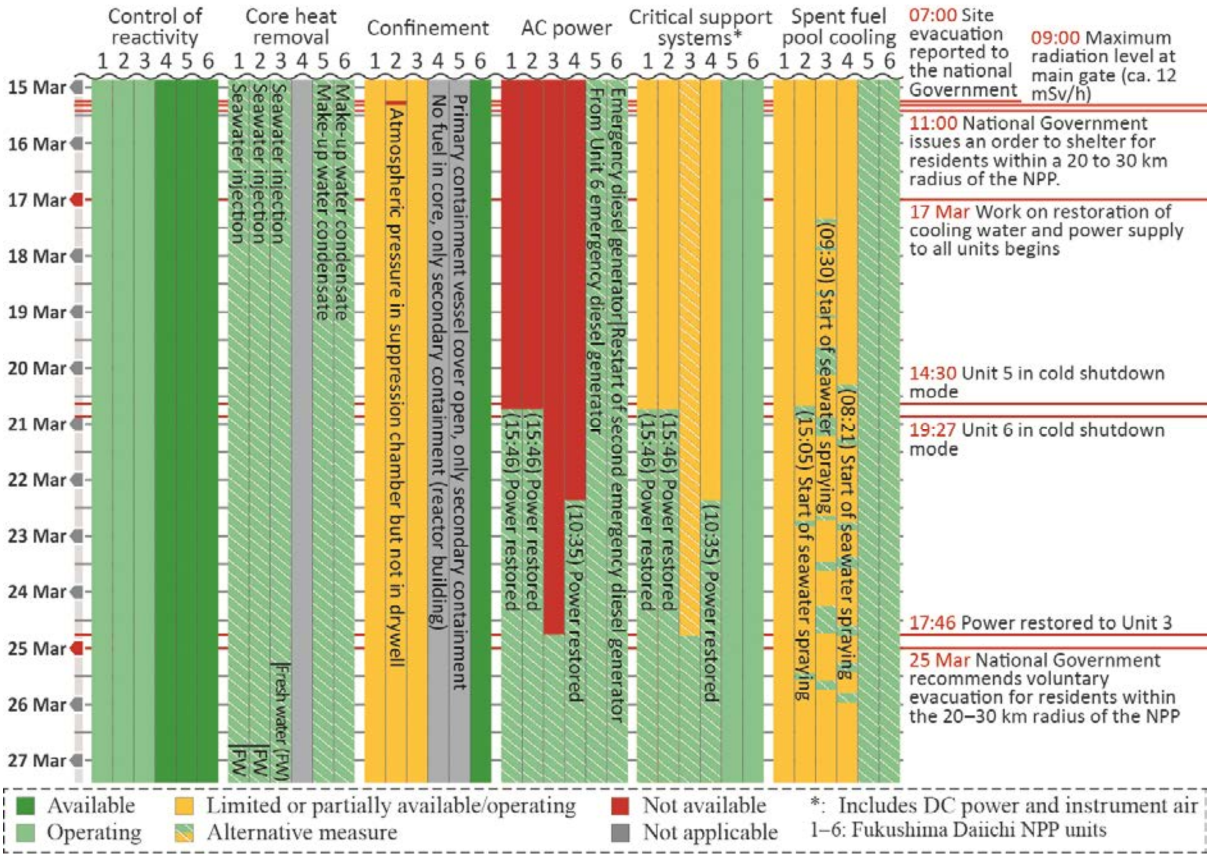

FIG. 1.1–9. Temporary restoration of fundamental safety functions at the Fukushima Daiichi NPP.

The roadmap established two conditions that would define the end of the accident state, or 'cold shutdown state'[47]: achievement of significant suppression of radiological releases and steady decline

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[47] The term 'cold shutdown state' was defined by the Government of Japan at the time specifically for the Fukushima Daiichi reactors. Its definition differs from the terminology used by the IAEA and others.

of radiation dose rates; and achievement of target values for certain plant parameters as prescribed in the roadmap. The Government and TEPCO (through the Government–TEPCO Integrated Response Office[48]) announced on 19 July that the first condition had been achieved in Units 1–3, and on 16 December 2011, that the second condition had also been achieved for these units. This announcement brought the 'accident' phase of events at the Fukushima Daiichi NPP to a close, according to the criteria set by the Government of Japan at the time.

However, some unstable plant conditions continued, such as fluctuations in temperatures, which were explained as being caused by instrumentation failures, or fluctuations in the measurement of fission products. More stable plant parameters were achieved between March and April 2012, while post-accident management efforts continued. Additionally, challenges in the management of waste, such as difficulties in dealing with the accumulation of radioactively contaminated water due to groundwater ingress to the buildings and occasional failures of equipment, continued. At the time of writing, the Government of Japan considered the Fukushima Daiichi NPP a 'specified facility as an accident site'[49].

1.2. CONTEXT WITHIN WHICH THE ACCIDENT OCCURRED

This section provides an overview of the status of the Japanese nuclear energy generation and the involvement of the various stakeholders, including legislators, governments, regulators, owners, operators, industry associations and suppliers. The description in this section details the structure and status of the relevant entities as well as the laws and regulations that shaped the nuclear energy strategy, the decision making process in the formulation of licensing arrangements, and the oversight and assurance procedures in Japan in or before March 2011.

After providing a general view of the structure and the interfaces of the Japanese nuclear industry's owners and operators, who had established a system that was aimed at the safe and economic generation of nuclear energy, information is presented on the development of the legal and regulatory framework and, in chronological order, the establishment of key laws, regulations and their associated entities.

The structures and roles of those entities that influenced the legislative, regulatory, and industrial environment in which the design, licensing, construction, operation and modification of the Fukushima Daiichi NPP occurred are analysed and evaluated in greater detail in Technical Volume 2 in the assessment of relevant factors.

1.2.1. Nuclear industry structure

1.2.1.1. Nuclear power in Japan

Nuclear power generation has been an important energy source in Japan for decades. In response to the oil crisis of the 1970s, the Government of Japan implemented a policy of reducing dependency on imported oil by encouraging energy efficiency and the diversification of power sources supplied by privately owned independent regional electric power companies. As a result of this government

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[48] On 6 May 2011, the Integrated Countermeasures Headquarters for the Fukushima Nuclear Power Plant Accident, which had been established on 15 March 2011 by the Prime Minister's Office, was reformed into the Government–TEPCO Integrated Response Office under the Nuclear Emergency Response Headquarters (NERHQ) of the Japanese Government.

[49] In accordance with the definition of 'specified nuclear facility', i.e. a facility that would require special measures for safety or physical protection of specified nuclear material, established by the regulatory body, the Nuclear Regulation Authority (NRA), on 7 November 2012.

policy, the contribution of nuclear power to the overall Japanese energy supply grew significantly until the time of the accident at the Fukushima Daiichi NPP. In 1973, the nuclear power generation was just 9.7 TWh, and its share in total commercial power generation was just 3%. Growth in nuclear power generation accelerated in the 1990s, backed by government policy and the efforts of the power companies, and reached a historical high of 332.2 TWh in 1998. During the mid-2000s, nuclear power generation decreased because of the impacts of the extended periods of shutdown of a number of NPPs following the Niigata-Chuetsu-Oki earthquake in 2007. Even so, nuclear power generation in 2010 was 288.2 TWh, accounting for 29% of the total power generation in Japan. In the year before the accident, nuclear power had the largest share in total power generation in Japan, slightly more than natural gas fired power generation. These two sources of energy were followed by coal (25%), hydro (9%) and oil (6%).

By March 2011, 54 nuclear power reactors were operating in Japan, producing a licensed total output of 49 GW. Thirty of those 54 reactors included boiling water reactor (BWR) technology. Three additional nuclear power reactors were under construction, and three were being decommissioned in the spring of 2011. The location of the NPPs in Japan is shown in Fig. 1.2–1. To support the operation of the NPPs, Japan also developed a full spectrum of fuel cycle activities, comprising enrichment, conversion, fuel fabrication, reprocessing and radioactive waste management.

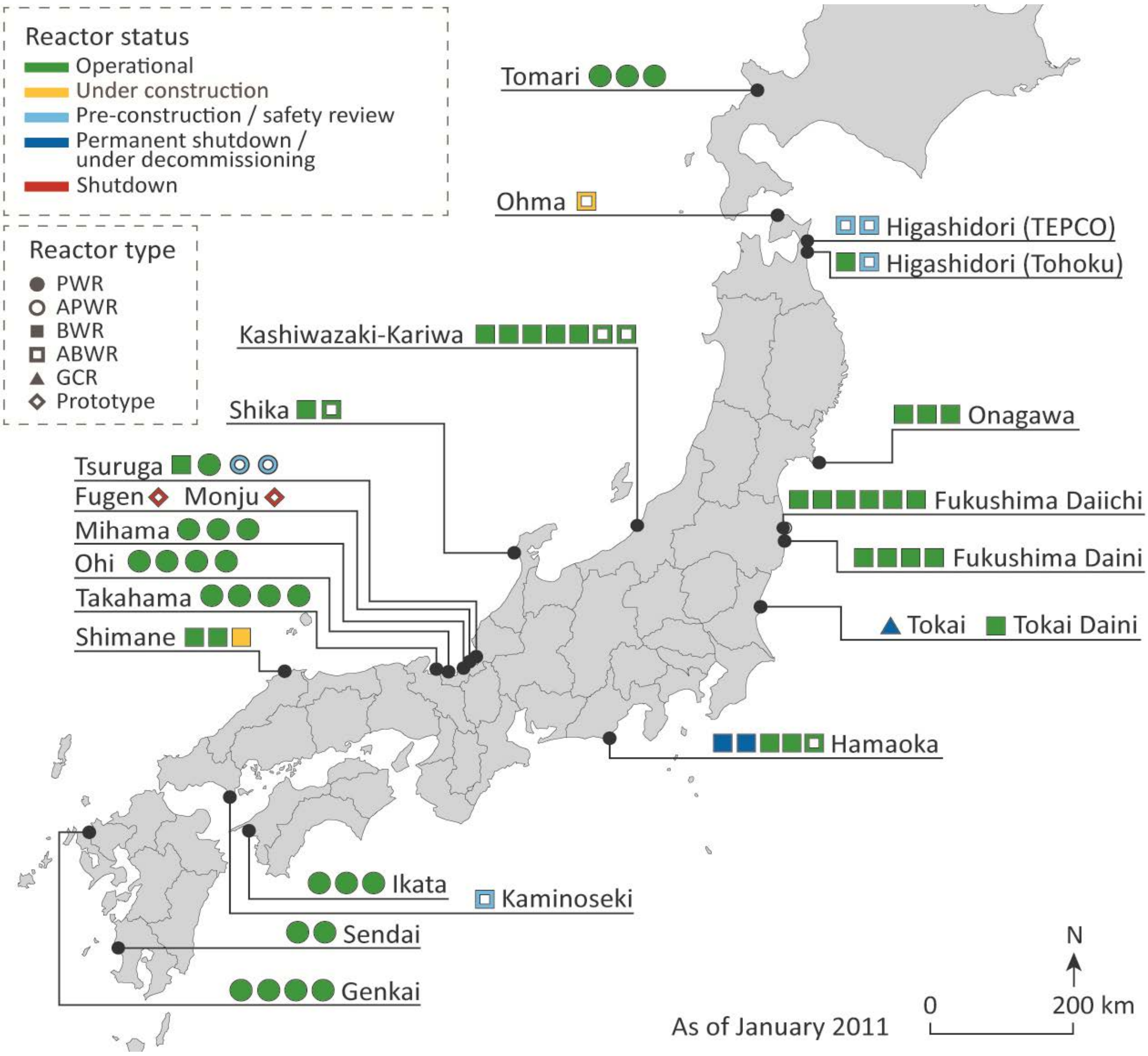

FIG. 1.2–1. Location of the NPPs in Japan [24].

The introduction of BWRs in Japan began with the construction, by the Japan Atomic Energy Research Institute (JAERI), of the Japan Power Demonstration Reactor, which ran from 1963 to 1976. Its construction and operation provided experience for the introduction of commercial light water reactors (LWRs) at the next stage. The first commercial BWR was constructed by the Japan Atomic Power Company (JAPC) in Tsuruga and started operation in March 1970.

Following the construction of the BWR in Tsuruga, TEPCO started to construct the first unit of the Fukushima Daiichi NPP in 1967. Both JAPC's Tsuruga and TEPCO's Fukushima Daiichi Unit 1 were imported under a turnkey contract with General Electric (GE). The necessary technology was transferred to the Japanese reactor vendors Toshiba and Hitachi under a system licence contract. After that, Units 2–5 of the Fukushima Daiichi NPP (designed as 780 MW(e) with a BWR/4 type) and Unit 6 (the first unit of 1100 MW(e) design in TEPCO) were also constructed under turnkey contracts with GE, GE/Toshiba, Hitachi or Toshiba. In parallel with Fukushima Daiichi Unit 6, Tokai Daini of JAPC was also constructed under contract with GE.

From the second half of the 1990s, there was a slowing down in the development of technology, and factors such as 'strong demands to reduce construction cost' and 'design changes based on external requests', in addition to 'project delays due to a protracted licensing and approval process' created an environment in which there was no additional technological consideration for further improvements in the reviewed and approved designs as they were confirmed to be safe and it was believed that the safety level was well established [25]. However, certain measures, which resulted from learning from significant events and became regulatory requirements, were implemented. Examples of these design improvements by TEPCO under regulatory guidance included changing the structure of the RB to incorporate lessons learned from the Niigata-Chuetsu-Oki earthquake and changing the design of the Higashidori NPP to improve the seismic tolerance above and beyond the previously reviewed and approved levels.

Efforts, such as the construction of a concentrated environment facility, i.e. seismically isolated building, the core shroud replacement, the augmentation of EDGs and the expansion of the SFP, were implemented mainly at the Fukushima Daiichi NPP. With the exception of the core shroud replacement[50], these were single-item work projects. Efforts to address technical research issues included: the introduction of mixed oxide (MOX) fuel (first introduced at Fukushima Daiichi NPP Unit 3 in 2010); the introduction of new designs with 1100+ MW(e) power (first operation at Kashiwazaki-Kariwa NPP Units 2 and 5 in May 2002); and long cycle operation (not yet introduced but intended for introduction at the Fukushima Daini NPP) [26].

1.2.1.2. Research and development organizations and institutions

In promoting the research and development (R&D) of the nuclear energy industry, the Government played a leading role in implementing projects that required long term commitments, specifically those aimed at identifying and commercializing potential capabilities of nuclear power as an energy option in the years ahead. Initially, the Japan Atomic Energy Commission (JAEC), as the most important Japanese nuclear energy policy making organ, provided advice on R&D policies, such as nuclear energy policy and development of new generation power reactors and fuel cycle facilities. These efforts were succeeded by the Framework for Nuclear Energy Policy (FNEP), which was first authorized by the Government in 2005.

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[50] The world's first such project was completed at the Fukushima Daiichi NPP Unit 3 in 1998, and later performed at Units 2, 5 and finally Unit 1.

All Japanese utilities participated in R&D planning and funding of the Steering Committee of the Federation of Electric Power Companies (FEPC), and these R&D decisions were carried out as joint research among utilities and reactor technology vendors. The joint R&D by utilities and vendors was not limited to existing LWRs. They explored next generation LWRs, fast breeder reactors (FBRs), fuel cycle technology (reprocessing and uranium enrichment) and radioactive waste treatment. The amount of non-governmental R&D funding decreased in the late 1990s and early 2000s. In the late 2000s, this trend was reversed; however, the additional funds were applied mainly to improve the performance and enhancement of safety, in which only limited funds were allocated to severe accident R&D activities.

1.2.1.3. Industry codes, standards and collaboration

In Japan, four standard development organizations are working to develop the industry codes and standards focusing on their specific areas as follows:

- The Japan Society of Mechanical Engineers (JSME) mainly focuses on the areas related to structural integrity of components. Publications of the JSME include design and construction codes (published in 2001, and revised in 2005) for design and manufacturing of components, and fitness-for-service codes for in-service-inspection of components.
- The Atomic Energy Society of Japan (AESJ) addresses topics related to nuclear safety, including probabilistic risk analyses, plant life management and radioactive waste treatment.
- The Japan Electric Association (JEA) develops codes and standards related to quality assurance in plant operation, inspection and evaluation of integrity, including the seismic design rule.
- The Thermal and Nuclear Power Engineering Society (TENPES) creates guidelines and standards related to application of thermal and nuclear power generating technologies, including topics such as environmental fatigue.

In July 2002, a committee of the regulatory body, the Nuclear and Industrial Safety Agency (NISA), published a report concerning industry codes and standards. In that report, the committee recommended that the regulation should be changed to a 'performance base rule' and that 'voluntary consensus standards' should be applied as the acceptable approaches after endorsement by the regulatory body. This recommendation was intended to shorten the time between the discovery of new knowledge, or the development of new technologies, and their implementation in the NPPs.

Following this recommendation, NISA revised the regulation, namely Ordinance No. 62, which became effective in January 2006, and started the technical review mechanism for endorsement of industry codes and standards after review by its technical support organization. Responding to the new regulation, industrial and academic bodies developing industrial codes and standards modified their codes and standards review processes. They also improved the transparency of their review process and the balance of participating members.

1.2.1.4. Industry cooperation

Japan Nuclear Technology Institute (JANTI)

The Japan Nuclear Technology Institute (JANTI) was established in March 2005 as an initiative of the industry with the aim of supporting the voluntary safety improvement activities towards 'excellence in performance'. The charter of JANTI[51] was similar to those of other national and international industry self-regulating initiatives, such as the World Association of Nuclear Operators (WANO) or the Institute

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[51] The Japan Nuclear Technology Institute (JANTI) was renamed and reorganized after the accident to Japan Nuclear Safety Institute (JANSI), with a revised charter to incorporate lessons learned from the Fukushima Daiichi accident.

of Nuclear Power Operations (INPO). JANTI's members included not only utilities but also vendors, component suppliers, fuel manufacturers, reprocessing and waste disposal facilities and construction companies.

JANTI's Operating Experience Analysis Division assumed and developed activities related to the collection, analysis and application of operating experience information that was previously handled by the Nuclear Information Center of the Central Research Institute of the Electric Power Industry (CRIEPI). Specifically, it conducted activities focused on providing recommendations, information for operation management and equipment maintenance activities, and support for the safety improvements of the utilities, based on information analysis results. Also, the division supported the safety activities of the utilities with regard to quality assurance and root cause analysis promotion and dissemination activities.

Japanese BWR Owners' Group (JBOG)

Since the introduction of BWRs in Japan in 1967, the utilities and vendors have cooperated, and this cooperation was formalized in 2006 with the establishment of the Japanese BWR Owners' Group (JBOG). JBOG's purpose is to enhance nuclear safety and plant reliability based on operating experiences and the examination of technical issues in the BWR technology. It also provides support in resolving common issues concerning BWR operation and design by cooperation.

JBOG is a private organization of seven utilities that operate BWRs: TEPCO, Tohoku, Tokyo, Chubu, Hokuriku, Chugoku and JAPC. Two BWR vendors, J-Power and Toshiba/Hitachi, are also members of JBOG.

Federation of Electric Power Companies (FEPC)

In 1952, nine electric power companies, including TEPCO, established the Federation of Electric Power Companies (FEPC) to promote efficient operations within the industry. Since then, FEPC has played a role as a base for close communication between the electric power companies and a forum for exchanging views on creating the electric power industry of the future. FEPC also undertakes various activities to ensure stable operations of the electric power industry.

1.2.1.5. International cooperation

Cooperation with the IAEA

Japanese NPP operating organizations have also solicited cooperation with the IAEA in the enhancement of safety and reliability, specifically by receiving the IAEA's Operational Safety Review Team (OSART) services through the invitation of the Government of Japan. Since the creation of OSART services in 1982, five OSART missions have been requested by the Government to be carried out in Japanese NPPs (TEPCO invited two missions), as listed in Table 1.2–1. The Fukushima Daiichi NPP has never been reviewed by an OSART mission.

TABLE 1.2–1. IAEA OSART MISSIONS TO JAPAN

Mission site	Mission date
Mihama	January 2009
Kashiwazaki-Kariwa	November 2004
Hamaoka	February 1995
Fukushima Daini	March 1992
Takahama	January 1988

Cooperation with the OECD/NEA

Japan is a member of the Organisation for Economic Co-operation and Development (OECD) and its specialized organization, the Nuclear Energy Agency (NEA). In this inter-governmental cooperation framework, Japanese owners/operators have participated in various activities representing Japan, such as the Task Group on Defense in Depth of Electrical Systems and Grid Interaction, the Working Group on Analysis and Management of Accidents, the Working Group on Risk Assessment, and the Working Group on Human and Organizational Factors; in addition, they have been members of other standing committees, ad hoc working groups and joint research projects.

Cooperation with the World Association of Nuclear Operators (WANO)

The Japanese industry cooperation with WANO started with a contribution to the founding of WANO and the establishment of its Tokyo Centre. The Japanese plants are affiliated with the WANO Tokyo regional centre. Cooperation is carried out through WANO's four main programmes: peer reviews, operating experience, technical support and exchange, and professional and technical development. Since the inception of the peer review programme in 1992, 31 peer reviews of the Japanese NPPs have been conducted. WANO peer reviews were conducted at the Fukushima Daiichi NPP in 2003 and 2009. Additionally, TEPCO was subject to a WANO corporate peer review in 2008. The main purpose of the corporate peer review is to identify areas for improvement at the corporate level in order to maximize the safety and reliability of NPPs.

1.2.1.6. Management systems

In 2003, the Japanese regulatory requirement for the establishment and implementation of a quality management system (QMS) for the installation, operation and maintenance of commercial power reactors in accordance with the JIS Q-9000 series[52] was introduced. In response to this requirement, the JEA established industry code JEAC 4111 and its associated guide JEAG 4121. This industry code and guide were based on JIS Q-9000 and adapted some of the IAEA's requirements and guidelines, including the application of graded approach, the independence of inspectors and the need for design verification by a third party.

After incidents of falsification of safety related records in 2002 (see Section 1.2.3), TEPCO implemented a series of additional programmatic countermeasures to prevent a recurrence of such events. These included the following corporate level commitments to improve corporate culture through a corporate system and climate of individual responsibility and initiative [6, 26]:

- Promoting the disclosure of information, ensuring transparency of nuclear operations and establishing an independent check of nuclear safety and quality control.
- Creating a work environment where proper operations could be carried out, strengthening functions that contributed to proper performance of job related duties.
- Strengthening internal audits, through a quality assurance/management system in the Nuclear Power Division, and building a corporate culture aimed to produce a cooperative atmosphere.
- Promoting observance of corporate ethics, with the support of education and training, and conducting internal and independent audits to keep a high degree of compliance.[53]

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[52] JIS Q-9000 is very similar to the 9000 series of the International Organization for Standardization (ISO).

[53] http://www.tepco.co.jp/en/corpinfo/overview/restor-e.html

1.2.1.7. Safety culture

The Japanese industry started activities relating to safety culture after the Chernobyl accident in 1986. After the criticality accident at the JCO facility in Tokaimura in 1999, which was Japan's worst nuclear accident at the time (see Section 1.2.3), the nuclear industry established NS-net (Nuclear Safety network). This organization included not only NPPs but also nuclear fuel manufacturing facilities and carried out peer reviews of those facilities and other activities aimed at enforcing safety culture in its member organizations. NS-net's activities included three-day peer reviews intended mainly for the review of documentation and the development of methods to analyse organizational strengths and weaknesses.

In 2007, NS-net's activities were taken over by JANTI. The peer review process was redesigned to focus on field observations, with a prolonged duration of two weeks. Reviewers from WANO and/or INPO were invited to participate in these peer reviews.

In addition, JANTI developed a method, called 'Safety Assessment', in which the strengths and weaknesses of an organization were analysed on the basis of information gained through interviews with workers.

TEPCO received a WANO corporate peer review in 2008, in which some areas for improvement were identified. Particularly, WANO pointed out that further attention needed to be given to the enhancement of safety culture attributes, while recognizing that, in the previous years, TEPCO's primary emphasis had been placed on improving transparency.

In response to the WANO review results, TEPCO established an approach to foster safety culture through seven principles. They corresponded largely to WANO's eight principles for a strong nuclear safety culture, with the exception of WANO's eighth principle ('nuclear safety undergoes constant examination') [27]. TEPCO's approach to safety culture is analysed in Technical Volume 2.

1.2.1.8. Operational experience

The Japanese nuclear industry utilizes a variety of operational experience networks, both internationally and domestically. International networks include information exchange with the IAEA, OECD/NEA, INPO, WANO, technology (BWR/PWR) Owners' Groups, vendors and research institutions for collecting and disseminating operational experience. Furthermore, licensees have individual agreements on information exchange with overseas utilities and manufacturers. Within Japan, dissemination of information and feedback is conducted by the industry's own system, mainly by JANTI. JANTI shares the information among all licensees in Japan, carrying out analyses and assessments of incidents and issuing recommendations for corrective actions to prevent recurrence. All Japanese NPPs are expected to respond to these recommendations and, in accordance with the membership agreement, inform JANTI of their solutions. JANTI and the regulatory body's technical support organization, the Japan Nuclear Energy Safety Organization (JNES)[54], had cooperated in a parallel operational experience network. For example, operating experience from the joint IAEA/NEA International Reporting System for Operating Experience (IRS) to the industry was initially managed through JNES. Later, JNES provided direct access to the web based IRS, in which all licensees and JANTI have participated. JNES and the Japanese utilities also have monitored operational experience collected by the regulatory bodies of other countries with similar reactor technologies, such as the

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[54] JNES was absorbed into the new regulatory body, the NRA, after reorganization based on lessons learned from the Fukushima Daiichi accident.

United States Nuclear Regulatory Commission (NRC), including the review of NRC Bulletins and Generic Letters.

TEPCO has monitored the operating experience information that was provided through these networks and has submitted its operating experience information to JANTI's database, the Nuclear Information Archives.

Technical Volume 2 further evaluates the effectiveness of Japanese nuclear industry's learning from operational experience.

1.2.1.9. Risk management

As most of the industry, TEPCO had in place a cross-functional risk management mechanism. In 2004, the Risk Management Committee was set up to comprehensively manage all risks that could have a serious impact on the company's business management. The risk management process was defined in three steps:

- Factors that hamper management and business goals were identified and a risk management table was prepared (recognition).
- A risk map was drawn up taking into account the level of impact and probability of each risk, setting the priority of further responses (evaluation).
- A response strategy was defined according to the evaluation (response).

The nuclear risk management meetings collected information on how risk management was handled at relevant departments in TEPCO and conducted verification and assessment from multiple perspectives.

In October 2010, at the last meeting before the accident, the Risk Management Committee assessed earthquakes and tsunamis as critical risks. The following risks, in particular, were noted: earthquake beyond design basis giving rise to seismic ground motion that causes difficulties with power supply due to long-term shutdown of multiple plants [6]. Tsunamis were also identified as having the potential for high impacts associated with receding tides and due to beyond design basis tsunamis.

More specifically, earthquakes were identified as a high impact risk with a medium possibility of occurrence, while tsunamis were identified as a high impact risk with a low probability of occurrence. In a follow-up, TEPCO concluded that this new knowledge had not yet been firmly established and that there was no proven adverse impact on the safety of nuclear power plants.

1.2.1.10. Knowledge management

Knowledge management at TEPCO, as in many other organizations, has been centred on collecting knowledge and placing it in shared media [28]. TEPCO's approach consisted of integrating knowledge management in its internal organizations through sharing of information, especially on non-conformances and operating experiences. This information was analysed to identify issues, such as operational risks, review the effectiveness of preventive maintenance, assess human performance strengths and weaknesses and supply evaluation reports to the TEPCO personnel concerned. For example, the 'just-in-time caution reports' to operating personnel were designed to supply the operators with timely and concise summaries of past operation experience, and were considered in procedure revisions and pre-job briefings. Similarly, TEPCO's plant technical support (i.e. engineering) teams stored key technical issues in the 'engineering notebooks' that were helpful to support and maintenance organizations, as these notebooks contained such information as important operating experience, engineering bases and tips for improvement of tasks.

1.2.2. Governmental, legal and regulatory framework of nuclear safety prior to the accident

From the initiation of nuclear power in Japan to the Fukushima Daiichi accident, three distinctive stages can be observed with respect to the adoption of legislative and regulatory rules, as well as the structures of governmental and public organizations for nuclear policy and regulations [24]. These three distinctive periods, marked by significant nuclear safety events, resulted in the review and revision and restructuring of the Japanese nuclear framework [29]:

- The first period (1955–1978) started with the launch of the Japanese nuclear energy programme and the enactment of nuclear laws. It covered the period until the radiation incident involving the nuclear powered ship 'Mutsu' in September 1974, which raised concern about the adequacy of the Japanese nuclear safety framework. The Fukushima Daiichi NPP, one of the earliest nuclear facilities in Japan, was licensed, constructed and put in operation during this first period of the governmental and regulatory framework [24].[55]
- The second period (1978–1999) started with the amendment of laws and organizational restructuring as a result of the findings of the 'Mutsu' incident by the Committee on Atomic Energy Administration, which had been commissioned by the Government as a result of public concern about the adequacy of the Japanese nuclear safety framework after the incident [29]. The results of this committee's review introduced a fundamental change in the regulatory framework and changes among the structures of the regulatory organization, including the creation of an independent entity, the Nuclear Safety Commission (NSC) [30].
- During the 1980s and 1990s, the regulatory enhancements reflected the lessons learned from the Three Mile Island accident in 1979 and the Chernobyl accident in 1986, including the review of requirements and enhancements of emergency and severe accident management. In 1986, a long term plan was established to meet energy requirements and security which included a programme for reinforcing nuclear safety enhancements through 2030 [24].
- The end of this period was marked by the JCO's Tokaimura criticality accident, which occurred in September 1999. The accident was at that time Japan's worst nuclear accident, which was classified as a Level 4 event on the IAEA's International Nuclear and Radiological Event Scale (INES) [31]. It resulted in two fatalities of workers from radiation exposure in addition to exposing hundreds of other workers and members of the public to radiation [32, 33, 34].
- The third period (1999–2011) started with the amendment of laws and organizational restructuring as a result of the lessons learned from the JCO's Tokaimura criticality accident and ended with the Fukushima Daiichi accident. The investigation committee looking into the JCO's Tokaimura criticality accident recommended in 2000, among other things, that the capacity and independence of the regulatory body be strengthened and that the regulatory standards and guidelines on the oversight of compliance be improved [33, 34]. These recommendations introduced another fundamental change in the regulatory framework and lead to modifications in the licensing of NPPs, the separation among the ministries of the supervision of research and power generation and changes among the regulatory organizations. Also in this period, the Nuclear Emergency Act was enacted and the regulatory guide on the technical aspects of nuclear emergency was revised [35].

The changes to the legislative and regulatory framework, as well as the revisions of the organizational structures and processes in each of these three periods, are discussed in detail in the following sections.

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[55] Unit 6 started operation in 1979; however, it was licensed and can be considered under the regulations of this period.

1.2.2.1. Nuclear laws and regulations

In 1955, the Government of Japan established a legal framework for nuclear safety. The main laws applying to different aspect of the nuclear structure are expanded on in subordinate laws, cabinet orders (i.e. regulations), ministerial ordinances and statutes (i.e. rules), and ministerial public notices (i.e. notifications). The main structure of the legal framework is illustrated in Fig. 1.2–2 [36]. The effectiveness of the framework is assessed in Technical Volume 2. The following key aspects of the main laws and their evolution are of particular relevance to the Fukushima Daiichi accident.

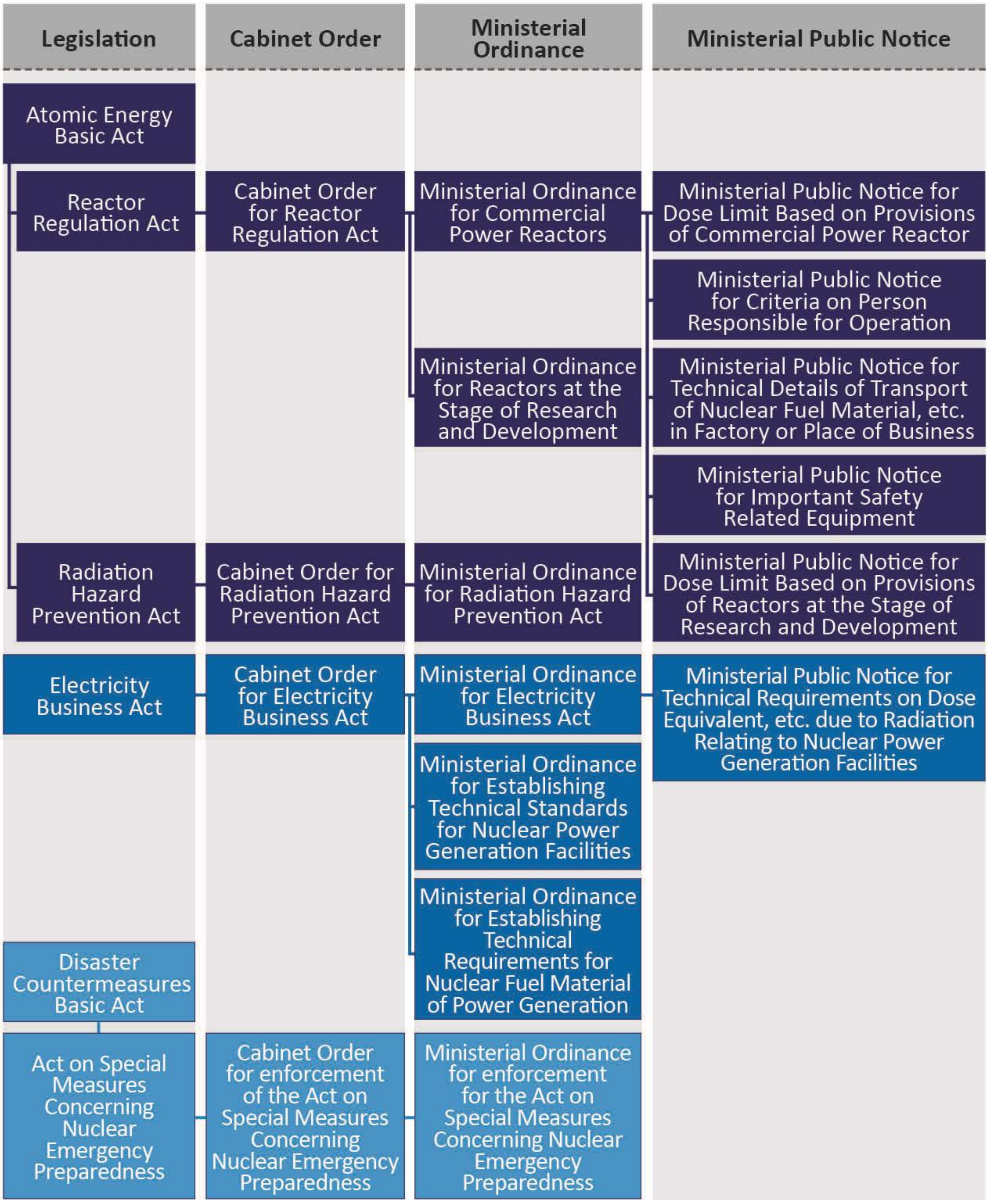

FIG. 1.2–2. Major legislation governing the safety regulation of nuclear installations [36].

The **Atomic Energy Basic Act**[56], first enacted in December 1955 (hereafter referred to as the Basic Act), is the foundation of the Japanese legal framework for nuclear energy. Its objectives are the security of energy resources, the promotion of research and development and the use of nuclear energy for peaceful purposes. The Basic Act establishes the framework for the regulation of nuclear activities. Its provisions deal with the mining of nuclear source materials, control over nuclear fuel materials, control over nuclear reactors, protection from radiation hazards, and compensation for damage caused by nuclear activities.[57] These broad provisions provide the state with the flexibility to exercise regulatory powers in these areas by means of subordinate legislation [33]. The Basic Act has two major subordinate laws, the Act on the Regulation of Nuclear Source Material, Nuclear Fuel Material and Reactors, which applies to the installation and operation of nuclear reactors, and the Law Concerning Prevention from Radiation Hazards due to Radio-Isotopes, etc. (Radiation Hazard Prevention Law), which applies to the use, sale, lease and disposal of contaminated material.

Act on the Regulation of Nuclear Source Material, Nuclear Fuel Material and Reactors[58] (hereafter referred to as the Reactor Regulation Act) regulates the utilization of nuclear source material, nuclear fuel material and reactors, i.e. the refining, fabricating and enrichment, storage, reprocessing and disposal of nuclear materials, and the installation and operation of nuclear reactors. The Reactor Regulation Act requires these activities to be limited to peaceful purposes, to be carried out in a planned manner and to ensure the safety of the public by preventing hazards and by providing for the physical protection of nuclear fuel material, in accordance with the Basic Act.

The Reactor Regulation Act specifies the processes of licensing and safety regulation in the construction and operation of nuclear facilities, including requirements for an establishment licence, approval of design and construction methods, pre-service inspection, facility periodic inspection, approval of an operational safety programme, operational safety inspection and decommissioning. It also defines violations and penalties, which consist of administrative measures such as the suspension or revocation of a licence, as well as criminal punishment, including imprisonment and fines.

Commercial nuclear power reactors are exempt from certain provisions of the Reactor Regulation Act. These exemptions relate to the approval of design and construction methods, pre-service inspection, welding methods, and inspection. These activities are subject to the 'Electricity Utilities Industry Law' (see below) [37].

Two of the ministerial ordinances issued under the Reactor Regulation Act directly apply to commercial nuclear power reactors:

— Ministerial Ordinance on Rules for the Installation, Operation, etc. of Commercial Nuclear Power Reactors (Ministerial Ordinance for Commercial Power Reactors). This ordinance implements the provisions of the Reactor Regulation Act and provides rules which apply to the majority of nuclear power plants in Japan.
— Ministerial Public Notice for Radiation Exposure Dose Limits. This ordinance mainly specifies the radiation exposure limits of workers and the radioactivity concentration limits.

The Reactor Regulation Act has been amended on several occasions following accidents and incidents that have occurred in Japan [38]:

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[56] Act No. 186 of 19 December 1955; last amendment: Act No. 155 of 3 December 2004.

[57] At the time of the nuclear accident, Japan was not Party to any of the conventions on civil liability for nuclear damage [1] containing the basic principles on nuclear liability. Japan ratified the Convention on Supplementary Compensation for Nuclear Damage (CSC) on 15 January 2015.

[58] Law No. 166 of 1957, as last amended by Act No. 84 of 2007.

- Following JCO's Tokaimura criticality accident in September 1999, the Reactor Regulation Act was amended in 2000 to strengthen the nuclear safety requirements for the management, operation and inspection of nuclear power facilities and nuclear processing plants. The new amendment required regular review of the management and operational programmes of nuclear facilities. It also modified the licensing process for nuclear facilities and provided for the appointment of regulatory inspectors for safety management [39]. Furthermore, the amendment introduced the protection of employees who reported violations from being subject to discrimination.
- In response to falsification of safety records by TEPCO in 2002, the law was amended to require a quality assurance programme to be included in the licensees' operational safety programmes, and it required the programme's regulatory oversight [40].

Electricity Utilities Industry Law[59] (hereafter referred as the Electricity Business Act) is the legislation "to protect the interests of electricity users and to achieve sound development of Electricity Business by realizing appropriate and reasonable management of Electricity Business and to assure public safety and to promote environmental preservation by regulating the construction, maintenance and operation of electric facilities" [37]. The Electricity Business Act regulates all electricity businesses in Japan, including construction, maintenance and operation of nuclear power plants.

The ordinances related to the Electricity Business Act which apply to power generation facilities, including nuclear installations, are:

- Ministerial Ordinance for the Enforcement of the Electricity Business Act. It sets out the enforcement powers of the Minister of METI to require an electrical utility to submit reports on matters related to safety in the construction, maintenance and operation of facilities used for an electricity business.
- Ordinance Establishing Technical Standards for Electrical Equipment. It sets out the rules and standards applied to the approval of construction plans, pre-service inspection and periodic inspection of electricity generation facilities including, but not limited to, nuclear power plants.
- Ministerial Ordinance of Establishing Technical Standards on Nuclear Fuel Material for Power Generation. It sets the technical standards that apply to the approval of nuclear fuel assembly design and fuel assembly inspection.
- Ministerial Public Notice for Technical Standards on Dose Equivalent, etc. due to Radiation Relating to Nuclear Power Generation Facilities. It specifies details of doses provided in the Ordinance of Establishing Technical Standards for Nuclear Power Generation Facilities.

In addition to the Basic Act and the Electricity Business Act, two main laws relevant to emergency situations in nuclear installations are the **Basic Act on Disaster Control Measures** (hereafter referred to as the Basic Act for Emergency Preparedness) and **Act on Special Measures Concerning Nuclear Emergency Preparedness**[60] (Nuclear Emergency Act). The latter was enacted in December 1999, following JCO's Tokaimura criticality accident [41], much later than the Basic Act for Emergency Preparedness (enacted in 1961) in order to complement the provisions for emergency response for natural disasters. The main provisions of the Nuclear Emergency Act include: requirements for nuclear operators to prepare emergency plans and set up emergency management organizations; requirements for the responsible ministers to designate off-site centres in each prefecture where nuclear installations are located; and requirements for the participation in emergency drills by the national Government, local authorities and operators [33, 38]. It also provides requirements for roles

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[59] Act No. 170 of 11 July 1964; last amendment: Act No. 87 of 2005.

[60] Last amendment: Act No. 118 of 2006.

and responsibilities in managing emergencies. Technical Volume 3 further discusses these laws for emergency measures and response.

1.2.2.2. Organization and responsibilities in the regulatory framework

The structures and roles of the governmental and regulatory organizations that are described in the nuclear laws and regulations have evolved since the enactment of the Basic Act in 1955. At the time of Fukushima Daiichi NPP licensing and construction, the structure was as set by the original laws of 1955. At the time of the Fukushima Daiichi accident, the structure had changed, mainly after major events, such as the Mutsu accident and JCO's Tokaimura criticality accident, towards enhancing regulatory effectiveness and assignment of responsibilities. These developments can be summarized chronologically as follows:

- Following the enactment of the Basic Act in 1955, the Atomic Energy Commission (AEC) was established as an independent body under the Prime Minister's Office to direct the national policy on research, development and utilization of nuclear energy. The Director General of the Science and Technology Agency (STA) was appointed as Chair of the AEC, while the STA served as the secretariat of the commission.
- The Reactor Regulation Act, enacted in 1957, gave the Prime Minister authority to approve licences for nuclear facilities. The Ministry for International Trade and Industry (MITI) was assigned responsibility for the development of nuclear power as an energy source, i.e. the promotion of nuclear energy in Japan.
- MITI was reorganized in 1966 to accommodate its increasing workload and to provide additional rules and regulations for the introduction of commercial LWRs in Japan [24]. The issuance of a construction permit for commercial nuclear power reactors required the consent of the Minister of MITI.
- Based on the findings of the Mutsu incident investigation, in 1978, the Japanese legislators amended the Basic Act and the Reactor Regulation Act and established the NSC [30]. The NSC was created as an advisory body on nuclear safety matters, separate from the AEC, although the STA commonly supported both organizations [29]. The NSC was composed of five commissioners appointed by the Prime Minister and provided comments and opinions to the relevant ministries.
- As part of the 1978 restructuring, the licensing of commercial nuclear power reactors was specifically assigned to MITI, and civilian marine reactors were regulated by the Minister of Transport. Research reactors, new reactor technologies and other aspects of the nuclear fuel cycle continued to be regulated by the Prime Minister.

Following the JCO's Tokaimura criticality accident, the investigation found that the direct causes of the accident were linked to human errors and inadequate procedures on the part of the operating organization. The contributing factors included the failure of the regulatory body, specifically STA, to adequately assess the hazards during the initial licensing of the JCO facility, and to effectively inspect its operation afterwards to identify non-compliance with the conditions of its licence. Hence, several organizational changes were implemented in the aftermath of JCO's Tokaimura criticality accident [32, 39, 41]. These principal measures, which established the structure that was in place at the time of the Fukushima Daiichi accident, can be summarized as follows:

- Strengthening the NSC: The NSC was moved under the Prime Minister's Office on 1 April 2000. The NSC's staff was increased from 20 to 92, and the NSC's involvement in regulatory oversight was anchored by adding a concurrent, 'double-check' review system [42].
- Reorganization of governmental bodies with responsibilities for nuclear safety: A reorganization of the Japanese Government took effect on 1 January 2001. This government reorganization was aimed broadly at reducing costs and improving the efficiency of government [43] and was unrelated to the JCO findings. However, a number of specific measures were taken in the

reorganization with the intention of strengthening the governmental and regulatory framework for nuclear safety. These arrangements can be summarized as follows [40]:

- Amendments to the Reactor Regulation Act provided for the appointment of inspectors for management of safety under the authority of the former STA and MITI.
- MITI was reformed as the Ministry of Economy, Trade and Industry (METI), with responsibilities for ensuring a stable and efficient energy supply, including the use of nuclear energy. Furthermore, METI was also assigned responsibilities for nuclear safety regulation and licensing of nuclear installations.
- Within METI, the Agency for Natural Resources and Energy (ANRE) was responsible for planning and overseeing the national energy supply. In implementing this responsibility, the Department of Electricity and Gas Industry administered the nuclear energy policy and radioactive waste management [33], while NISA regulated the safety of nuclear and other energy sources as well as industrial safety and emergencies at nuclear facilities.
- As the regulatory body, NISA's main functions were codified by the law [33, 38, 44] as: regulation of milling, refining, fabrication, storage, reprocessing and waste disposal activities; regulation of nuclear power generating facilities to ensure safety; control of explosives, safety of high-pressure gas, mining safety and other industrial safety matters under its jurisdiction.
- The Ministry of Education, Culture, Sports, Science and Technology (MEXT) was created through a merger of the STA and the Ministry of Education. The former responsibilities for nuclear safety regulation of the STA were reallocated between METI and MEXT. Accordingly, the regulation of nuclear fuel cycle facilities, including uranium refining and fuel fabrication, spent fuel storage, reprocessing, nuclear waste management, and related transportation of nuclear materials, were transferred from the STA to NISA [34, 42].
- MEXT retained responsibility for the science and technology aspects of nuclear energy, including policy and the development of nuclear technologies, safety regulations governing research reactors, protection against radiation hazards, the use and transportation of nuclear and radioactive materials and safeguards. MEXT also supervised the National Institute of Radiological Sciences (NIRS), the Japan Atomic Energy Research Institute (JAERI) and the Japan Nuclear Cycle Development Institute. The latter two organizations merged in 2005 to become the Japan Atomic Energy Agency (JAEA) [24, 45].
- The Ministry of Foreign Affairs (MOFA) was responsible for the international aspects of nuclear energy utilization, including the implementation of the related international treaties and conventions.

— The Nuclear Emergency Act set out the roles and responsibilities of the national Government, local governments, and licence holders in case of a nuclear emergency [40]. The Nuclear Emergency Law also provided that, in the event of a nuclear emergency, several organizations were to be activated. Within the Cabinet Office, the Nuclear Emergency Response Headquarters, led by the Prime Minister, were to be established in Tokyo; the Technical Advisory Organization composed of NSC commissioners and advisors for emergency response would give technical advice to the Prime Minister; the Nuclear Emergency Response Local Headquarters were to be set up at the concerned Off-site Centre (OFC) by the relevant ministries; and a Joint Council for Nuclear Emergency Response was to be established at the OFC in order to share information between the national Government and related organizations, such as local governments, licensees, and other relevant organizations, and, when necessary, to coordinate emergency measures by the respective organizations.

— Amendments to Ordinances for the Compensation Law and the Law on the Indemnity Agreement for Compensation of Nuclear Damage, which were implemented by a cabinet order in 1999, established the amounts for which nuclear operators were liable.

— In 2003, a METI ordinance established the process for notifying or reporting major events to NISA. NISA would assess the results of the licensee's investigations and the adequacy of countermeasures. In case of serious events, the NSC could set up its own investigation group. For coordinating the collection and evaluation of the domestic and international operating experience on the regulatory side, and for considering its use in the development of regulations, NISA and JNES established a high level review group.

1.2.2.3. Staffing and resources of the regulatory body

To carry out its assigned functions, NISA, the regulatory body at the time of the accident, was organized in eleven divisions, which reported to the Director General at the headquarters. Nuclear safety inspectors and senior specialists for nuclear emergency preparedness were also stationed at each nuclear facility. NISA started in 2001 with approximately 260 staff working on nuclear safety [42]. By 2010, the staff dedicated to nuclear safety was 370 [37].

In 2003, the Japan Nuclear Energy Safety Organization (JNES) was established as a technical support organization for NISA by merging parts of the Nuclear Power Engineering Corporation, the Japan Power Engineering and Inspection Corporation and the Nuclear Safety Technology Center. The law establishing JNES was enacted by an extraordinary session of the National Diet of Japan, held in the autumn of 2002, at the time of a crisis in public confidence precipitated by the discovery of TEPCO's falsification of safety records [40]. JNES's main functions, as assigned by law, consisted of conducting inspections at nuclear facilities, review of licensees' periodic inspections, safety analysis and evaluation, nuclear emergency preparedness support, research and testing for code/standard development, and collection, analysis and distribution of safety information [37, 38].

JNES had approximately 400 employees as of 1 April 2010, and 60% of NISA's FY 2010 budget was allocated to JNES. JNES had the status of an 'incorporated administrative agency'. As such, JNES was free of the administrative rules that applied to Japanese Government departments. Consequently, JNES had more flexibility on matters of staffing and budget, which better enabled it to retain a cadre of professional experts [38].

The NSC was supported by its own secretariat, composed of a Secretary-General and four divisions with a total of about 100 staff members. Several advisory councils and committees on safety, emergency preparedness and other regulatory matters also supported the NSC [37, 38].

1.2.2.4. Regulatory guidance

The guidelines developed by NISA and the NSC were for their internal use to conduct reviews [46]. Technical standards and codes were prepared by industrial and academic bodies and endorsed by NISA (see Section 1.2.1).

Neither NISA nor its predecessor organizations had any legal authority under their respective statutes to issue regulations that were binding on applicants and licensees. Instead, the requirements for licensing, inspection and enforcement of nuclear power plants were described in detailed laws enacted by the National Diet of Japan and in ministerial ordinances, and the regulatory body issued requests to the licensees. For example, in case of severe accident management guidance, in accordance with the decision by the NSC[61], MITI requested, in July 1992, to consolidate accident management (AM) measures of the licensees. In response, the Japanese licensees, including TEPCO, prepared AM measures. Some of those measures, such as the primary containment vessel venting systems and accommodations for sharing emergency diesel generators between the units, were implemented over the period from 1994 to 2002. However, thereafter, it was deemed by the licensees without a

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[61] "Accident Management as a Measure against Severe Accidents at Power Generating Light Water Reactors" (decision of the Nuclear Safety Commission, May 1992).

regulatory guidance that no further knowledge regarding severe accidents was found, and the existing and implemented AM measures were adequate.

1.2.2.5. Authorization of facilities and activities

The Fukushima Daiichi NPP, as noted above, is one of Japan's oldest nuclear sites, dating from the early days of the nuclear programme and licensing process in Japan. The establishment permit (EP) of the Fukushima Daiichi facility was issued on 1 December 1966 by the Prime Minister, after review of TEPCO's application by the AEC's Nuclear Reactor Safety Review Committee.

The AEC's Safety Review Committee, at that time, had the following five expert groups to conduct the safety review of the Fukushima Daiichi site:

- The Reactor Group, responsible for the review of physics, thermal and mechanical features and fuel and material properties;
- The Environment Group, responsible for review of meteorological and radiological effects;
- The Seismic Group, responsible for review of the seismic design;
- The Plant and Power Generation Group, responsible for the evaluation of plant performance;
- The Safety Review Group, responsible for the evaluation of accidents and emergencies.

The review was carried out in accordance with various guides prepared by the AEC's Committee on Nuclear Reactor Safety Standards, as well as the information from the 'draft' General Design Criteria regulation of the United States of America. After the EP was granted in 1966, TEPCO had to apply for approval of the construction plan under the Electricity Utilities Industry Law. MITI reviewed and approved the construction plan in September 1967 and then conducted the pre-service inspection tests before fuel loading, and the commissioning tests in accordance with the Electricity Utilities Industry Law. It should be noted that the construction of later units at the site was authorized through amendments to the same EP. There was no requirement for submission of a Final Safety Analysis Report (FSAR) for each unit, since the original EP as amended served as site safety analysis. The same authorization procedure was followed for facility modifications which had a significant safety impact on the basic design.

This authorization process was revised in 2007, to establish a 'double-check' approach consisting of a primary review that was performed by NISA and a secondary review that was performed by the NSC and AEC.

1.2.2.6. Authorization of long term operation

The establishment permits for Japanese NPPs were issued for an unlimited period. However the Ministerial Ordinance, under the Reactor Regulation Act, requires an 'ageing management technical review' for plants that reach 30 years of operating life, and Ageing Management Technical Assessments (AMTA) thereafter at 10-year intervals. The licensee is required to develop a ten year long term maintenance programme (LTMP) based on the AMTA results and submit it to NISA for review and subsequent oversight.

TEPCO submitted the report presenting the results of the AMTA for 40 years of operation and the LTMP for Unit 1 of the Fukushima Daiichi NPP to NISA on 25 March 2010. NISA reviewed the report with technical support from JNES, and approved the operation of Unit 1 for an additional ten year period on 7 February 2011, one month before the accident.

1.2.2.7. Requirements for periodic safety reviews

Licensees in Japan also conduct periodic safety reviews (PSRs) every ten years after the commencement of operation. Conduct of PSRs started as a voluntary activity in 1992 and became a legal requirement in 2003, through an amendment to the Ministerial Ordinance on 'Rules for the Installation, Operation, etc. of Commercial Nuclear Power Reactors' under the Reactor Law[62] [4]. Before the 2003 amendment, PSR reports were provided to the regulator for review and information to the NSC. After the 2003 amendment, PSRs, although mandatory, were regarded as 'self-assessments', and the licensees were not required to submit the results and implementation plans to NISA for review and approval. The regulatory body confirmed by its quarterly safety inspections that each licensee had adequately conducted its PSRs.

Furthermore, neither before nor after the 2003 amendment did the scope of PSRs involve the re-examination of the design or the reassessment of external hazards in light of new standards, data and/or methods. The Japanese National Report to the Fifth Review Meeting on the Convention on Nuclear Safety stated: "Periodic Safety Review in Japan covers the operator safety activities at nuclear installations in operation, but it does not cover the design review. The nuclear installations have been designed with sufficient safety margin, [rather] than...they just met the necessary design criteria so that back-fitting has not been institutionalized" [37].

1.2.2.8. Requirements for backfitting

There was no legal provision in Japan for 'backfits' of a plant, because of the understanding between the regulator and the industry that nuclear installations were designed with a sufficient safety margin, and hence a backfitting did not need to be institutionalized. Although NISA did not have a legal basis for ordering backfits, it had a policy to request 'backchecks' when technical standards were revised or new knowledge was gained. In response to NISA's request, the licensees' evaluation was carried out on a voluntary basis. For example, the Seismic Design Review Guide that was issued by the NSC in July 1978 (revised in 1981, 2001 and September 2006) provided the technical standards for review of the new plant EPs, including the revised acceptable methods for defining the design basis earthquake. After the 2006 revision of this guide, NISA requested licensees to conduct a 'backcheck' of seismic and tsunami hazards. TEPCO started the re-evaluation but had not finished its 'backcheck' before the accident at the Fukushima Daiichi NPP.

1.2.2.9. Inspections of facilities and activities

The inspection programme was structured by the Reactor Regulation Act, which prescribes the definite type and exact frequency of inspections of facilities and activities (see Fig. 1.2–3). Additionally, the Electricity Utilities Industry Law specifies the periodic plant inspection, while the Reactor Regulation Act specifies the inspection of compliance with the safety management programmes, both of which are to be conducted by METI.

The operators' safety management activities were governed by the operational safety programme that NISA reviewed and approved. NISA conducted quarterly operational safety inspections to check the operators' compliance with the programme. Periodic inspections were also conducted by NISA/JNES at intervals not exceeding 13 months, which focused on the operators' maintenance of structures, systems and components (SSCs) of the facility. Periodic inspections focused on the safety significant SSCs, belonging, for example, to the reactor shutdown system, the reactor coolant pressure boundary,

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[62] All NPP units in Japan older than ten years were reported to have conducted at least one PSR at the time of the IAEA Integrated Regulatory Review Service (IRRS) mission in 2007.

the residual heat removal system and the containment system. These regulatory procedures were carried out in addition to the licensees' own inspection and maintenance management of nuclear installations, periodic safety assessments, and technical evaluations for ageing management [37].

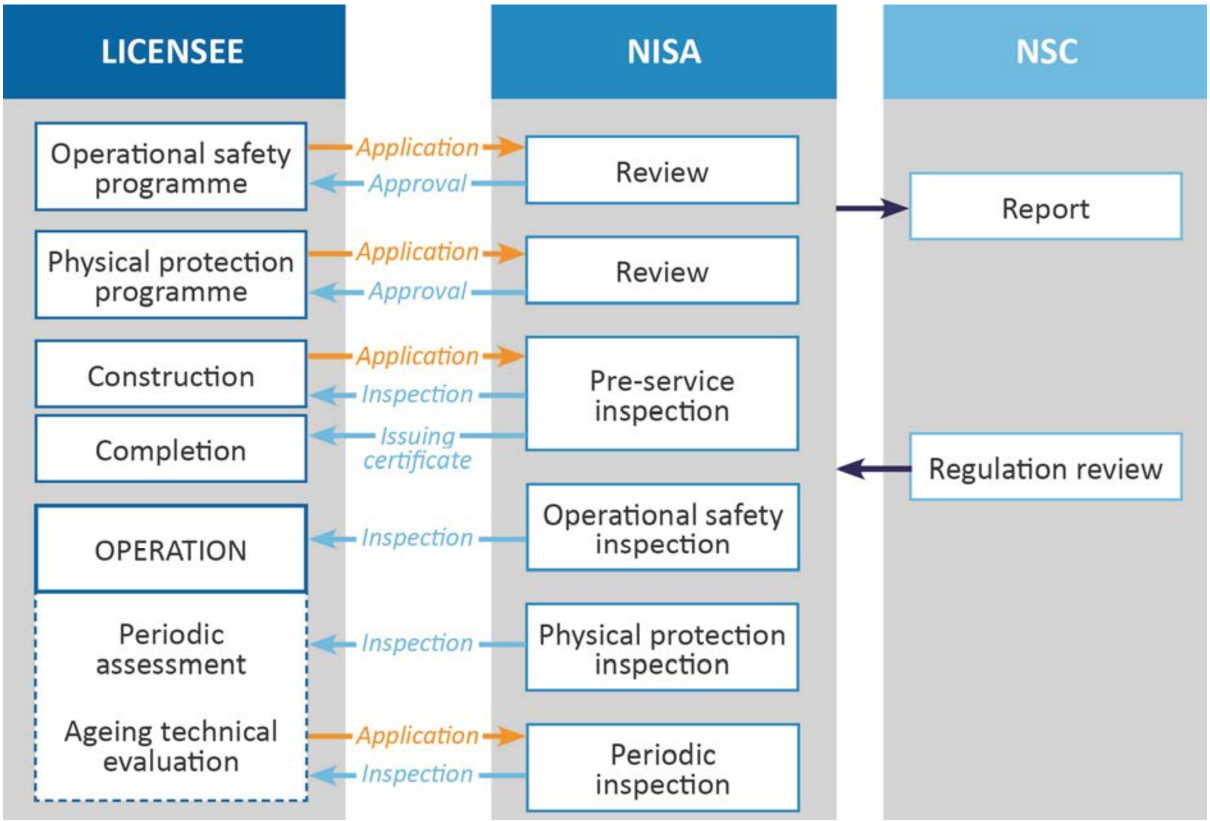

FIG. 1.2–3. The regulatory inspection process at the time of the accident for the operating stage of NPPs in Japan [37].

By law, the presence of NISA inspectors was required before the licensee could complete certain tests and surveillance. There were only specific periods at which inspectors were not allowed to be present and specific areas to which NISA was not permitted access for inspection because of the plant state and conditions restricting physical access. On 1 November 2006, the licensees accepted the request sent to them in NISA's formal letter for cooperation for the 'free access' of NISA inspectors to the facilities. On 8 May 2007, all the offices of the NISA inspectors started the operation of inspections with 'free access'. NISA was authorized to access the nuclear facility and examine the records, documents and other necessary matters at any time when the Minister of METI recognized it is necessary [37].

The repeated discoveries of non-compliance and falsification of test records that occurred in 2002 and in 2007 raised questions about the effectiveness of regulatory inspections and enforcement actions at that time. The initial falsifications were discovered as a result of allegations raised by former employees. However, in spite of follow-up inspections by NISA, regulatory orders to licensees and various other measures to strengthen self-checking and regulatory oversight, the true extent of the falsifications did not come to light for several years [38]. TEPCO's Fukushima Daiichi facility was also implicated in several cases, involving, for example, falsification of containment leak rate tests by employees at Unit 1, which resulted in a one year licence suspension by METI [40]. Consequently, improvements of the inspection system were ordered in January 2009 in a revision of the earlier ministerial ordinance. Greater flexibility was introduced considering the characteristics of individual nuclear installations, and enhancements were made to the inspections during operation as well as at the time of plant shutdown in response to lessons learned from the data falsification events [37].

1.2.2.10. Requirements for qualification of reactor operators

Licensing of the plant operators was required by the Japanese regulation only for the shift managers, also called shift superintendents or shift supervisors (SSs), who would be in command and control of the shift team.

The licensing regulatory requirements for SSs were established by Ministerial Ordinance No. 77[63] of the Reactor Regulation Act, and the SS qualification and licensing process was implemented by the industry's self-regulating organization, JANTI. JANTI followed the industry guidance JEAC 4804 [47], which was issued on 12 February 2008, in the licensing of SSs after evaluating their knowledge and skills (Fig. 1.2–4) [48]. The SS licence had to be renewed every three years by completing the renewal training.

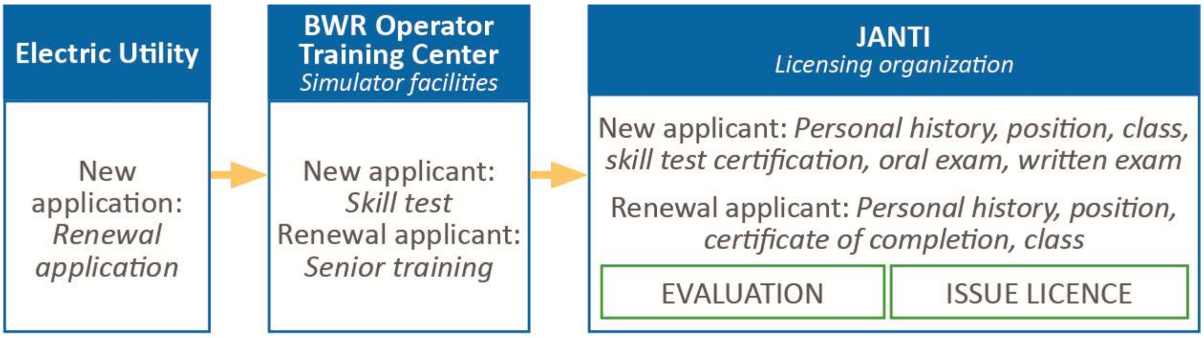

FIG. 1.2–4. Qualification and licensing process for shift supervisors in Japan [49].

The SS licence was issued upon the operator's demonstration of the necessary knowledge, skills and experience required in the position description, e.g. shift manager. These skills were listed in the governmental guidelines and included [50]:

- Ability to monitor the plant status during normal operation and accident conditions;
- Ability to manage and make accurate judgements and decisions during accident conditions;
- Knowledge of the laws and regulations concerning nuclear safety;
- Knowledge of nuclear reactor facilities and performance;
- Knowledge of leadership.

1.2.2.11. Operational experience

JNES managed the database containing domestic and overseas safety information, including incident and accident data, and shared it with NISA. The overseas information on reportable events was collected from international organizations such as the IAEA/NEA International Reporting System for Operating Experience (IRS) and from national regulatory agencies.

JNES performed the first screening of the incidents and, when needed, analysed them, assessing the applicability of the issues involved for domestic NPPs and proposed appropriate regulatory actions.

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[63] The Reactor Regulation Act Article number was changed to No. 87 after regulatory system changes following the accident.

In case of operational experiences necessitating regulatory actions, NISA/JNES discussed the issue with the licensees. If necessary, NISA required the licensees to investigate and to take corrective actions. To ensure their implementation, NISA issued regulatory letters to recommend or require that the utilities take actions and requested them to report after the actions had been completed. The status of the recommended or required corrective actions was checked during the PSR of each plant by the licensee, and NISA confirmed, by its quarterly safety inspections, that each licensee had adequately conducted its PSRs, including the corrective actions. In case that operational experience constituted a change in laws, the laws would be amended by NISA, and codes and/or standards were established or revised by the appropriate codes and standards organizations.

1.2.2.12. International cooperation

The Japanese Government has been a Party to the following international conventions related to nuclear safety: Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency, Convention on Early Notification of a Nuclear Accident (since 1987) and the Convention on Nuclear Safety (since 1995), as well as the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management (since 2003). It has also supported the multilateral and bilateral cooperation activities within the IAEA framework by participation in the International Nuclear Safety Group (INSAG) and the Commission on Safety Standards. It has also contributed, through extra-budgetary programmes, to projects that are aimed, for example, at enhancing the safety of nuclear installations in South-East Asia, Pacific and Far East countries (since 1997), to the Asian Nuclear Safety Network (since 2002) and to the International Seismic Safety Centre (since 2008).

Japan’s regulatory organizations received an IAEA Integrated Regulatory Review Service (IRRS) mission in 2007. At the request of the Japanese Government, a team of experts visited NISA and carried out a review of the legislative and governmental responsibilities; the authority, responsibilities and functions of the regulatory body; the organization of the regulatory body; the authorization process; review and assessment processes; inspection and enforcement activities; the development of regulations and guides; and the management system of the regulatory body. This mission report was made publicly available and the results are referred to in more detail in Technical Volume 2, Section 2.7 [38].

In addition to the international cooperation with the IAEA, the Government of Japan has been a member of the OECD/NEA and a participant in its Steering Committee and other committees, such as those on Nuclear Regulatory Activities, Safety of Nuclear Installations, Radiation Protection and Public Health and Radioactive Waste Management.

1.2.3. Stakeholder involvement and public communication

1.2.3.1. Stakeholder involvement and public communication in nuclear power in Japan

Since nuclear power was first introduced in Japan, the objectives of all communication activities were to make the public understand the need for nuclear power for the post-war reconstruction of the country as an engine for economic growth, and to emphasize the importance of nuclear safety.

The dialogue established by the Japanese nuclear sector was focused on the safety of the plants. As the Japanese Government supported nuclear power, it managed to counterbalance the concerns raised by the movement against nuclear power at national level (which had developed in the late 1960s) by supporting local communities that agreed to host NPPs with incentives and development initiatives [51]. In the early 1970s, the Government implemented the three energy source development laws, or so called ‘Dengen Sanpo’, which created a system of subsidies for local governments which accepted power plants, aiming at the promotion of nuclear power and its understanding.

The Chernobyl accident in 1986 seriously damaged public confidence in the safety of nuclear energy in Japan. Public concerns were addressed by the nuclear industry with a communications strategy emphasizing reassurance, based on the confidence that a severe accident could not happen in Japan.

1.2.3.2. Events that raised public concerns

The recent history of nuclear power in Japan includes several episodes that have had a negative impact on the public perception of the nuclear industry.

In 1974, high radiation leakage occurred during the initial voyage of Japan's first nuclear powered ship, the Mutsu, when it reached 1.4% of rated power. This accident affected the public's perception of institutions responsible for nuclear safety. Following the formal investigation, the final report that was submitted on July 1976 included the following recommendations for the reform and improvement of Japan's nuclear safety approach:

- Separation of the functions related to nuclear safety from those dealt with by the AEC and the establishment of a new independent commission to oversee nuclear safety and to 'double-check' the safety reviews carried out by the administrative agencies for enhancing and ensuring nuclear safety.
- Consistent implementation of safety regulations in accordance with the types of nuclear reactors — i.e. commercial power, marine, test and research applications and advanced technologies — with clear responsibilities among administrative agencies for ensuring their safety.
- Implementation of governmental and public checks and balances, including such measures as holding public hearings and discussions to dispel people's concern and to gain public understanding and cooperation for nuclear energy development [52].

In 1999, JCO's Tokaimura criticality accident led to the death of two workers and exposure to varying levels of radiation doses of hundreds of people [32, 34, 41]. Moreover, the local community was financially impacted by concerns about the safety of consuming local products. The report of the NSC investigation committee [53] identified three issues related to communication that have proved relevant to the Fukushima Daiichi accident:

- Lack of timely communications to the local residents from both JCO and NISA;
- Lack of coordination and understanding of their respective roles by the national, local and municipal governments;[64]
- Problems with the company's communication and emergency response systems.[65]

The NSC report also acknowledged the fact that the accident had a very significant social impact. A few months after the accident, the Japan Atomic Industrial Forum (JAIF) published a declaration on the reform of the nuclear industry, in which it admitted that "…the private-sector nuclear industry of Japan has betrayed the public trust, especially that of the people of Tokai mura" [54].

In 2002, TEPCO found 16 cases of misconduct in the management of nuclear inspections and repair work, which had been carried out systematically in an inappropriate manner for a long time [55], leading to the resignation of the TEPCO chairman and three other top management officials. TEPCO admitted to as many as 200 cases between 1977 and 2002 in which information had been falsified. In 2003, all 17 of its nuclear plants were shut down temporarily after a scandal over falsified safety

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[64] For example, the mayor of Tokaimura recommended evacuation of the local residents without guidance or advice from the central and prefectural governments, creating confusion.

[65] The National Emergency Preparedness for Nuclear Disaster Law in Japan did not include fuel fabrication facilities; hence, there was no clear process for communication, or a point of contact to answer questions from the public.

inspection reports. In 2006 and 2007, there were further revelations of unreported and systematically false reporting of incidents that had occurred in the 1970s and 1980s.

In order to promote public understanding of the safety activities implemented by NPPs in light of these scandals, the Japanese nuclear industry, in 2003, established a publicly accessible database called ‘Nuclear Information Archives’, which covers the entire nuclear power generation history in the country and has recorded about 350–400 events per year.

In 2007, the Niigata-Chuetsu-Oki earthquake caused the shutdown of TEPCO’s Kashiwazaki-Kariwa NPP. A review report by NISA stipulated that “NISA and plant operators must engage in communication with local communities on a regular basis via public hearings and PR activities”. The NSC also indicated its opinion on various points, including the need to “constantly strive to secure transparency of information to the public and disseminate information related to radiation safety to ease public worry or anxiety concerning nuclear power safety” [56]. A subsequent IAEA report also highlighted the long time it took for TEPCO to report the event to the authorities [57]. Based on the lessons learned from the response to the earthquake, TEPCO assigned spokespersons to every key facility to provide accurate information quickly in coordination with the public relations department in the case of unusual events, incidents or accidents.

Also in 2007, the Hokuriku Electric Power Company announced that, in 1999, during a periodic inspection at the Shika NPP, the reactor had temporarily reached unplanned criticality and that this event had been covered up [58] without informing either the national Government or local municipalities of the incident [59].

1.2.3.3. Public perception of nuclear power

Public perception in Japan was generally in favour of nuclear power. However, even before the Fukushima Daiichi accident, public opinion had been influenced by various events, as confirmed by several surveys[66].

With respect to nuclear power in general, local communities that already hosted nuclear power plants were supportive of new construction; however, this was not the case with potential new localities. In one example from Maki in Niigata Prefecture, 66% of the population who participated in an official local referendum in 1996 voted against the siting of a nuclear power plant planned by Tohoku Electric Power Company, which eventually had to select another location. In general, the OECD/NEA public survey of 2010 showed that 61% of the Japanese respondents wanted to keep existing plants running, but only 21% supported new construction [58, 59].

With respect to the role of the regulatory authorities, in 2007, only 19% of the respondents to a survey conducted by Shin Joho Center Inc. agreed that current rules and regulations were sufficient to control nuclear power, showing a low level of trust in the regulation of nuclear power in the country.

1.2.4. Training and qualification

Training and qualification of operators in charge of plant activities and in command and control of the accident management played an important role in the accident and are described in the following sections.

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[66] In particular, in a survey conducted at the end of 1999 by the local authority, the percentage of respondents who supported nuclear power after the JCO’s Tokaimura criticality accident fell from 52% to 32%, and the number of respondents who said that nuclear power facilities were unsafe rose from 32% to 78%, according to an OECD/NEA 2010 survey published in: OECD NUCLEAR ENERGY AGENCY, Public Attitudes to Nuclear Power, OECD, Paris (2010), 45.

1.2.4.1. Operator training

As stated in Section 1.2.2, licensing for the operators was required by the Japanese regulation only for the shift manager or shift supervisor (SS), who would be in command and control of the shift team; there was one SS per control room. The SS qualification process was implemented by JANTI.

The Nuclear Power Training Center Ltd. (NTC) and the BWR Operators' Training Center Corporation (BTC) trained reactor operators and SSs by means of simulators of pressurized water reactor (PWR) NPPs and BWR NPPs, respectively. The NTC and BTC also carried out the qualification examinations for the SSs on behalf of the electric power companies. In addition, each electric power company has its own training facility. However, after JANTI started to implement the qualification process in accordance with the regulations, BWR SS and deputy SS (DSS) training for licensing were conducted by BTC.

Qualification and/or certification of control room operators other than the SSs was determined and performed by the individual NPP operating organization. In accordance with JEAG 4802, TEPCO also established a training programme similar to BTC's, including classroom, on-the-job, self-study, and simulator training (Fig. 1.2–5) that is described in the sections below. As such, both the initial and renewal training for Fukushima Daiichi operators were performed at the Fukushima site training centre and at the BTC facilities.

1.2.4.2. Reactor operator qualification and certification requirements

In-line with the Japanese nuclear industry practices, the operator certification programme by TEPCO primarily set different levels of training and qualification based on the required scope and skills for such positions as auxiliary operator (AO), senior operator (SO), system senior operator (SSO) and DSS:

- The AOs were expected to be able to 'walk down' in the nuclear facility and identify any early indication of an abnormality and promptly address or rectify the abnormality, to operate field equipment during start-up, shutdown and other plant conditions, and to report and describe equipment conditions to the control room (to the SS) in the case of an accident.
- The SOs/SSOs were expected to have the proficiency to operate and monitor the nuclear plant for startup, shutdown and other plant conditions and provide instructions for field operations; demonstrate a thorough understanding of emergency operating procedures (EOPs) and be able: to perform the necessary operations; to give instructions for field operations to mitigate and stabilize an equipment failure and/or accident; and to operate the plant appropriately to mitigate and stabilize the situation under the direction of the SS in the case of an accident or a severe accident.
- The DSSs were staff who had been selected for promotion to SS in the near future, and who were receiving on the job training prior to their SS licensing application. In addition to meeting all the proficiencies of SOs/SSOs, the DSSs were expected to demonstrate leadership skills and capabilities to manage, direct and control the shift team, with the understanding that their highest priority was on safety issues, including industrial safety and equipment integrity. They also had to demonstrate skills in taking decisions in the case of an accident and/or a severe accident. This included the determination of when to enter into or exit from EOPs or Severe Accident Operating Procedures (SOPs) and the ability to give directions for appropriate operation during an accident.

The operators (other than the SSs) were required by the TEPCO programme to renew their qualifications every four years.

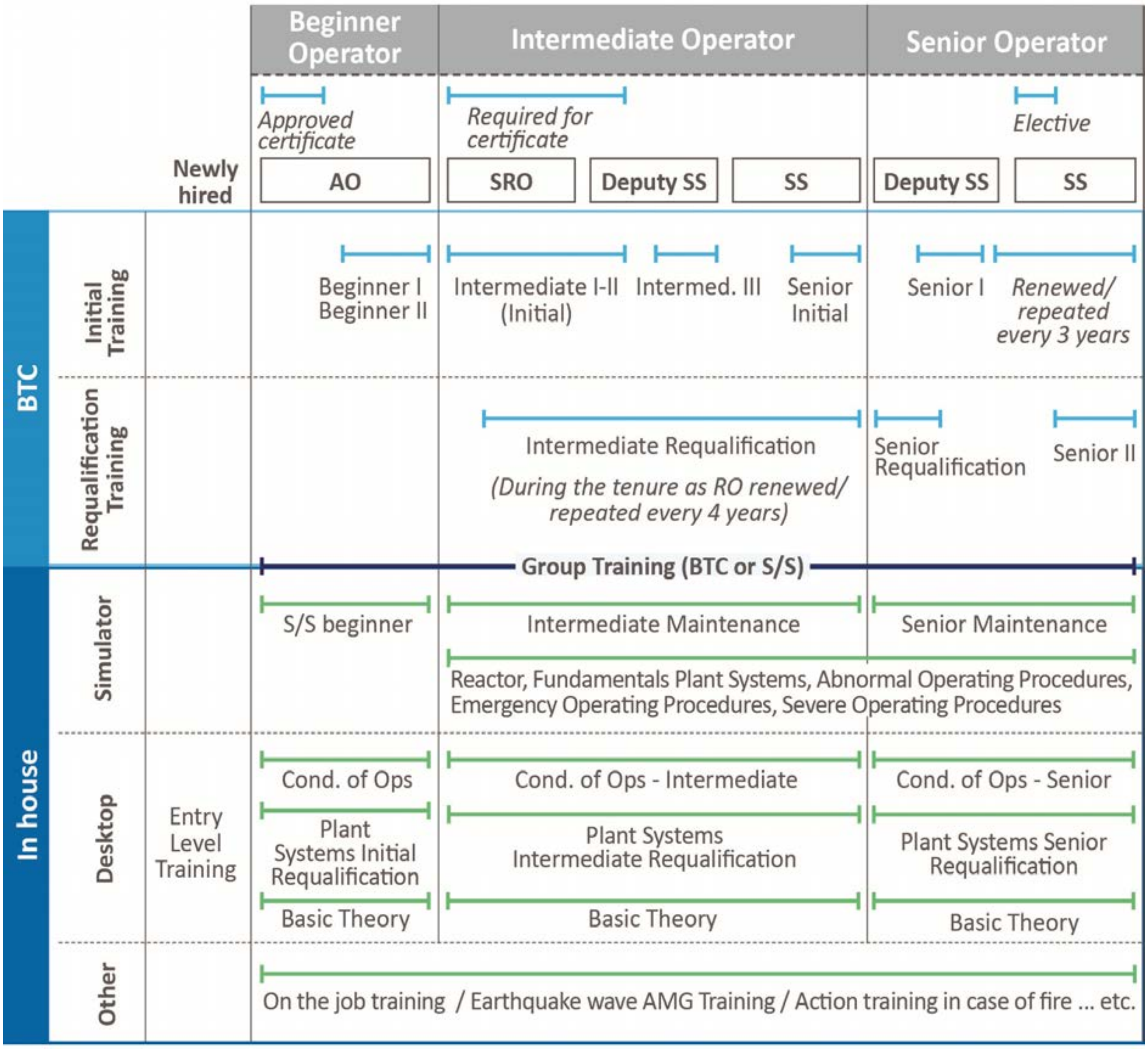

FIG. 1.2–5. TEPCO Operator Training and Qualification Programme.

1.2.4.3. Simulator training

Besides the classroom, on the job and self-study training, the training programmes of Japanese operating organizations also required operators to complete simulator training, either at on-site simulators or at BTC's simulators. There was no regulatory requirement for utilities in Japan to have full-scale unit specific simulators. However, every Japanese NPP had at least one full scope simulator at its site or in a nearby facility that was modelled after a specific unit or specific units at that site. These site representative simulators, which consisted of a replica unit from the site, had small and unique differences in design or equipment compared to other units on the same site.

Full-scale/full-scope simulator training for BWR reactor operators, especially for SSs/DSSs, was traditionally conducted at the BTC's full-scale simulator facilities.[67] The BTC provided simulator training for NPP operators with simulators that were modelled after selected reference plants,

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[67] BTC's Fukushima Centre simulators went out of service following the accident, and replacement simulators were put in service at the Shimane provisional facilities.

including the Fukushima Daiichi NPP units (see Table 1.2–2). TEPCO operators also utilized and were trained in two full-scope BTC simulators, which were modelled after Fukushima Daiichi Units 3 and 4 (BWR/4) at a nearby facility.

TABLE 1.2–2. SIMULATOR TYPES AND LOCATIONS OF BTC TRAINING CENTRES [49]

Simulator No.	MCR type	Reference plant	Location	Training start year	Status at the time of accident	Current status
1	First Generation Control Panel 800 MW(e)	Fukushima Daiichi NPP Unit 3 (BWR/4)	Fukushima Centre	1974	In service	Closed
2	Second Generation Control Panel 1100 MW(e)	Fukushima Daini NPP Unit 3	Fukushima Centre	1983	In service	Closed
3	First Generation Control Panel 800 MW(e)	Fukushima Daiichi NPP Unit 4 (BWR/4)	Fukushima Centre	1989	In service	Closed
4	Second Generation Control Panel 1100 MW(e)	Kashiwazaki-Kariwa NPP Unit 4 (BWR/5)	Niagata Centre	1993	In service	Closed
5	Third Generation Control Panel 1356 MW(e)	Kashiwazaki-Kariwa NPP Unit 6 (ABWR)	Niagata Centre	1994	In service	In service

At the Fukushima Daiichi NPP site, there was one full-scale/full-scope simulator that was put in service in 2003. This simulator was modelled after the Fukushima Daiichi NPP Unit 3 (a BWR/4 and Mark-I containment) configuration.

Additionally, the Fukushima Daiichi NPP site housed a full-scale/limited-scope (compact) simulator based on the Unit 1 (BWR/3 with IC) configuration. After the activation of the full-scale/full-scope simulator in 2003, this compact simulator was utilized by the operators for self-study.[68] The Fukushima Daiichi NPP operators also utilized full-scope desktop training simulators (plant analysers) that individually modelled every unit at a given site for specific plant operation training.

1.2.4.4. Severe accident management training

In Japan, classroom and full-scope training simulators have been used for the training of operators for the prevention of core damage, i.e. mainly on design basis accident (DBA) procedures and scenarios. For the purposes of severe accident management (SAM) training of the TSC (Technical Support Centre) staff and operators, an education and training system (ETS), executed on personal computers, was developed by Japanese BWR utilities and vendors [60]. The ETS provided an interactive learning tool (both for individuals and for shift crews) for AM by visual means and utilized a commercial computer code.

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[68] The site had another compact simulator modelled after Unit 4, which was used from 1996–2002 but was abandoned following the opening of the full-scale/full-scope simulator.

The computer simulations also included AM countermeasures based on the plant and equipment models, radioactive mitigation models and monitoring system models. Plant parameters calculated by the virtual simulator and the plant conditions were simultaneously displayed on several computer monitors connected over a network. Furthermore, core status, such as core damage and RPV failure, was mapped and displayed. Trainees could learn plant behaviour during severe accidents and the use of severe Accident Management Guidelines (AMGs) through the input of SAM actions during simulation. In the group training, the TSC staff and control room operators were able to perform emergency exercises simultaneously. These systems provided plant operators and TSC personnel with a training tool for AM. TEPCO conducted an emergency exercise simulating a hypothetical severe accident in March 2000, using the ETS tool.

TEPCO operators were required to complete the computer based SAM training every three years.

1.2.4.5. General emergency training and preparedness

Emergency training in the Japanese nuclear industry was guided by the Japan Electric Association Guide JEAG 4102 [61], which was the industry standard and was originally issued in 1996.

Following the JCO's Tokaimura criticality accident in 1999, when emergency plans of other countries were consulted as benchmarks, gaps in emergency preparedness and associated training were identified by Japanese regulators, utilities and international organizations. These were also raised in the IAEA report on lessons learned from the JCO's Tokaimura criticality accident [32]. The IAEA report also included recommendations concerning emergency preparedness.

In 2010, as a result of the trend in Western countries and the increased emphasis by the regulatory body, the Japanese nuclear operating organizations, through JANTI, initiated a revision of those guidelines and planned to implement enhanced nuclear emergency preparedness training. The JANTI task force started to prepare industry guidelines for emergency preparedness training, including the addition of the 'evaluation' concept to the 'conduct' aspect of training. Revision to JEAG 4102 was completed in September 2010. However, when the Fukushima Daiichi accident happened in March 2011, the guidelines had not yet been implemented.

1.2.5. Characteristics of the Fukushima Daiichi site

This section gives a general description of the Fukushima Daiichi site and its siting analysis for natural external hazards, such as earthquakes and tsunamis. It explains the site characteristics that were important for the course of the accident, such as the excavations that had lowered the site so that the reactors rested on bedrock and the placement of some essential systems at lower elevations.

The information in this section is derived mainly from the site description in the establishment permit (EP)[69], the Japanese equivalent of a safety analysis report (SAR) [15]. The EP was written almost 50 years ago, in accordance with the regulations at the time.

Although each of the six units at the Fukushima Daiichi site (Fig. 1.1–3) has its own site characterization in the EP, many parts of these are identical. The site characterization used for Unit 1 in 1966 was reused for Unit 2 in 1968, Unit 3 in 1970, Unit 5 in 1971 and Units 4 and 6 in 1972.

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[69] Further information on Japanese terminology for licensing documentation is included in Section 1.3 and in Technical Volume 2.

1.2.5.1. Description of the site

The Fukushima Daiichi NPP site lies approximately 220 km north of Tokyo at almost the midpoint of the Pacific coast of Fukushima Prefecture (North latitude: 37°25’, East longitude: 141°00’). It straddles Okuma and Futaba townships of Futaba County in the Fukushima Prefecture. Its area is approximately 3.5 km^2.

The population density around the site was sparse, with 9241 people living within 5 km of the site and 52 539 people within a 15 km radius.[70] The nearest inhabited homes were at least 0.9 km from the site. Three hamlets lie between 0.9 km and 3 km from the site, Ottozawa, Hosoya and Koriyama, and there are 18 hamlets within 5 km.

1.2.5.2. Weather

The region has an oceanic climate influenced by the warm waters of the Japan Current, which makes summers cooler and winters warmer than in inland areas.

No site specific long term weather data were collected at the site; year-round data were derived from weather stations nearby, mainly the Onahama Weather Station, which had similar meteorological characteristics.

The EP presented statistics on general weather patterns, including average annual temperatures, high temperatures, low temperatures, rainfall and wind speeds.

For extreme temperatures, precipitation and wind speeds, the EP used data from the previous 35 years from the nearest weather stations. It did not consider typhoons or tornadoes.

1.2.5.3. Topography

The sea floor next to the site consists of irregular protrusions approximately 2–3 m high that run parallel to the shoreline at approximately 600 m, 1000 m and 1300 m off the coast. The slope of the ocean floor is steep, approximately 1/60, until approximately 450 m offshore. Thereafter it is more gentle, approximately 1/130.

Before it was excavated, the site’s elevation was approximately 35 m, and the elevation at the top of the cliffs was approximately 30 m. Since TEPCO selected grade levels of 10 m for the block of Units 1 to 4 and 13 m for the Unit 5 and 6 block, significant excavation was required, as shown in Fig. 1.2–6. The reasons for selecting grade levels of 10 m and 13 m are described in the section on ‘Geology’ below and are further discussed in Technical Volume 2, Section 2.1.

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[70] At the time of accident, approximately 1900, 6000, 51 000 and 78 000 people resided in 2 km, 3 km, 10 km and 20 km radii, respectively.

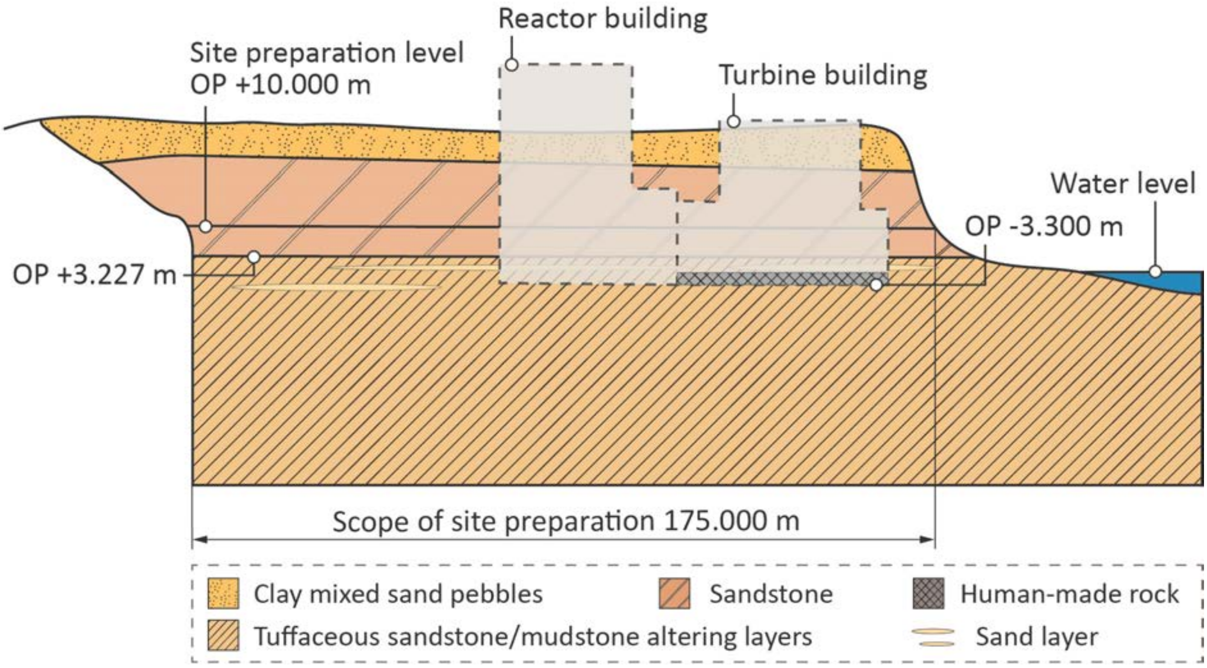

FIG. 1.2–6. Cross section of the Fukushima Daiichi construction site, including soil characteristics (Figure 1.3.2 of Establishment Permit [15]).

1.2.5.4. Geology

The site is made up of the Tomioka Formation, which is approximately 200–400 m thick and consists of sandstone and mudstone at the bottom and a lenticular sand layer sandwiched by tuffaceous fine grain sandstone and mudstone at the top. This is covered by coastal terrace sediments approximately 5–10 m thick and made up of pebbles, sand, silt and clay. In order to build the plant on an acceptable bedrock foundation, the site was excavated, and the main plant and buildings of Units 1–4 were built at an elevation of approximately 10 m.

The thick sediment of sandstone and mudstone was sufficient for bedrock supporting nuclear reactor buildings, so the primary structures were constructed directly on this mudstone.

1.2.5.5. Hydrology

There is groundwater in the 20–30 m thick layer of sand and clay immediately below the site's thin layer of topsoil. Underneath the layer of sand and clay is an impermeable Neogene mudstone layer; groundwater flows through the layer of sand and clay towards the coast (Fig. 1.2–7) at approximately 10 cm/d.

1.2.5.6. Oceanography

The tide measurements used in the design of the plant were recorded at the Onahama Port (OP), approximately 50 km south of the site.

In the EP, tsunami heights were considered as part of the maximum/minimum tidal level for plant design presented in Table 1.2–3. This gave a design basis tsunami height of 3.122 m above the OP level.

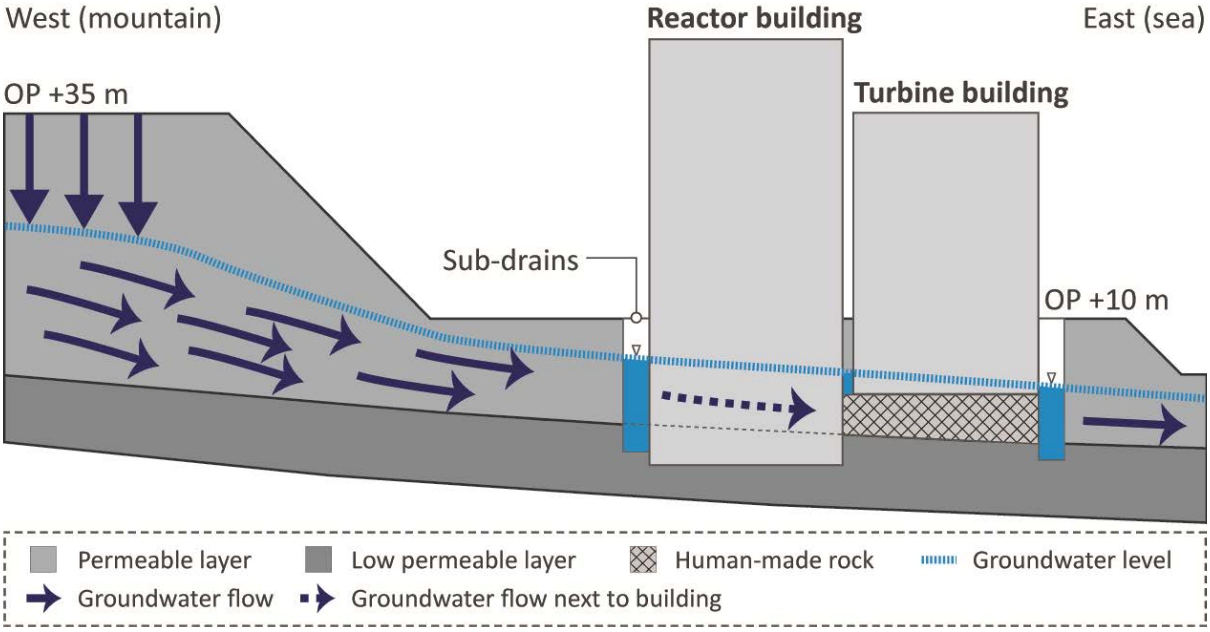

FIG. 1.2–7. Shallow layer groundwater cross-sectional diagram [15, 62].

TABLE 1.2–3. FUKUSHIMA DAIICHI ORIGINAL (EP) DESIGN BASIS TIDE LEVELS [15]

Tide level	Design basis height	Remarks
Maximum (High-high water level)	OP +3.122 m	Based on Chile earthquake and tsunami of 24 May 1960
Syzygy mean high (Mean high tide level)	OP +1.410 m	—
Mean (Mean tide level)	OP +0.824 m	—
Syzygy mean low (Mean low tide level)	OP +0.075 m	—
Minimum (Low-low water level)	OP −1.918 m	Based on Chile earthquake and tsunami of 24 May 1960

TABLE 1.2–4. SUMMARY OF FUKUSHIMA DAIICHI TSUNAMI RE-EVALUATIONS

Year	Tsunami height evaluation	Countermeasure
1966	Establishment Permit OP +3.122 m (observed height resulting from Chilean tsunami in 1960)	—
2002	Japan Society of Civil Engineers (JSCE) assessment method OP +5.7 m	Raise elevation of pumps Make buildings watertight
2007	Disaster Prevention Plan by Ibaraki Prefecture Government approx. OP +4.7 m	Unnecessary
2007	Disaster Prevention Plan by Fukushima Prefecture Government approx. OP +5 m	Unnecessary
2009	Latest bathymetric and tidal data on the basis of the JSCE assessment method OP +6.1 m	Raise elevation of pumps

This initial EP tsunami design basis was re-evaluated in 2002 following updated guidance from the Japan Society of Civil Engineers (JSCE) and re-evaluated again in 2009 using the latest bathymetric and tidal data. It was also re-evaluated twice in 2007 on the basis of the disaster prevention plans by the local prefectures at Ibaraki and Fukushima. Table 1.2–4 summarizes the results of the re-evaluations, and they are further discussed in Technical Volume 2, Section 2.1.

The EP did not consider combinations of tsunamis and other oceanographic events, such as storm surges or high winds.

1.2.5.7. Water for plant cooling

Seawater from the ocean was used for condenser cooling water and auxiliary equipment cooling water. A seawall was built in the ocean in front of the power station with open channels behind it that led from the power plant to the ocean. Water was drawn in through sluice gates and pump rooms installed for each unit and then transferred to the condenser by two pumps installed in the pump rooms.

Water from the condenser was discharged through a covered concrete culvert into the ocean in front of the south side of the sea wall.

1.2.5.8. Earthquakes and ground conditions

The subduction zone off Japan's Pacific coast has been the source of numerous earthquakes affecting Japan. It is part of the nearly circular subduction zone around the Pacific Ocean, the Circum Pacific Belt or so-called 'Ring of Fire'. It is the source of the world's largest earthquakes, including the Chilean earthquake of 1960 (M 9.5) and the Alaskan earthquake of 1964 (M 9.2), which occurred a few years before the Fukushima Daiichi NPP Unit 1 was designed.

The Fukushima Daiichi Unit 1 EP considered and analysed the following earthquakes as further discussed in Technical Volume 2, Section 2.1:

- Aizu earthquake, September 1611 (M 6.9)
- Sendai earthquake, June 1646 (M 7.6)
- Iwashiro-no-kuni Koori earthquake, October 1731 (M 6.6)
- Earthquake south-east off the coast of Shioyazaki, May 1938 (M 7.5)
- Earthquake east off the coast of Fukushima Prefecture, November 1938 (M 6.5)

Earthquakes in north-eastern Japan were grouped into: (1) those near the Japan Trench; (2) those near plate boundaries; (3) those within the Earth's crust under land; and (4) those within the sinking Pacific Plate. The following earthquakes were regarded as possible near the Fukushima Daiichi site:

- Earthquakes near the plate boundary: The largest earthquakes in the ocean near the site were in Rikuzen in 1646 and in Sendai in 1835. The Sendai earthquake had magnitude of M 7.6. The maximum potential magnitude for earthquakes in the area was estimated to be 7.75. It was therefore assumed that an earthquake with a magnitude of M 7.8 could occur near the plate boundary off the coast of Fukushima Prefecture ($\Delta = 50$ km, epicentre depth (H) = 40 km).
- Land based earthquakes: The largest earthquake on land near the site was in Nikko in 1683. It was likely to have been between M 7.3 and M 7.5. Due to connections with active faults in the area, it was assumed that an M 7.5 earthquake could occur in the western marginal fault zone of the Fukushima Basin ($\Delta = 65$ km).

Analysis of destructive earthquakes in these areas led to the following conclusions:

- M 8 class earthquakes occurring near the Japan Trench and further eastward had little impact at the power plant because they were so far away.
- Earthquakes around M 7.5 occurred offshore of Miyagi, Fukushima and Ibaraki prefectures near plate boundaries.
- Earthquakes around M 7.0–7.5 were thought to occur in the Earth's crust under land west of the Ou Mountains, the Kitakami River basin and near Nikko.
- No large earthquakes that could impact the Fukushima Daiichi site were likely to occur inside the sinking Pacific Plate.

Therefore, the EP concluded that the Fukushima Daiichi site was in an area of little seismic activity, and the design basis for the plant was based on large intra-slab earthquakes (up to M 7.1) beneath the site.

For Units 1 and 2, the original design basis for the seismic horizontal ground motion was calculated to be 250 Gals for the zero period ground acceleration (ZPGA), with 470 Gals static acceleration. The seismic design basis was re-evaluated under guidelines that were revised in 2006, and the results were submitted to NISA in 2008. The re-evaluation increased the design basis horizontal acceleration for all units except for Unit 6 and added a vertical acceleration design basis as shown in Table 1.2–5.

TABLE 1.2–5. DESIGN BASIS GROUND MOTION FOR FUKUSHIMA DAIICHI NPP UNITS [62]

Fukushima Daiichi NPP Unit	Maximum response acceleration value (Gal)					Static horizontal acceleration (Gal)
	Revised design basis (2008)			Original design basis (1966)		
	N/S*	E/W**	U/D***	N/S*	E/W**	
Unit 1	487	489	412	245		470
Unit 2	441	438	420	250		470
Unit 3	449	441	429	291	275	470
Unit 4	447	445	422	291	283	470
Unit 5	452	452	427	294	255	470
Unit 6	445	448	415	495	500	470

Note: *North/South; **East/West; ***Upwards/Downwards.

1.2.6. Description of the Fukushima Daiichi plant systems

This section describes the Fukushima Daiichi NPP's BWRs. It focuses on the major structures, systems and components (SSCs) most relevant to preventing, protecting and mitigating accidents, specifically the systems for shutdown heat removal, overpressure protection, emergency core cooling, containment, off-site power configuration, on-site emergency power generation and fission product release prevention. Response and behaviours of these systems are evaluated in Technical Volume 2, Section 2.2.

1.2.6.1. General plant characteristics of the Fukushima Daiichi reactors

In general, BWRs use a closed, two-phase, direct steam cycle loop to remove heat from the reactor core, as shown schematically in Box 1.1–1. The working fluid is demineralized water that is used both as the coolant to remove heat and the moderator for controlling the reactivity. During normal operation, bulk boiling of coolant water at a pressure of approximately 7 MPa (70 bar) takes place in the core, where the core exit steam quality reaches around 15% or less. This corresponds to a core exit void fraction of around 65% or less at the operating pressure of 7 MPa (70 bar). After passing through the turbines, the steam is condensed to water by being cooled by the condenser tubes that are filled with cold water taken from a heat sink, e.g. the ocean. The water resulting from condensation is then pumped back to the reactor as feed water.

The evolution of BWR technology during the 12 years from the start of construction on Unit 1 in 1967 to commercial operation of Unit 6 in 1979 was reflected in the six reactors of the Fukushima Daiichi NPP. After Unit 1, which was an earlier BWR/3 design, Units 2–5 were BWR/4 designs and Unit 6 was a BWR/5 design, which was the first unit with a capacity of 1100 MW(e). Some of the differences in design information and characteristic are noted in Tables 1.2–6 and 1.2–7.

TABLE 1.2–6. COMMERCIAL DESIGN INFORMATION FOR THE FUKUSHIMA DAIICHI NPP REACTORS [63]

Description	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5	Unit 6
Reactor type	BWR/3	BWR/4				BWR/5
Electrical output (MW(e)) (gross)	460	784	784	784	784	1100
Thermal output (MW(th))	1380	2381	2381	2381	2381	3293
Commercial operation start	March 1971	July 1974	March 1976	October 1978	April 1978	October 1979

Unit 1 licensed power (operating maximum power) was in ‘MW-electric’ output, while the other Fukushima Daiichi units were operated at licensed ‘MW-thermal’ power.[71]

TABLE 1.2–7. MAJOR DESIGN CHARACTERISTICS OF THE FUKUSHIMA DAIICHI NPP REACTORS [63]

Description	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5	Unit 6
Reactor pressure vessel inner diameter (m)	4.8	5.6	5.6	5.6	5.6	6.4
Reactor pressure vessel height (m)	20.0	22.0	22.0	22.0	22.0	23.0
Reactor pressure vessel total weight (t)	440	500	500	500	500	750
Reactor pressure vessels design pressure (gauge)	8.62 MPa (86.2 bar)					
Reactor pressure vessel design temperature (°C)	302					

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[71] In Japanese regulation, for the Establishment Permit, the licensed power is the reactor system thermal output, while the Construction Plan review licences the electric output. Starting in 2000, it has been allowed to operate in larger electrical output than the licensed value in the Construction Plan, providing that thermal output is limited by the licensed thermal output of Establishment Permit. An evaluation showing that turbine and generator systems can be operated in these circumstances had to be completed and accepted by the regulatory body, NISA.

1.2.6.2. Heat generation

In BWRs, the heat is generated in the core that is composed of the fuel assemblies, which are the fuel pins bundled in square arrays and enclosed in a zirconium alloy fuel channel box[72], and the control rods, which are cross-shaped arrangement of blades containing boron carbide (B_4C) neutron poison. The fuel pins consist of low enrichment uranium oxide or mixed (uranium and plutonium) oxide (MOX) fuel pellets enclosed and sealed in zirconium alloy cladding tubes.

The BWR fuel design and reactor core arrangements evolved over the years. The reactor cores in the Fukushima Daiichi NPP units at the time of the accident had some differences in their arrangements as shown in Table 1.2–8. Section 1.4 provides further details of the fuel composition.

TABLE 1.2–8. THE FUKUSHIMA DAIICHI NPP REACTOR CORES [64, 65]

Description	1	2	3	4	5	6
Fuel assembly (No. of assemblies in the core)	400	548				764
High burnup 8 × 8 fuel assemblies	68	—	—	—	—	—
9 × 9 fuel (A type) assemblies	—	—	516	—	—	—
9 × 9 fuel (B type) assemblies	332	548	—	548	548	764
8 × 8 MOX fuel assemblies	—	—	32	—	—	—
Number of control rods	97	137				185

1.2.6.3. Shutdown heat removal

Normal shutdown cooling of BWRs at high reactor pressure is accomplished by directing the steam from the reactor to the main condenser, bypassing the turbines (see Box 1.1–1). However, when the reactor is isolated, i.e. the main steam isolation valves (MSIVs) are closed, the turbine bypass path is not available and shutdown cooling is provided by the systems designed for an isolated reactor under high pressure conditions. In the design of the Fukushima Daiichi NPP, those were: the isolation condenser (IC) system for Unit 1 (the earlier design) and the reactor core isolation cooling (RCIC) system for Units 2–6.

When the reactor temperature is lowered enough by depressurization[73] by high pressure shutdown cooling systems, the shutdown cooling at low pressure is provided by a shutdown cooling (SHC) system for Unit 1 and residual heat removal (RHR) systems for Units 2–6.

High pressure heat removal systems

Isolation condenser system

In the BWR/3 design (Unit 1), there are two separate and redundant IC loops (Trains A and B) with separate isolation logic circuits, each powered by a separate power supply. In these closed loops, the primary side of the IC received steam is generated in the reactor and is condensed it by cooling inside

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[72] The functions of the fuel channel are to position the rod bundle, provide guide surfaces for the control rods that are inserted between the fuel assemblies, and allow for flow to the individual assemblies through orifices.

[73] In BWRs, the reactor cooldown is monitored and controlled by the reactor pressure which, in turn, corresponds to the reactor temperature.

the heat exchanger tubes that are submerged in colder water tanks (isolation condenser pools) located outside the PCV. Condensed steam is then sent as cold water back to the reactor by gravity (Fig. 1.2–8). Without mixing with the radioactive primary side water, the secondary side water in the IC pools boiled, and the evaporated steam is vented to the atmosphere, which served as the heat sink. The secondary side water volume of the IC (both trains together) is sufficient for eight hours of cooling before requiring replenishment [15] from a dedicated water source. Make-up of secondary water is provided from the fire water system or other suitable water source.

As shown in Fig. 1.2–8, there are two isolation valves on the steam lines going into each IC and two isolation valves on condensate lines coming out of each IC. The outboard valves (i.e. the valves outside the containment) on the condensate lines (MO-3 in the figure) are closed during normal operation. The inboard valves (i.e. the valves inside the containment) on the condensate lines (MO-4 in the figure), as well as the inboard and outboard valves on the steam lines (MO-1 and MO-2 in the figure) are normally kept open. The control of the IC is kept in automatic mode during normal operations, and if the pressure in the reactor exceeds and remains above the set point of 7.13 MPa (71.3 bar) (gauge) for longer than 15 seconds [63], the valves on the condensate line will open, enabling operation of IC.

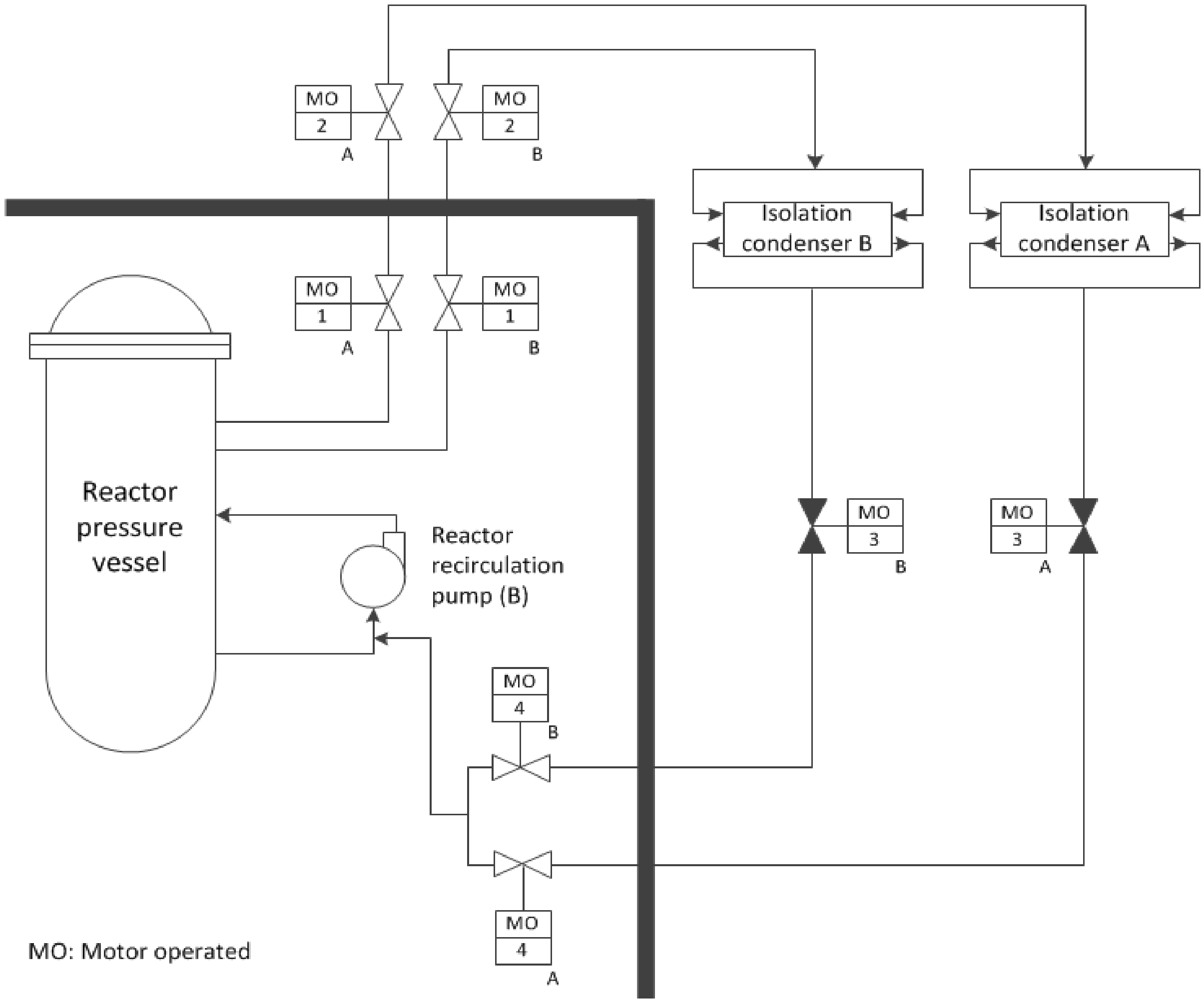

FIG. 1.2–8. Schematic of isolation condenser (IC) [1].

By conserving the water in the reactor pressure vessel (RPV), ICs eliminate the need for additional high pressure make-up systems. By removing decay heat, the system also limits reactor pressure increases to below the safety relief valve (SRV) set points and prevents the SRV from being activated following reactor isolation.

All steam line valves and condensate line valves are designed to shut automatically to isolate the IC system if sensors detect high IC steam flow or high condensate return flow, either of which would indicate a line break.

The actuation of inboard steam supply and condensate return isolation valves are AC powered, and the outboard steam supply and condensate return isolation valves are DC powered. Both inboard and outboard isolation valves fail ‘as-is’ upon loss of actuation power. Also, if the power to control the system circuit is lost, all valves will fail ‘close’ as long as the actuation power is available.

The IC system instrumentation and control circuitry consists of initiation and containment isolation logic circuits. These circuits provide different functions, both of which are important to system reliability. The initiation circuitry provides for automatic and manual start of the system. The purpose of the containment isolation circuitry is to initiate closure of appropriate primary containment isolation valves to limit fission product release should a steam line rupture occur. The IC system is automatically isolated if high IC steam flow or condensate return flow is sensed, indicating a line break. This isolation shuts all the steam and condensate isolation valves and the steam line vent valves, rendering the IC system inoperable. The steam line vent valves will also automatically shut on a low vessel water level condition. Isolation of the vent valves for a prolonged period of time could render the heat exchanger inoperable due to the build-up of non-condensable gases. However, failure of this circuit to close the vent valves would not preclude operation of the system.

Reactor core isolation cooling system

In the BWR/4 designs (Units 2–6), shutdown cooling at high pressure is achieved by reactor core isolation cooling (RCIC) systems. These systems are open cycle cooling systems that consist of a turbine driven pump, associated piping, valves and instrumentation and control circuits, and a source for adding water to the reactor system. The system is designed to operate initially on an open cycle, taking water from a dedicated water source and injecting it into the RPV either through a main feedwater line (Units 2–5) or a reactor vessel head spray nozzle (Unit 6).

The steam from the reactor drives a small turbine which, in turn, runs a pump that injected water into the reactor at high pressure (Fig. 1.2–9). The steam that runs the turbine is discharged and accumulated in the suppression pool section of the PCV, which serves as the heat sink for absorbing waste heat. The water lost from the reactor is replenished by taking water from a dedicated water source.

During normal operations, the RCIC controls are kept in automatic. When the reactor is isolated, the pressure in the RPV increases and SRVs open to discharge steam and reduce the RPV pressure, resulting in the reactor water level decrease. The RCIC system is started automatically if low water level signals are detected in the reactor. Initially, the turbine-driven pump supplies make-up water from the condensate storage tank (CST) to the reactor vessel at the normal reactor operating pressure. When the CST water level is low or the suppression pool water level is high, the suction line from the CST is isolated and the RCIC pump takes water that has accumulated in the suppression pool, making the system essentially a closed loop cycle.

The start and operation of the RCIC system is independent of external AC power sources, since the primary motive energy is from the steam in the reactor vessel, while all the valves to control the amount of water injection are driven by DC power from the batteries. The required mission time for the RCIC in the Fukushima Daiichi NPP units in an SBO situation was four hours [8]. The RCIC can operate longer depending on the manipulation of plant systems consuming DC power.

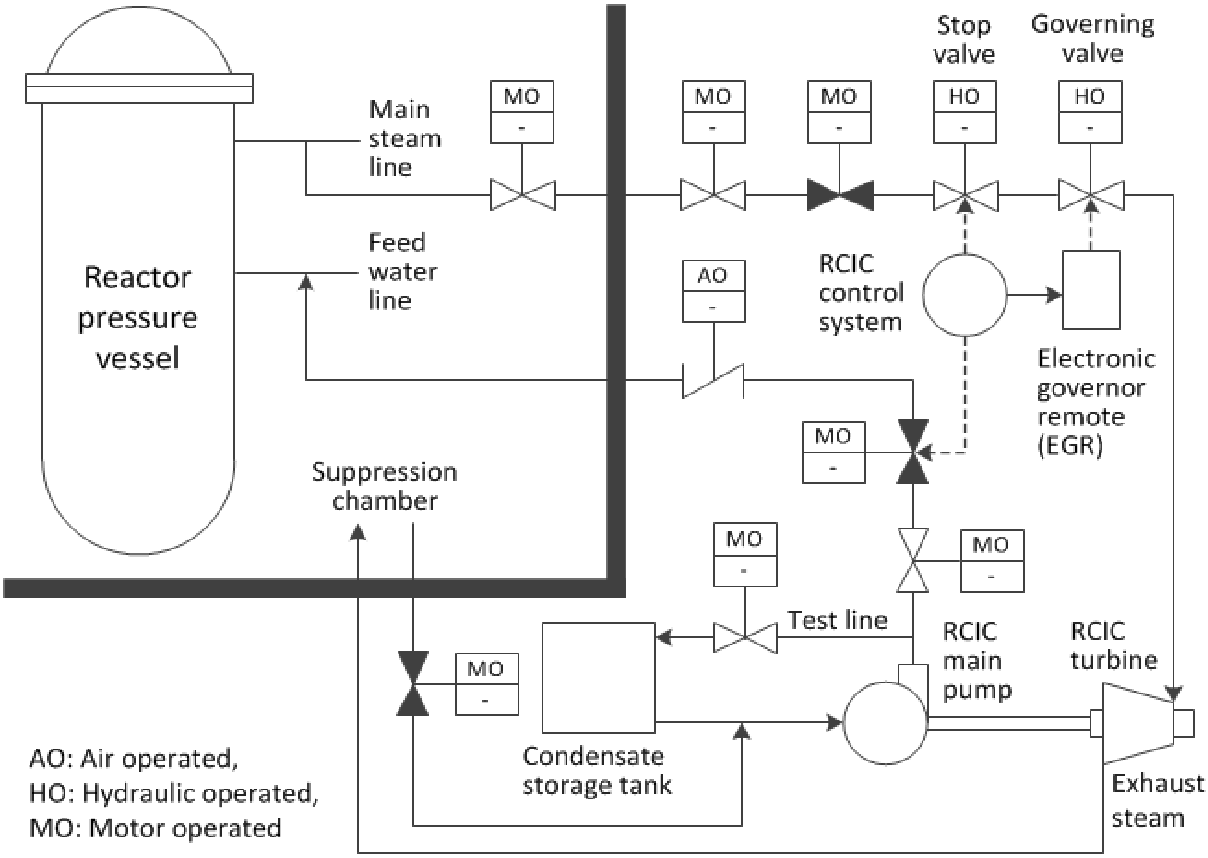

FIG. 1.2–9. Schematic of reactor core isolation cooling (RCIC) [1].

During the RCIC operation, the discharged energy to the SC will heat up the suppression pool. To keep the suppression pool temperature within prescribed limits under longer period of RCIC operation, the residual heat removal (RHR) system can be used to cool the suppression pool and complete the heat transfer path to the ultimate heat sink. However, the operation of the RHR systems' pumps and motor operated valves require AC power from off-site sources or on-site emergency AC power sources.

Low pressure heat removal systems

The Fukushima Daiichi NPP's Unit 1 had a shutdown cooling (SHC) system, and Units 2–6 had residual heat removal (RHR) systems to cool the cores after initial cool down by the high pressure heat removal system and depressurization to about 0.862 MPa (8.62 bar).

In the SHC system, hot water flows into the heat exchangers from a reactor recirculation loop, on the suction side of an idle recirculation pump. After being cooled in the heat exchangers, the water feeds back into either a main feedwater line or a recirculation line on the discharge side of an idle recirculation pump.

Similarly, the RHR system provides for post-shutdown core cooling after the initial cooldown and depressurization by the RCIC system. A residual heat removal and cooling seawater (RHRS) system, i.e. service water loop for the RHR system, supplies the cooling water to the RHR heat exchangers.

Because the RHRS system pumps have a relatively high discharge pressure (about 2.2 MPa (22 bar)), the system can also be utilized for an emergency flood of the core at lower pressures, or the PCV. This can be done by opening the cross-tie between the RHRS and the RHR return line to the reactor coolant system (RCS). In a multimode RHR system, this return line branches to the RPV, the suppression chamber (SC) and the drywell (DW).

1.2.6.4. Overpressure protection

In the design of the Fukushima Daiichi NPP units, overpressure protection is provided by means of safety valves (SVs) and/or safety relief valves (SRVs), which are connected to the four main steam lines (Fig. 1.2–10).

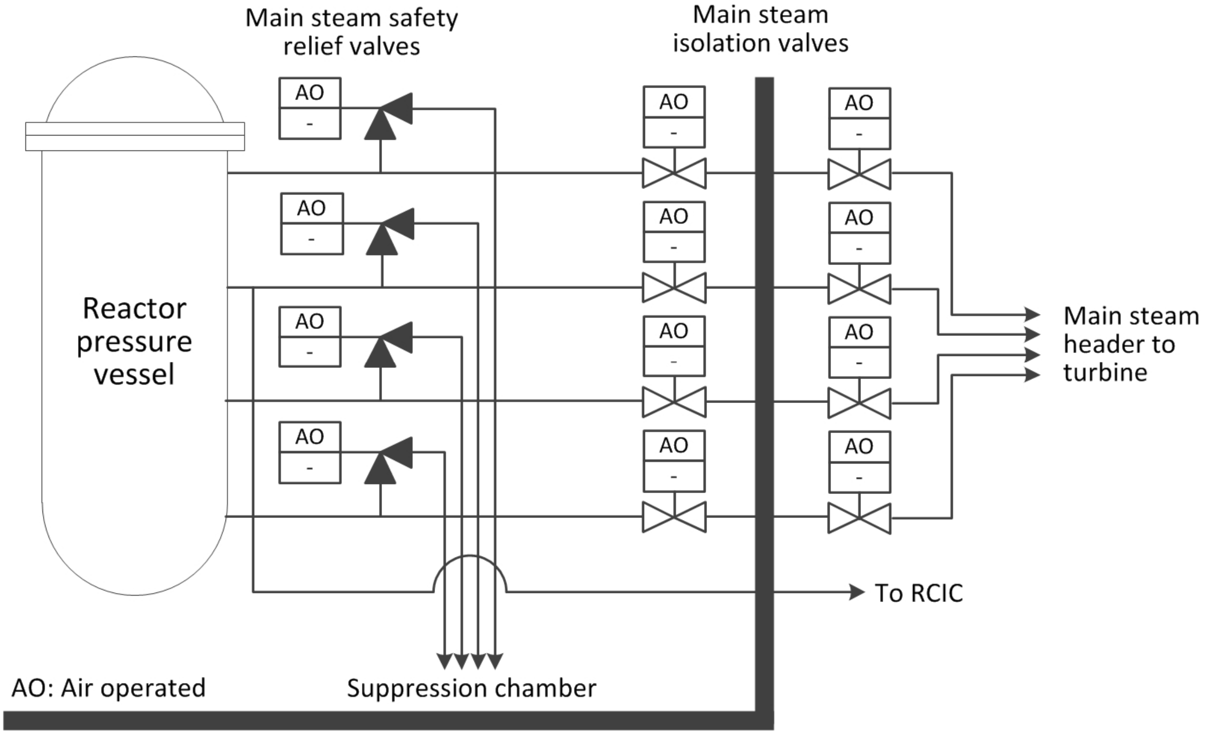

FIG. 1.2–10. Typical safety relief valve arrangement [1].

Fukushima Daiichi units provide for RCS overpressure protection, pressure relief, and RCS depressurization in various ways. The safety/relief valves are capable of both lifting mechanically on high pressure and being actuated at lower pressures to perform either the pressure relief or the automatic depressurization system (ADS) function.

- In the earliest plants (BWR/1 and some BWR/2 types) overpressure protection was provided by safety valves that mechanically open on high pressure in the RCS. In these plants, the automatic depressurization system (ADS) function is accomplished by ‘Electromatic’ type power-actuated relief valves (PARVs) that are controlled by a solenoid pilot valve.
- In the BWR/3 product line (Unit 1), the trend was away from PARVs to safety/relief valves that were capable of both lifting mechanically on high pressure and being actuated at lower pressures to perform either the pressure relief or the ADS function.
- In the BWR/4 product line (Units 2–5), the trend was away from safety valves to safety/relief valves for accomplishing the overpressure protection function.
- Later BWR/4 models, and all BWR/5 (Unit 6) plants only use safety/relief valves to accomplish the overpressure protection, pressure relief and ADS functions.

Based on their age and design, therefore, the Fukushima Daiichi NPP units had different overpressure protection configurations. Units 1–3 each had 3 SVs that discharged steam to the DW in addition to the SRVs (4 SRVs in Unit 1 and 8 SRVs in Units 2 and 3) that discharged to the SC. Units 4 and 5 had 11 and Unit 6 had 18 SRVs discharging to the SC. Some of the SRVs were also used for the ADS, as mentioned in the next section.

1.2.6.5. Emergency core cooling systems

BWRs are equipped with a safety grade emergency core cooling system (ECCS) to mitigate adverse effects of a loss of coolant accident (LOCA) by maintaining core cooling to prevent core damage. These systems also play a role in beyond design basis accidents (BDBA), and anticipated transient without scram (ATWS) and station blackout (SBO).

Depending on the age and design, the ECCS of a BWR may include various high and low pressure systems as well as the depressurization systems:

- A typical BWR/5 (Unit 6) employs high pressure core spray (HPCS), low pressure core spray (LPCS), ADS and low pressure coolant injection (LPCI) as parts of the ECCS.
- A typical BWR/4 (Units 2–5) employs high pressure coolant injection (HPCI), core spray (CS), ADS and LPCI as parts of the ECCS.
- As an earlier BWR/3 product line, Unit 1's ECCS does not include LPCI.

High pressure coolant injection system

The HPCI applies to the Fukushima Daiichi Units 1–5. It is a safety system designed to maintain adequate reactor vessel water inventory and core cooling during small break LOCAs. It also aids depressurization of the reactor vessel to allow low pressure ECCS to inject during intermediate break LOCAs. Under reactor vessel isolation conditions, it also serves as the backup to the non-safety RCIC system[74].

The HPCI system is an independent ECCS; it does not require AC power or instrument air to perform its function. The HPCI system consists of a turbine, turbine driven pump and the auxiliary systems required for turbine operation and associated piping and instrumentation.

The HPCI system initially operates on an open cycle, taking water from the CST, as illustrated-in Fig. 1.2–11, and injecting into the reactor vessel via a main feedwater line. When the CST water level is low or the suppression pool water level is high, the HPCI pump suction is aligned to the suppression pool and the suction line from the CST is isolated. Heat from the primary system is transferred to the suppression pool by the continuous or intermittent operation of the SRVs. Suppression pool cooling must be initiated to complete the heat transfer path to the ultimate heat sink. The HPCI system provides primary system make-up at RPV pressures ranging from the operating pressure to injection pressure of low pressure ECCS (Table 1.2–9). By supplying cool water and using the steam generated by the decay heat for driving the HPCI turbine, the reactor depressurizes and allows the injection by the low pressure ECCS. When the primary steam pressures are less than about 1 MPa (10 bar), the operation must be terminated because of poor steam conditions for the two-stage HPCI turbine drive that would affect the system's reliability.

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[74] The flow capacity of an HPCI is about ten times higher than that of an RCIC.

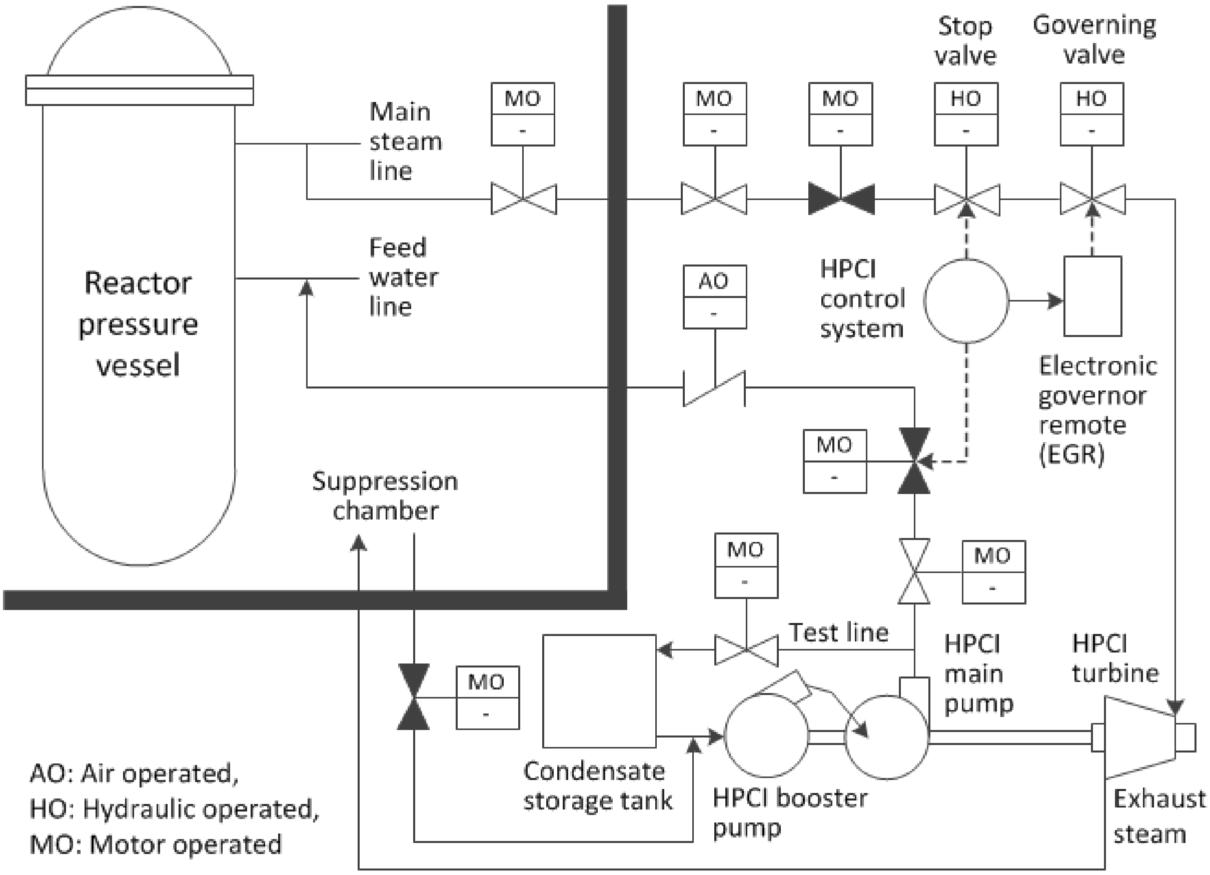

FIG. 1.2–11. Schematic of high pressure coolant injection (HPCI) system [1].

TABLE 1.2–9. HPCI PARAMETERS [63]

Description	Unit 1	Units 2–5	Unit 6
Reactor pressure (MPa)	72–10.3	72–10.3	72–10.3
Flow (m^3/h)	682	965	965

System initiation can be accomplished by automatic signals or remote-manually from the main control room (MCR). Receipt of either a low reactor water level or high drywell pressure indication will automatically start the HPCI system.

The 125 V DC power supply provides the energy for the controller, the motor operated valves; hence, if DC power is lost, the function to control the HPCI will cease.

In the Fukushima Daiichi Unit 6 (BWR/5), the high pressure ECCS subsystem was the HPCS system, which has a single motor driven pump that initially operates on an open cycle, taking water from the CST, as illustrated in Fig. 1.2–12, and injecting into the reactor vessel via a spray sparger located above the reactor core. Similar to the HPCI system, when the CST water level is low or the suppression pool water level is high, the HPCS pump suction is aligned to the suppression pool, and the suction line from the CST is isolated; suppression pool cooling must be initiated to complete the heat transfer path to the ultimate heat sink.

Automatic depressurization system

Under the scenario of a high pressure core cooling system failure, the ADS is designed to rapidly reduce the RPV pressure to allow the low pressure emergency core cooling systems to work upon a predetermined low reactor water level signal and high PCV pressure signal. The actuation signal of the ADS controls solenoid valves feeding nitrogen gas into the SRV cylinder from the ADS accumulator to open the SRV.

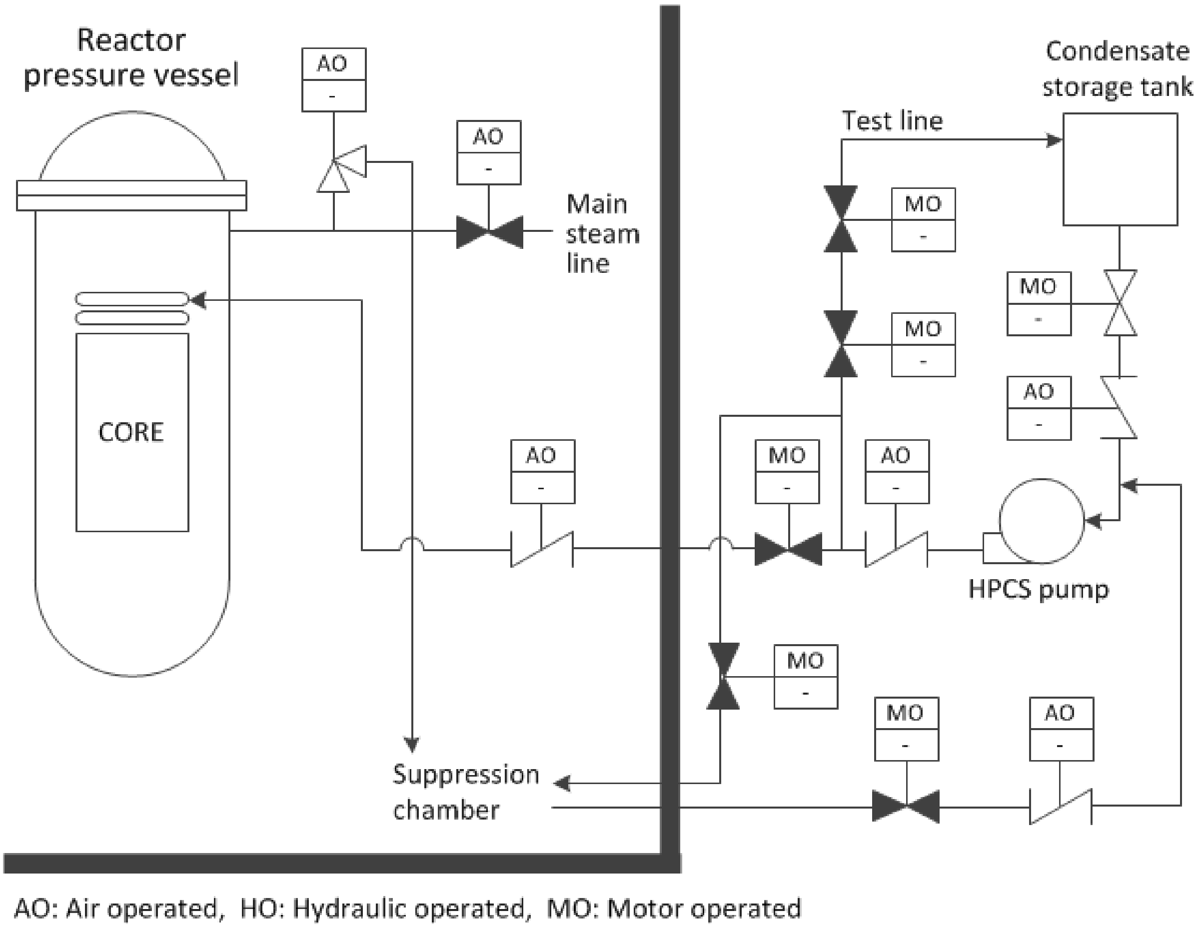

FIG. 1.2–12. Schematic of high pressure core spray system (HPCS) [1].

Core spray system

The purpose of the core spray (CS) system, which was in the design of all Fukushima Daiichi NPP units, is to provide low pressure make-up water to the reactor vessel for core cooling under LOCA conditions. All Fukushima Daiichi NPP units, like all BWRs, the core spray system was designed to inject water from the suppression pool to the core at low pressures using one or more spray spargers located above the core. The CS system automatically initiates upon receipt of either a predetermined low level reactor vessel water level signal or a high drywell pressure. The water was delivered by motor-driven pumps that required AC power to operate.

The CS system in the Fukushima NPP Units 1–5 (BWR/3 and BWR/4s), consisted of two 100% capacity trains with two separate spargers, while in Unit 6 (BWR/5), there was a single-train low pressure core spray (LPCS) system that was supplemented by a single-train HPCS system to provide a redundant low pressure core spray capability. These LPCS and HPCS systems in Unit 6 were designed to inject through independent loops, each containing a low pressure pump, minimum flow line, test line, spray sparger and the associated motor operated valves and instrumentation necessary to perform its function.

Low pressure coolant injection system

In addition to the CS system, the ECCS of BWRs (except BWR/3, i.e. Unit 1) is equipped with an LPCI system that provides a core flooding capability at low pressures. This ECCS subsystem was introduced into a later BWR designs as a dedicated injection system (i.e. not integrated into a multimode RHR system) that delivered water from the suppression pool. The LPCI systems in the Fukushima Daiichi NPP Units 2–5 (BWR/4) were designed to inject via a recirculation loop, while the LPCI system in Unit 6 (BWR/5) had a direct injection path into the reactor vessel, inside the core shroud.

In the Fukushima Daiichi NPP Units 2–6, the LPCI system was an operating mode of the RHR system, constituting one of the ECCSs. In the LPCI mode for post-LOCA long term cooling, the RHR pumps take water from the suppression pool and feed back into the reactor. Spills from the break return to the suppression pool, establishing a closed loop for post-accident cooling.

The LPCI part of the ECCS was never utilized during the accident, since Unit 1 did not have an LPCI system, and, in other units, its operation required AC power.

1.2.6.6. Containment systems

Units 1–5 at the Fukushima Daiichi NPP had Mark-I containments, while Unit 6 had a Mark-II containment. Both designs use a common pressure suppression concept to condense steam from the RPV before it can create high pressure in the containment.

The BWR containments have two fission product barriers: the primary containment, or primary containment vessel (PCV), and the secondary containment, or reactor building (RB). The PCV has two major compartments. The compartment where the reactor vessel is located is the drywell (DW). The DW is connected to the second compartment, the suppression chamber (SC), which holds a large amount of water and enough space to suppress pressure increases and store increased amounts of water.

During normal operation, both the Mark-I and Mark-II containments are filled with nitrogen to provide prompt control of any hydrogen generated during an accident. If accumulation of hydrogen does build up, hydrogen recombiners equipped inside the PCV are started, if AC power is available, to avoid possibilities of hydrogen deflagration or detonation. They are not, however, installed in the RB outside the PCV.

If there is a severe accident in which the core is damaged, the suppression pool can also be used to ‘scrub’ some radioisotopes out of gases that might be discharged to reduce their radioactivity.

The RB surrounds the primary containment and provides the second fission product barrier and is commonly called as secondary containment. In case of an accident, the standby gas treatment system (SGTS), which needs AC power for operation, filters the gases and keeps the inside pressure below the atmospheric pressure to prevent radioactive materials release. Fig. 1.2–13 shows the containment configuration used in Unit 1. The same configuration, with some minor differences, was also used in Units 2–5.

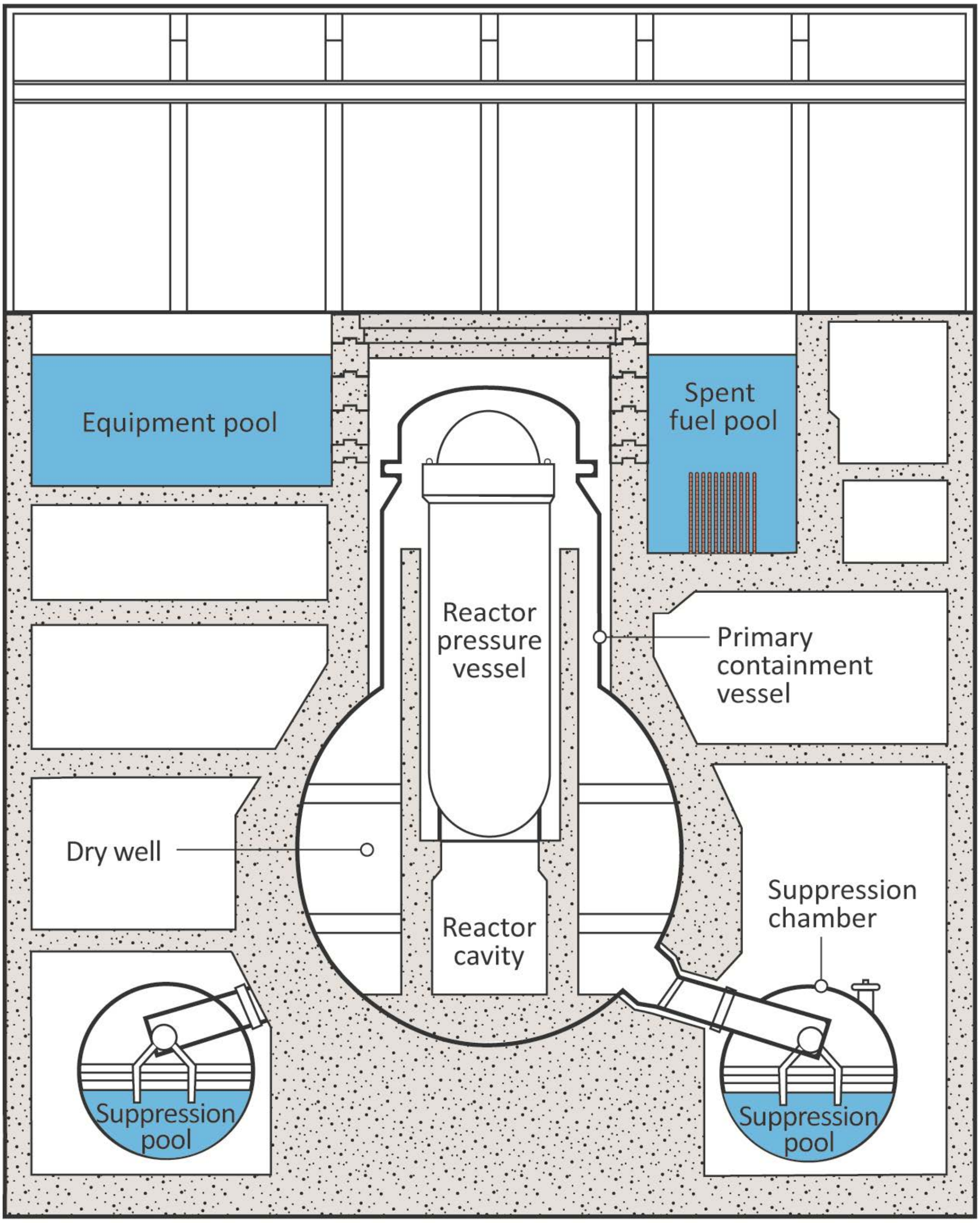

FIG. 1.2–13. Simplified representation of the Mark-I containment configuration [66].

The inverted light bulb shape of the DW is the distinctive characteristic of the Mark-I design. The DW is connected to a toroidal shaped compartment of the SC via large ducts. The torus contains a large amount of water, called the suppression pool. During a LOCA, the design allows hot steam to be vented through downcomer pipes and spargers to condense below the surface of the suppression pool water and reduce excessive pressure. The DW, the SC (including the suppression pool) and the connecting pipes are all part of the primary containment.

The Mark-II design uses the same pressure suppression concept as the Mark-I. Only Unit 6 at the Fukushima Daiichi NPP had a Mark-II containment, which is shown in Fig. 1.2–14.

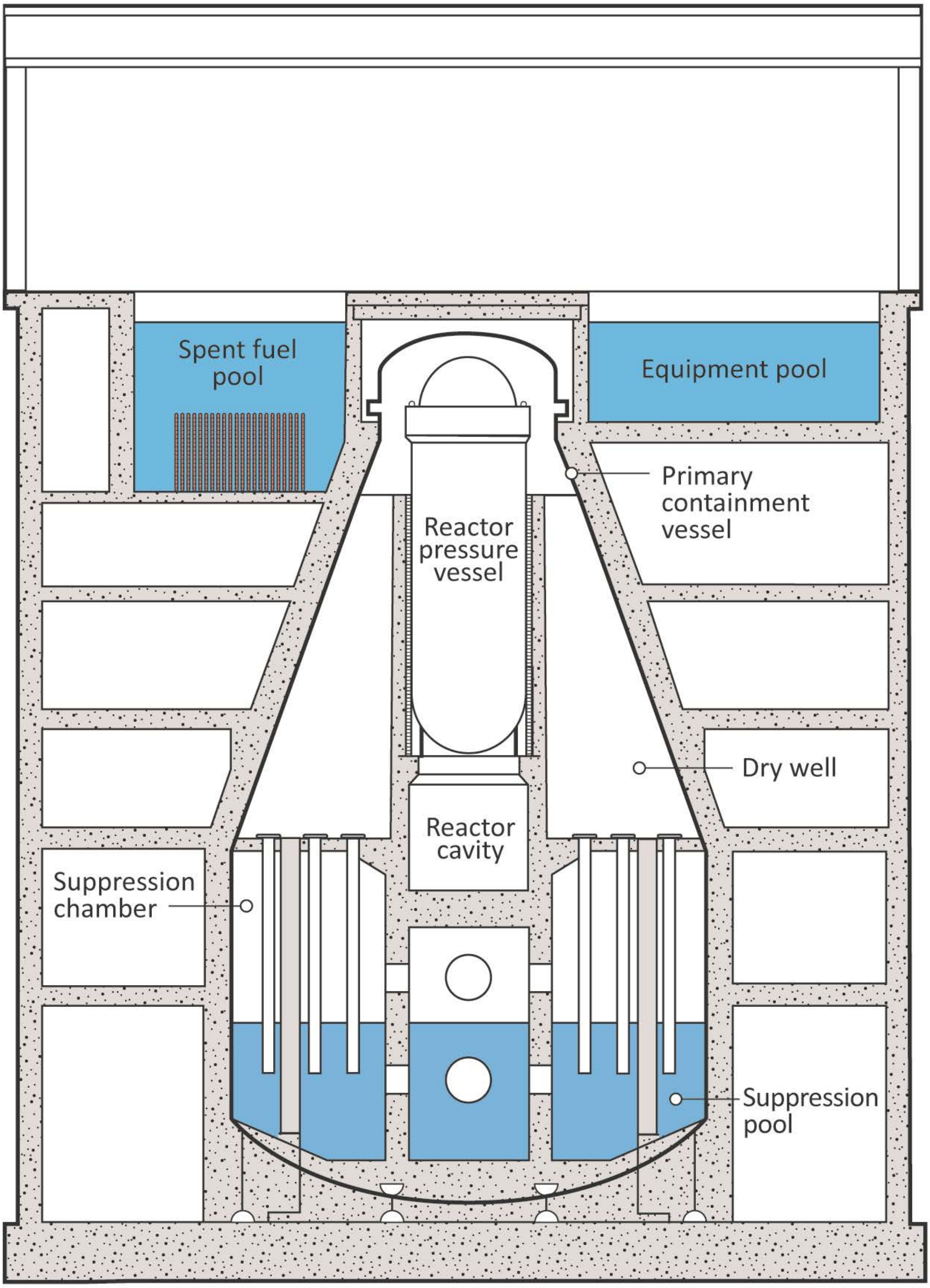

FIG. 1.2–14. Simplified representation of the Mark-II containment configuration [66].

1.2.6.7. Containment vents

As a measure to improve the ability to cope with severe accidents, ‘hardened vents’ (i.e. pressure relief devices with relatively thick walled discharge piping) were installed in the units at the Fukushima Daiichi NPP in the 1990s following a regulatory decision [21, 22]. The purpose of the containment venting system is to prevent overpressurization of the primary containment by allowing controlled release of energy inside the PCV. Although the preferred path of venting was from the SC, in order to benefit from the removal of radioisotopes by the water pool, the vent path included another route from the DW to allow rejecting higher energy from the containment to protect the integrity in a timely manner (Fig. 1.2–15). Either path could be aligned by manipulating valves from the MCR, controlling the amount and duration of the release through a stack shared between the pair of units.

In the Fukushima Daiichi NPP, the vent line also contained a rupture disc that was set to burst when the containment pressure exceeded a pre-set pressure, thereby preventing premature venting. The underlying philosophy in Japan was not to vent until it was inevitable, and as a last resort for maintaining the integrity of the primary containment in order to delay or prevent the direct release of radioactive material to the environment. In line with the delayed venting strategy, venting through aligning the valves was procedurally delayed until the containment pressure had reached a value that was twice the design.

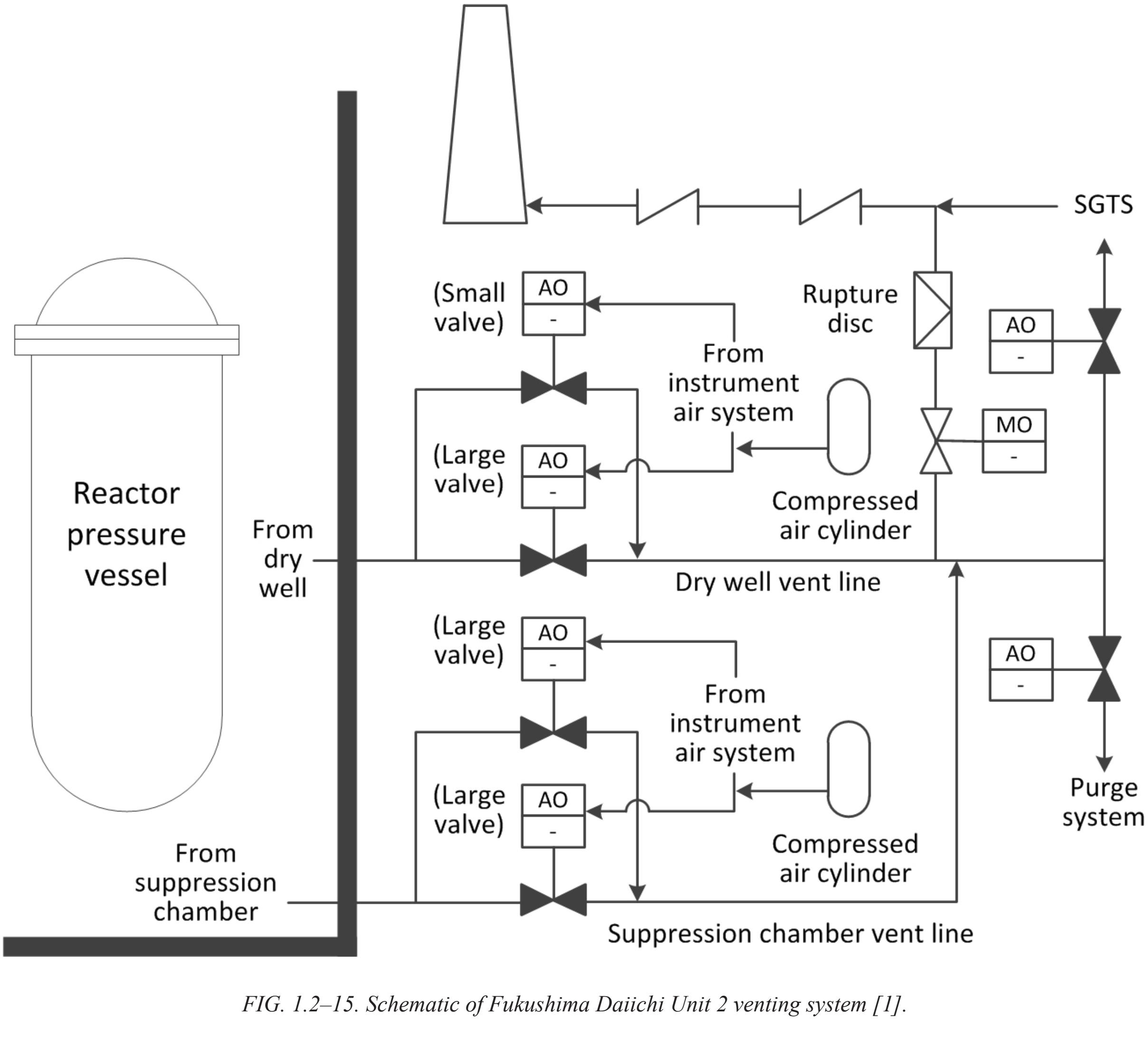

FIG. 1.2–15. Schematic of Fukushima Daiichi Unit 2 venting system [1].

1.2.6.8. *Off-site power configuration*

Off-site power for the Fukushima Daiichi NPP (Figs 1.2–16 and 1.2–17) consisted of a total of seven lines, with six transmission lines and one line feeding power to Unit 1 from Tohoku Electric Power Company (66 kV TEPCO Nuclear Circuit Line). Their supply to the units was as follows:

- Of the transmission lines from the Shin Fukushima Substation, Okuma Line 1L and 2L were connected to Units 1 and 2.
- Okuma Lines 3L and 4L were connected to Units 3 and 4.
- Futaba Lines 1L and 2L were connected to Units 5 and 6.
- The Yonomori Lines 1L and 2L were connected to Units 5 and 6.
- The TEPCO Nuclear Circuit Line was configured such that it could be connected, as a spare line, to the Unit 1 normal high voltage power panel.

Each line passed through a switchyard and fed on-site power systems.

Furthermore, in order to allow power to be supplied from (operating) main generators of adjacent units or transmission lines, the configuration allowed interconnection of normal high voltage power panels (metal clad switch gear, M/C) between Units 1 and 2, Units 3 and 4, and Units 5 and 6. However, there was no interconnection available across the Units 1–4 and Units 5–6 complexes.

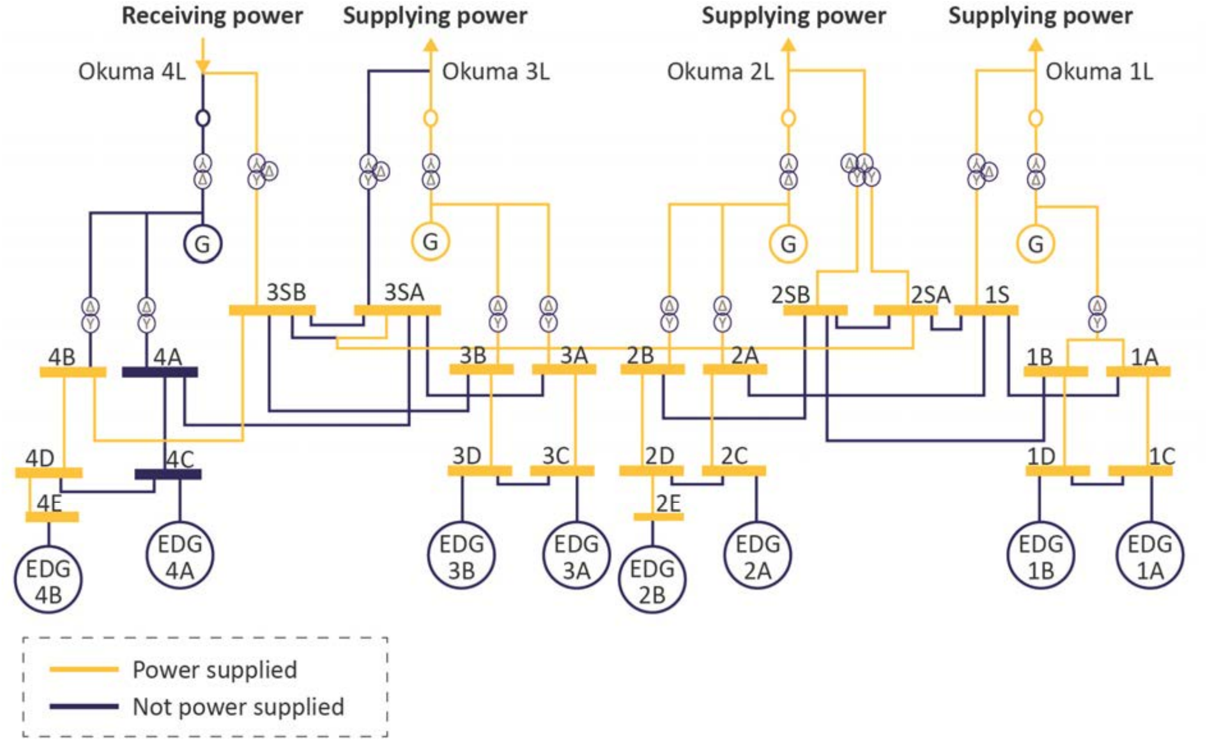

FIG. 1.2–16. Off-site power configuration for Units 1–4 [63].

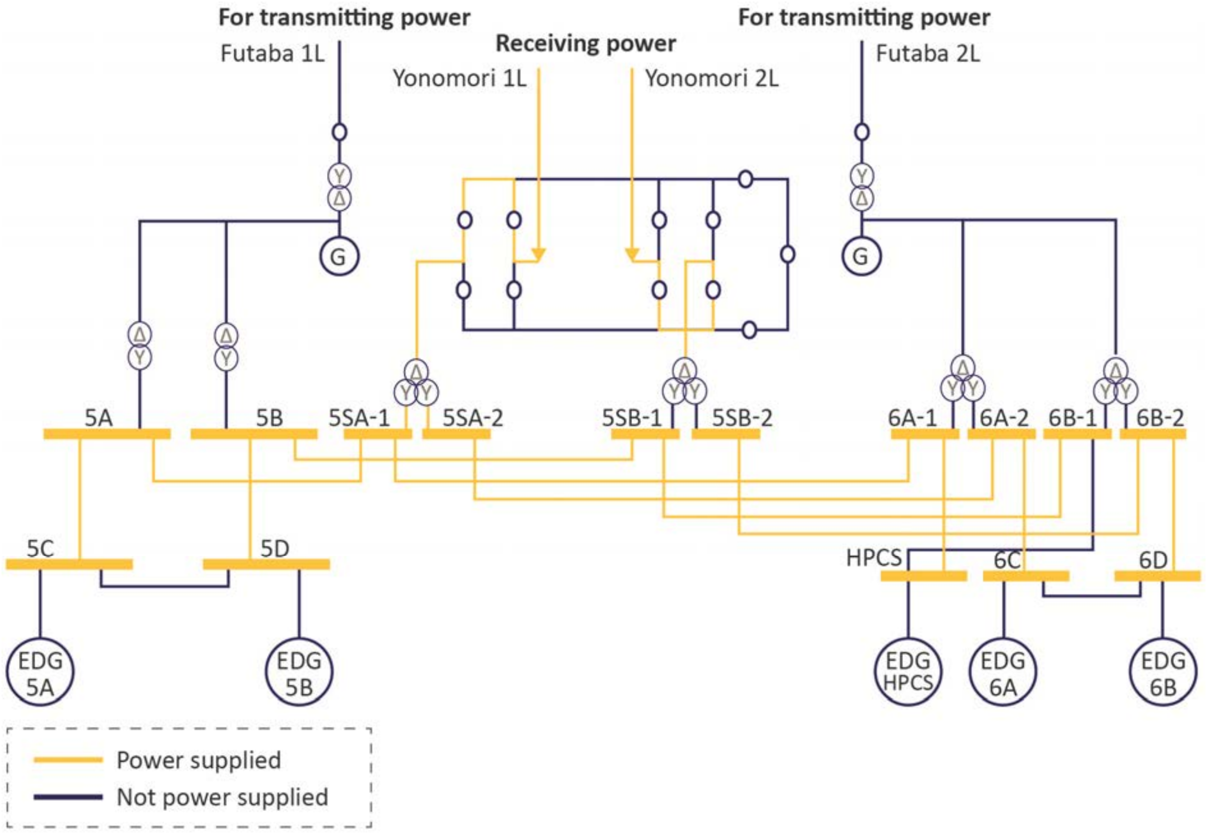

FIG. 1.2–17. Off-site power configurations for Units 5 and 6 [63].

1.2.6.9. On-site emergency power sources

Each unit at the plant was equipped with a redundant backup on-site power system composed of multiple emergency diesel generators (EDGs) to supply AC power, and a battery system to supply DC power.

During normal operation, the EDGs were idle, and the batteries were kept fully charged by battery chargers that also supplied the DC power loads. Nuclear power plants are designed to use their EDGs to withstand a loss of offsite power (LOOP) event and to use DC power sources (e.g. batteries) to cope with an SBO.

As shown in Table 1.2–10, Units 1–5 had two EDGs each and Unit 6 had 3 EDGs. In Units 2, 4 and 6, one of the EDGs was air cooled. These EDGs provided emergency AC power, if needed, to core cooling safety systems, as well as to charge the DC batteries. Most of the EDGs were located in the basements of the reactor or turbine buildings, i.e. 7–8 m below the plant grade.

NPPs are generally equipped with on-site DC and additional backup AC power sources (e.g. gas turbine generators or diesel engines) to withstand an SBO for a limited period of time varying between 4 and 72 hours[75]. The Fukushima Daiichi NPP units, similar to other plants of the same age, had design provisions to withstand an SBO with the DC battery capacity of eight hours. The batteries

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[75] The determination of the coping period is based mainly on the time that it would take to restore AC power sources to the NPP and the capacity of the available measures. During that time, equipment such as DC batteries, DC/AC inverters and other secondary backup AC sources (e.g. gas turbines or diesel generators) is used.

were located in the basements of the control building (Units 1, 2 and 4) or in the mezzanine levels of the turbine buildings (Units 3, 5 and 6).

TABLE 1.2–10. TEPCO'S FUKUSHIMA DAIICHI ON-SITE AC POWER SOURCES

Unit	Number of EDGs	Type	Location	Floor level
Unit 1	2	Water cooled	Turbine Building	Basement
		Water cooled	Turbine Building	Basement
Unit 2	2	Water cooled	Turbine Building	Basement
		Air cooled	Common Spent Fuel Pool Building	Ground
Unit 3	2	Water cooled	Turbine Building	Basement
		Water cooled	Turbine Building	Basement
Unit 4	2	Water cooled*	Turbine Building*	Basement*
		Air cooled	Common Spent Fuel Pool Building	Ground
Unit 5	2	Water cooled	Turbine Building	Basement
		Water cooled	Turbine Building	Basement
Unit 6	3	Water cooled	Reactor Building	Basement
		Air cooled	DG Building	Ground**
		Water cooled	Reactor Building	Basement

* Was in maintenance and out of service.
** The ground level of the Unit 6 DG Building is higher than that of Unit 1–3 TBs and Common SFP Building.

1.2.6.10. Additional accident management systems

Several modifications had been carried out in order to utilize existing facilities for AM measures, including:

- A new automatic depressurization function had been added recently to Units 2–6 as one of AM measures. It triggers the ADS without a DW high pressure signal and enables low pressure core cooling systems to work swiftly. Unit 1 did not have this function because it had two high pressure core cooling systems, IC and HPCI.
- Connecting lines and motor operated valves were installed to allow for injection of cooling water into the RPV from the FP through the MUWC system to the CS (in Unit 1) or the LPCI (in Units 2–6) by operating from the MCR.
- In order to prevent failure of the PCV due to overpressurization and release of radioactive materials, a new vent line was installed. It allowed operators to release PCV pressure remotely from the SC or the DW to the main stack. In case of DW venting, the scrubbing effect of the suppression pool water is expected to remove a majority of radioactive materials (as mentioned in Section 1.2.6).
- Power source cross-tie lines were installed to adjacent units, i.e. between Units 1 and 2, Units 3 and 4, and Units 5 and 6, to provide electricity to each other in case of all power loss.

Based on the experience at the Kashiwazaki-Kariwa NPP during the Niigata-Chuetsu-Oki earthquake of July 2007, the seismically isolated building had been constructed, which was equipped with a gas turbine generator as an independent power facility, telecommunication systems, a video conferencing system and a ventilation system with filters. The station ERC was established in this building, serving as the central point for accident response.

Also from lessons learned from the fire at the Kashiwazaki-Kariwa NPP, caused by the Niigata-Chuetsu-Oki earthquake, TEPCO had deployed fire engines to all its nuclear power stations by February 2010. TEPCO's Fukushima Daiichi NPP had three fire engines within its premises. However, core injection using the fire engines through the FP system was not a part of the AM.

1.2.7. Plant resources and capacity at the time of the accident

This section provides information on the availability, capacity and capability of resources (both human and equipment) which played a role in responding to and managing the event. It is organized to give a snapshot of the plant personnel and the physical and administrative tools available at the time of the accident and in the immediate aftermath.

1.2.7.1. Plant staffing

On 11 March 2011, Fukushima Daiichi NPP Units 1, 2 and 3 were in power operation and Units 4, 5 and 6 were undergoing planned refuelling outages. Prior to the earthquake, approximately 6400 employees (including contractors) were at the Fukushima Daiichi NPP site [63].

Of these 6400 employees, approximately 2400 workers (750 TEPCO personnel and 1650 contractors) were working in the controlled area, with the majority of those (approximately 2000) carrying out activities in support of the planned refuelling outages. A breakdown of the number of staff present and their locations at the time of the event is shown in Table 1.2–11.

TABLE 1.2–11. PERSONNEL CAPACITY AT THE TIME OF THE EARTHQUAKE [6]

Number of staff	Assignment location within the controlled area				Total
	Units 1 & 2	Units 3 & 4	Units 5 & 6	Common facilities	
Unit personnel	160	1200*	800*	240	2400
MCR personnel	24	29	44	—	97
On-shift operators in MCR	14	9	9	—	32
Work management operators in MCR	10	8	8	—	26
Outage support operators in MCR	—	12**	27	—	39

* 2000 of the 2400 workers within radiation control areas were concentrated in Units 3 and 4, and Units 5 and 6. This was due to shroud replacement work at Unit 4 and RPV leak test evolution at Unit 5.

** Supporting Unit 4 outage.

After the second tsunami wave, 33 additional incoming shift operations personnel joined the initial response shift listed above (17 operators in Units 1 and 2, 7 operators in Units 3 and 4, and 9 operators in Units 5 and 6) on the evening of 11 March.

As Table 1.2–11 illustrates, 32 on-shift operators were distributed among the three MCRs for Units 1–6, with additional support from 26 work management team members, who were also operators. The units that were in planned refuelling outage and 39 additional operators were supporting the outage activities in and around the control rooms.

Following the earthquake, a tsunami warning was communicated by the MCR staff via the plant internal announcement system. The initial prediction for the tsunami was 3–4 m in height[76], thus evacuation and reassembly instructions were provided mainly for personnel who were working at lower elevations. Based on the assignment on essential or non-essential duties, most of the personnel from the 4 m elevation were moved to topographically higher elevations, and the emergency response duty personnel reported to the seismically isolated building and began to staff and activate the Earthquake Emergency Response Team.

After the earthquake and tsunami, many contractors returned home, except for necessary personnel. At 17:08 on 11 March, it was announced that TEPCO employees should return home if they could. The evacuation by busses to evacuation areas began at 05:15 on 12 March and continued until 13 March mainly for contractors and TEPCO female employees that had evacuated to the seismically isolated building.

Following the evacuation of personnel after the earthquake and tsunami, approximately 400 people (about 130 TEPCO employees and 270 contract personnel for maintenance and outage work) remained on site for the continuing accident response process; this number included personnel dispatched from other sites to provide assistance.

During the response and recovery phase in the following days, additional personnel, both TEPCO staff and contractors' employees who were called in by TEPCO Headquarters ERC in Tokyo, reported to the site. Those personnel included, among others: a crew for restoring power and monitoring equipment, fire brigade units (who also operated fire engines to inject cooling water into reactors), a health physics team that monitored radiation levels within the Fukushima Daiichi NPP site and its surroundings and a procurement team for needed supplies (see Table 1.2–12).

TABLE 1.2–12. PERSONNEL DISPATCHED TO THE FUKUSHIMA DAIICHI NPP BY TEPCO HEADQUARTERS AFTER THE ACCIDENT (NUMBER OF TEPCO EMPLOYEES GIVEN IN PARENTHESES) [6]

Function	Days				
	11 March	12 March	13 March	14 March	15 March
Response/recovery	245 (152)	332 (257)	374 (304)	439 (346)	272 (253)
Fire brigade	—	10	6	21	31
Health physics	—	25 (25)	66 (25)	158 (42)	162 (42)
Procurement	11	87	52	38	55
TOTAL	256	454	457	540	400

1.2.7.2. Shared facilities

The close proximity of the six units on the Fukushima Daiichi NPP site, and the various pieces of shared equipment, were both an advantage and a challenge in the accident response and recovery efforts. An event at one unit that had a physical connection to other units could affect the progress of the accident at all the units, benignly or adversely. For instance, emergency response activities at one

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[76] The height of tsunami waves was forecasted by JMA to be 3–4 m at 14:50, then revised at 15:14 to 6 m, and revised again at 15:31 to 10 m.

reactor could be adversely affected by the progress of the accident at the adjoining units, while shared connections to available equipment could help operators respond to other aspects of the event.

In addition to the shared (common) equipment dictated by the design — e.g. off-site power lines, switchyard, electrical cross-ties, raw water tank, seawater intake structure, SGTS (common vent stack), fire protection system — there were other common structures that played a role in the response to and mitigation of the accident. These were:

- Common main control rooms (MCRs): For the Fukushima Daiichi site, one control room was shared between two units. Hence, each pair of units, Units 1 and 2, Units 3 and 4, and Units 5 and 6, shared a common control room. Although the unit control panels were separated, they were housed in one room, providing close interaction between the shift personnel controlling their respective unit under the command of one SS per MCR.
- Service building (SB) for unit personnel: Similarly, SBs in the controlled area were shared. Ingress/egress of personnel and equipment to the controlled area were through common gates, which included common exit personnel dose monitors/counters and common vehicle exit/entry gates.
- Seismically isolated building (activated after the earthquake): Emergency response functions for all six units at the Fukushima Daiichi site were conducted in the newly built earthquake hardened centre (built in response to lessons learned from the earlier Kashiwazaki-Kariwa seismic event).
- Firefighting equipment: The Fukushima Daiichi site had three fire engines and a nine person fire brigade that was shared among the six units at the time of the earthquake and tsunami.

1.2.7.3. Operating procedures

The procedures available to the operators determine the effectiveness, timeliness and appropriateness of actions to be taken during normal, abnormal, emergency and severe conditions. For design basis accident (DBA) response and management at the Fukushima Daiichi NPP, abnormal operating procedures (AOPs) and emergency operating procedures (EOPs) were utilized. The AOPs were event based, while the EOPs were symptom based and were primarily developed in accordance with the General Electric (GE) standard response procedures [67]. The EOPs also included the conditions for transition from EOPs to severe accident management procedures, to be applied after detection of core damage. EOPs were developed in Japan in the 1980s after the Three Mile Island accident in the United States of America in 1979. The AOPs were implemented, together with the installation of associated instrumentation and hardware (e.g. wide range monitors), around the same time [68].

For beyond design basis accidents (BDBAs), two sets of procedures were provided for utilization by the severe accident response and management personnel, inside and outside the MCR, respectively: (1) Severe Accident Operating Procedures (SOPs) for use in the MCR by the operators; and (2) Accident Management Guidelines (AMGs) for use in the technical support centre (TSC) in the ERC. The SOPs were designed for explicit actions to be taken on a given strategy, while the AMGs were designed for setting up the AM strategies. The AMGs contained figures and graphs of analytical results and provided the technical bases and criteria for the identification of plant conditions. Based on the AMGs, the TSC personnel established AM countermeasures and evaluated the outcomes. The SOPs contained the key action aspects of the AMGs and were prepared using a flow chart format to allow quick response by MCR staff to symptoms and facilitate recovery of systems (e.g. functional recovery procedures for RHR, EDGs, etc.).

Although the AOPs and EOPs were adopted from GE standard response procedures in Japanese BWRs, the development of severe accident response and management procedures, SOPs and AMGs, took a different approach from the Severe Accident Management Guidelines (SAMGs) developed by the United States BWR Owners' Group (BWROG) in the 1990s.[77] Developed by Japanese BWR utilities and owners under the guidance of the regulatory bodies, the severe AM strategy was established. In development of severe accident response and management, Level 1 and targeted Level 2 probabilistic safety assessments (PSAs) were applied in Japan, both by the regulatory body and the industry. AM measures were developed to address mitigation strategies, such as the utilization of conventional systems, electric power supply from an adjacent unit, alternative measures for reactivity control, water injection and heat removal and recovery of failed components. These measures were identified on the basis of PSA results obtained in the 1990s [68]. The industry was to have implemented these AM countermeasures programmatically for both physical and procedural aspects around 2000. TEPCO had implemented them by 2002.

Procedures relevant to the accident

At the Fukushima Daiichi NPP site, each unit had its own unit specific set of AOPs, EOPs, SOPs and AMGs. The following procedures are relevant to the accident and the associated response:

- The event based AOP, 'Natural Disaster Accident', Section IV, Natural Disasters, Chapter 22 [69], specified the post-earthquake actions to be taken and provided instruction for carrying out those actions in response to an earthquake event. This procedure had three levels, based on the intensity seismic activity: 1–10 Gal; 10–45 Gal; and greater than 45 Gal. The seismic event on 11 March 2011 met the criterion for the highest level which, among other things, contained the following instructions: control room status check, responsibilities for performing structure, system and component (SSC) checks and general plant area walk-downs.
- Post-trip actions were implicit in the event based AOP for verification of reactor shutdown, e.g. verification of insertion of control rods and decreased reactivity.
- The event based AOP, Section II, Turbine and Electrical, Chapters 12, 13 and 14, addressed the external system fault, loss of off-site power and electrical system fault, respectively.
- The symptom based EOPs provided standard response actions for protection and/or recovery of key safety functions following the loss of all AC power after the tsunami. These included: reactor control, containment control, reactor water level recovery, rapid depressurization and loss of reactor water level indication. These EOPs described the actions to be taken from the MCR as well as the local-manual actions. However, these symptom based procedures were unusable when the MCR lost all its indicators.
- SOP (MCR severe accident procedure) and AMG (ERC severe accident procedure) procedures were activated upon the potential of core damage and provided a flow chart for AM using the available systems, and for mitigation of fission product barrier failures.

Procedural actions relevant to the accident

Some specific actions from the procedures noted above played important roles during the accident progress and station response. These actions (and related strategies) can be summarized as follows:

- PCV venting strategy: Although the Japanese BWRs were equipped with a hardened venting system to prevent containment vessel overpressurization, the underlying philosophy was to vent as late as possible (or not to vent until it was inevitable), in order to delay or prevent direct release of radioactive material to the public and the environment.

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[77] Although foreign companies were participating in BWROG activities, BWROG is mainly composed of members from the United States of America. While TEPCO and several other Japanese utilities were members of BWROG, some Japanese BWR utilities were not and, hence, did not have access and permission to use BWROG products, compelling separate efforts to establish guidelines in Japan.

- PCV venting conditions: In line with the delayed venting strategy, the procedures instructed the operators to delay venting until the containment pressure had reached a value that was twice the design pressure (although the rupture disk was designed to burst at the design pressure), and a number of other conditions had occurred as the prerequisites for venting, e.g. the containment spray system was deemed to be unrecoverable or the water level in the SC was below the SC vent line.
- PCV venting operator actions: In addition to the rupture disk provided by design, remote-manual operation was necessary, and the SOPs instructed the operators how to line up the system for venting. However, the procedure did not contain instructions for local-manual actions in case of a total loss of AC and DC power, for loss of instrument air for air operated valves in the venting system, or for situations when the local conditions impeded access to those valves. Thus, additional procedures were improvised and developed for those situations as the accident progressed.
- SBO coping strategy: The (loss of all AC) procedure was designed to meet an 8-hour coping time which had been selected taking into consideration the availability or recovery of multiple off-site transmission lines, backup (AC and DC) power equipment, extensive features to cross-tie and share electric and water power sources among the units and equipment load shedding. The procedures to meet a specific coping time vary, in the strategies and instructions, among the NPPs.
- Hydrogen control/removal strategy: The AOP (Section I, Reactor, Chapter 2, LOCA) directed that the flammability control system (FCS) was to be utilized for hydrogen control to reduce the potential for hydrogen explosions during a design basis large break loss of coolant accident (LBLOCA) by maintaining the inert atmosphere in the PCV. However, the FCS and associated hydrogen monitoring systems were not operable, since the continuous AC power was unavailable for their function (i.e. similar to other NPP design basis accident conditions, LBLOCA did not consider a concurrent extended loss of AC power for flammability control). Thus, the AOP instructions did not deal with this specific event combination. Furthermore, for BDBAs, the instructions to remove hydrogen were not explicitly covered in the EOPs and/or SOPs/AMGs, on the assumptions that the flammability control during a DBA would be provided by the inert atmosphere, and that the venting strategy for pressure control during a severe accident would simultaneously serve this purpose.
- Loss of MCR indication response: There were no procedures that considered and addressed the event of a total loss of control room indications, including the safety parameter display, due to total and extended loss of AC and DC power.
- There were also other procedures that did not explicitly address certain strategies for mitigation or that were specifically intended to cover certain conditions; however, these procedures could be interpreted and utilized, with some modifications, to apply to those conditions. They were improvised to establish countermeasures, in some cases, without clear scope and evaluation of the system response to confirm whether they did or did not achieve the objectives. For instance, there were fire protection procedures instructing the utilization of fire engines to inject water via the external injection points. The intent of these procedures was ‘fire mitigation’ and ‘PCV flooding for fire suppression’ (modifications that had been installed following the lessons learned from the Kashiwazaki-Kariwa event). During the accident response, these procedures were considered and improvised for ‘core-cooling by RPV injection’. However, the system line up for ‘core-cooling’ was not intended or described in the existing procedure, and fire engine water was diverted from RPV injection via system backflows and bypasses which were intended for fire mitigation and PCV flooding.

1.3. ONSET AND PROGRESSION OF THE ACCIDENT

This section describes how an extreme natural event combined with design and operational issues led to a severe nuclear accident in which radioactive material was released to the environment. It describes the effects of the initiating natural event (the Great East Japan Earthquake) and the subsequent natural event (the tsunami) on the Fukushima Daiichi site.[78]

1.3.1. Onset of the accident at the Fukushima Daiichi NPP

1.3.1.1. Initiating natural event: The Great East Japan Earthquake

The Great East Japan Earthquake of 11 March 2011 occurred in the subduction zone off the Pacific coast of Japan's Tohoku region. It was a magnitude M 9.0 earthquake [10]. Its hypocentre was 24 km deep, and its epicentre was approximately 180 km north-east of the Fukushima Daiichi NPP[79], and 130 km east of the Onagawa NPP. Its duration was about 140–160 seconds, with 2–3 significant pulses. The rupture impacted an area in the fault zone approximately 500 km long and 200 km wide.

The closest NPP to the epicentre was the Onagawa NPP. It experienced the highest accelerations of all of Japan's NPPs (See Fig. 1.1–1).

The main shock at 14:46 JST had been preceded by a major foreshock two days earlier and was followed by numerous aftershocks. Table 1.3–1 lists the shocks that were magnitude M 7.0 or higher.

TABLE 1.3–1. SHOCKS AND THE ASSOCIATED EVENTS EXCEEDING M 7.0 OF THE GREAT EAST JAPAN EARTHQUAKE [62]

Shock	Date	Location		Magnitude
		Epicentre	Depth	
Foreshock	9 Mar. 11:45 (JST)	N38d20m, E143d17m	8 km	M 7.3
Main shock	11 Mar. 14:46 (JST)	N38d06m, E142d52m	24 km	M 9.0
Aftershocks	11 Mar. 15:08 (JST)	N39d49m, E142d46m	32 km	M 7.4
	11 Mar. 15:15 (JST)	N36d07m, E141d15m	43 km	M 7.6
Associated events	11 Mar. 15:25 (JST)	N37d55m, E144d45m	11 km	M 7.5
	7 Apr. 23:32 (JST)	N38d12m, E141d55m	66 km	M 7.2
	11 Apr. 17:16 (JST)	N36d57m, E140d40m	6 km	M 7.0

The ground acceleration from the earthquake did not exceed the design seismic ground motion limits for the Fukushima Daiichi Units 1, 4 and 6, but it did so for Units 2, 3 and 5, as shown in Table 1.3–2. The earthquake damaged the off-site power lines and switchyard equipment and caused extensive damage to the infrastructure at and around the site.

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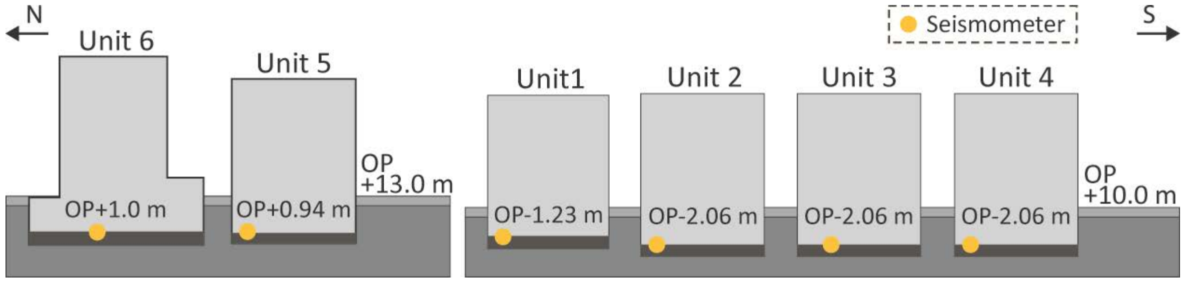
[78] All times in this narrative are in Japan Standard Time (JST) and all pressure values in units of bar absolute and megapascal (MPa). The times of events and values of plant parameters such as pressures, temperatures and water levels mentioned in this section are approximate. Though not explicitly mentioned individually, these values could have some uncertainty.

[79] The seismic intensity level of the Japan Meteorological Agency (JMA), showing the damage produced by the earthquake at towns near the Fukushima Daiichi and Daini sites, was 6+ (with the maximum level being 7 on the JMA scale).

TABLE 1.3–2. ACCELERATIONS EXPERIENCED AT THE FUKUSHIMA DAIICHI NPP UNITS AT INDICATED SEISMOMETER LOCATIONS[80] [62]

Fukushima Daiichi NPP Unit	Maximum measured acceleration value (Gal)		
	N/S*	E/W**	U/D***
Unit 1	460	447	258
Unit 2	348	550	302
Unit 3	322	507	231
Unit 4	281	319	200
Unit 5	311	548	256
Unit 6	298	444	244



Note: *North/South; **East/West; ***Upwards/Downwards.

1.3.1.2. Initiating event: Loss of off-site power (LOOP) due to the earthquake

The earthquake damaged the switchyard equipment and all six off-site power lines. Units 1–3 each experienced a reactor trip with a concurrent LOOP event. The reactors of Units 1–3 were shut down automatically when sensors at the plant detected the ground motion and triggered reactor protection systems in accordance with the design. As the ground motion exceeded the value that was set to activate the reactor seismic protection, the insertion of control rods was automatically initiated, which stopped the nuclear reaction. Because Units 4–6 were in outage modes, they experienced a LOOP event, i.e. no need for a reactor trip. The LOOP event automatically started all of the emergency diesel generators (EDGs) in order to establish AC power in all six units.

Also, as a result of the power interruption during the LOOP, the reactors of Units 1–3 were automatically isolated from their turbine systems by the closure of all main steam isolation valves (MSIVs). This resulted in increases in the temperature and pressure of the reactors due to the decay heat. Following isolation, the cooling of these reactors was accomplished by means of the following design and operational provisions:

— In Unit 1, as the reactor pressure increased, both loops of the IC system started automatically and continued to cool the reactor. The operation of both IC loops lowered the reactor pressure and temperature so rapidly that the operators manually stopped them, in accordance with procedures, in order to prevent thermal stress on the RPV. Afterwards, only one of the loops was used by the operators to control the pressure to keep the reactor pressure between 6 MPa and 7 MPa (60 bar and 70 bar).

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[80] These records were obtained at the foundation basemat level and not at free field. The values are therefore likely to be lower than the corresponding free field maximum accelerations due to soil structure interaction effects.

- In Units 2 and 3, the increase in reactor pressure automatically activated SRVs, which were designed to protect the reactor from overpressurization by releasing steam from the RPV to the suppression pool of the SC section of the PCV. This resulted in a decrease in the reactor water levels. In response, the operators manually activated the RCIC system in accordance with procedures.

The decay heat from the nuclear fuel in Units 4–6 also had to be removed:

- In Unit 4, the equipment for cooling and refilling of SFP water stopped working as a result of the loss of off-site power. The Unit 4 SFP, containing more than 1300 spent fuel assemblies, had the largest amount of decay heat to be removed among all the SFPs of the units.
- In Unit 5, the reactor pressure, which was being kept elevated by the use of a pump for pressure testing purposes at the time of the earthquake, initially dropped when the pump stopped as a result of the LOOP. The pressure started to rise due to decay heat, but unlike in Units 2 and 3, it remained well below the levels to activate the SRVs.
- In Unit 6, the reactor was near atmospheric pressure and room temperature with fuel in the core, and the decay heat was low.

In the SFPs of all units and the common SFP[81], which lost cooling and refilling capabilities upon the LOOP, the temperatures of the pool water continued to increase due to decay heat.

In response to the earthquake and the LOOP, the operators activated the ‘event based’ AOPs in all three MCRs[82] of the six units. An earthquake emergency response team was activated at the on-site emergency response centre (ERC) located within the seismically isolated building[83]. The Site Superintendent was responsible for directing the site response and for coordination with on-site and off-site organizations, as the head of TEPCO’s on-site ERC. Three shift superintendents in each of the main control rooms were responsible for directing the actions in their units under the command of the Site Superintendent.

1.3.1.3. Concurrent natural event: The tsunami triggered by the earthquake

The fault rupture that caused the earthquake deformed the seabed and the upper-plate crustal block, on which the islands of Japan are situated, moved about 50 m east-south-east and rose some 7–10 m upwards [70]. The seabed’s deformation triggered several tsunami waves affecting almost the entire east coast of Japan as shown in Fig. 1.1–5.

The seabed’s deformation triggered a two stage tsunami. The second wave was higher than the first wave and reached a run-up height of more than 30 m [13, 71].[84]

Shortly after the main earthquake shock, the Japan Meteorological Agency (JMA) issued tsunami warnings. At 14:50, the JMA forecast a wave with a height of 3–4 m arriving on the coast between 15:00 and 15:10 [14]. The height of the tsunami forecast by JMA was later revised at 15:14 to 6 m, and revised again at 15:31 to 10 m.

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[81] As a shared auxiliary facility among the units, the common SFP, located in a separate building near Unit 4, stored over 6000 spent fuel assemblies, all of which needed to have their decay heat removed.

[82] Each pair of units shared a common control room, i.e. Units 1 and 2, Units 3 and 4, and Units 5 and 6.

[83] The seismically isolated building was built as a result of experience gained from the effects of the Niigata-Chuetsu-Oki earthquake at the Kashiwazaki-Kariwa NPP in 2007, and put into operation in July 2010. It was designed to withstand earthquakes and was equipped with backup power. Filtered ventilation and shielding were provided for protection from radioactivity.

[84] Survey results of coastal tsunami run-up, for example >30 m near the central Sanriku-Oki region.

At 15:27, approximately 40 minutes after the earthquake, the first tsunami wave reached the Fukushima Daiichi site [4]. It was over 4 m high. From 15:36 to 15:37, the second tsunami wave reached the plant. Its run-up height was 14–15 m. It exceeded the tsunami design basis for all six of the Fukushima Daiichi NPP units, and topped the tsunami walls which were designed for a maximum run-up height of 5.5 m. It flooded the site, damaged many of the plant's structures, systems and components (SSCs), and covered much of the site with sand, silt and debris. Additional damage was caused by the hydrodynamic force of the tsunami and the debris it swept along.

1.3.1.4. Concurrent event: Station blackout due to flooding from the tsunami

The tsunami waves started reaching the Fukushima Daiichi NPP site about 40 minutes after the earthquake. The second and largest tsunami wave engulfed all structures and equipment located at the seafront, as well as the main buildings (including the reactor, turbine and service buildings) at higher elevations (Fig. 1.3–1), causing the following sequence of events:[85]

— The wave flooded and damaged the unhoused seawater pumps and motors at the seawater intake locations on the shoreline. This meant that essential plant systems and components, including the water cooled EDGs[86], could not be cooled to ensure their continuous operation as all six units lost their ultimate heat sink (UHS).

— The wave flooded and damaged the dry cask storage building located near the seashore between the Units 1–4 and Units 5–6 complexes. There were no significant impacts on the casks and the fuel stored in them, as was later confirmed [17].

— Water entered and flooded buildings, including all the reactor and turbine buildings, the common spent fuel storage building and diesel generator building. It damaged the buildings and the electrical and mechanical equipment inside at ground level and on the lower floors. The damaged equipment included the EDGs or their associated power connections, which resulted in the loss of emergency AC power. Only one of the air cooled EDGs — that of Unit 6 — was unaffected by the flooding.[87] It remained in operation, continuing to supply emergency AC power to the Unit 6 safety systems and allowing cooling of the reactor.

As a result of these events, Units 1–5 lost all AC power, a situation referred to as a station blackout (SBO).

Because of the SBO in Units 1–5, the emergency operating procedures for 'loss of all AC power' [20] were initiated. A 'specific event', as defined in the regulations[88] [18] associated with the Nuclear Emergency Act [19] based on the condition of 'station blackout'[89], was declared by the Site Superintendent, who was the head of the on-site ERC of the operating organization, TEPCO. Consequently, the relevant off-site agencies were informed in accordance with the requirements of the Nuclear Emergency Act.

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[85] The administration buildings and the seismically isolated building that contained the on-site ERC were on a cliff at an elevation of approximately 35 m (which was the original topographical site elevation before the site area was excavated for placing the units during construction).

[86] Each unit had a pair of EDGs, and Unit 6 had an additional generator. Of those 13 EDGs, Units 2, 4 and 6 each had one that was air cooled. Since they were air cooled, the operability of these generators was not directly affected by the loss of cooling water caused by the damage to the seawater pumps.

[87] The air cooled EDGs of Units 2, 4 (located in ground floor of the common spent fuel building) and 6 (located on the first floor of a separate diesel generator building at higher elevation) appeared to be not affected by the flooding. However, the components (i.e. switchgears, power centres, panels, etc.) of the air cooled EDGs of Units 2 and 4, which were located in the basement of the common spent fuel building, suffered water damage.

[88] Cabinet order in reference to the Nuclear Emergency Act.

[89] Due to the loss of all AC power supplies for longer than 5 minutes.

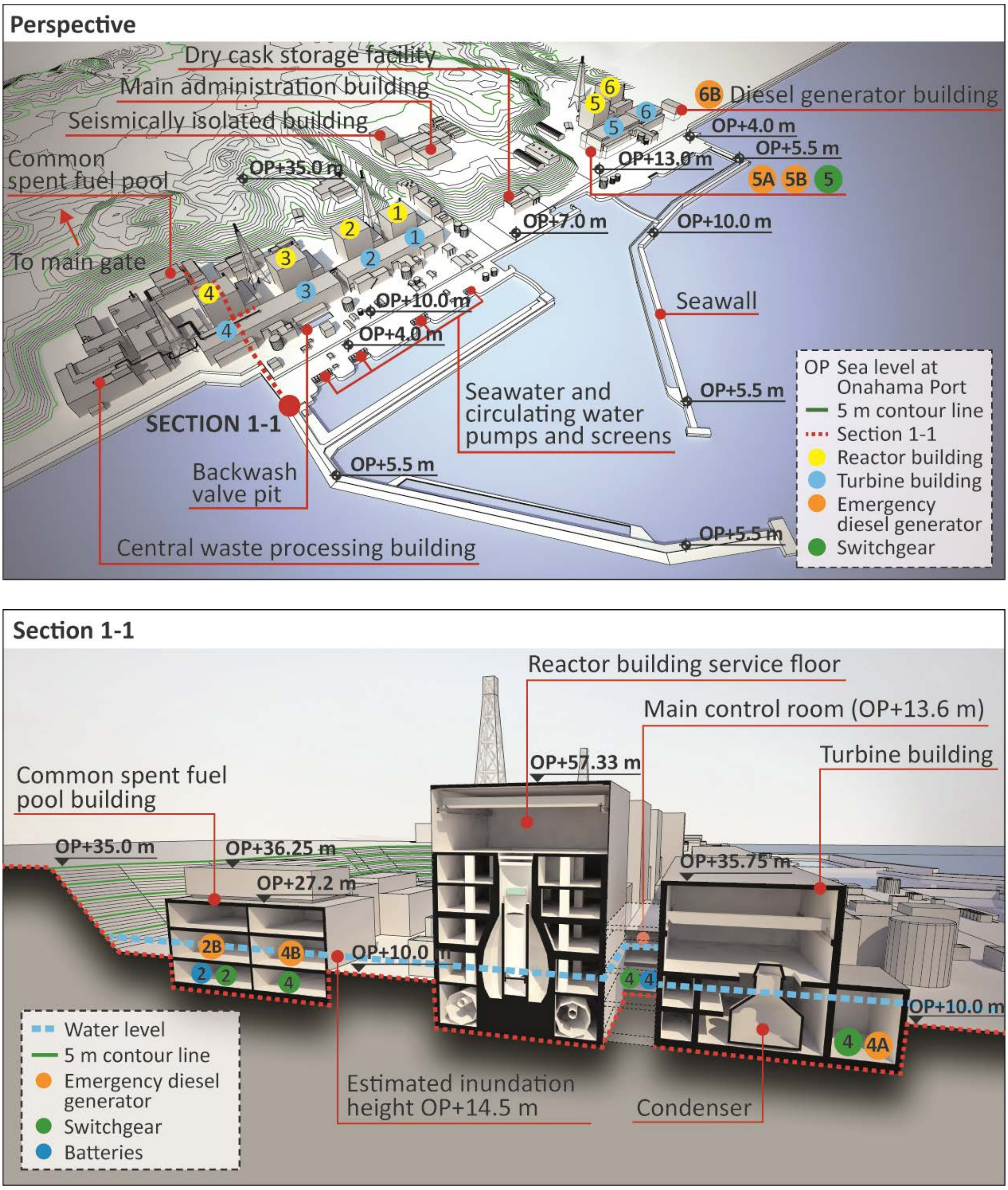

FIG. 1.3–1. The elevations and locations of structures and components at the Fukushima Daiichi NPP [16].

The flooding also inundated the DC power panels and batteries, and DC power was gradually lost in Units 1, 2 and 4 [4].

Due to the loss of all AC and DC power, the operators of Units 1 and 2 could no longer monitor essential plant parameters, such as the reactor pressure and reactor water level, or the status of key systems and components used for core cooling. As mentioned earlier, the heat removal capability for the spent fuel pool in all units was already lost following the loss of off-site power. The additional loss of DC power in Units 1, 2 and 4 meant that operators could no longer monitor the water temperature and levels in the spent fuel pools of these units.

In the absence of procedures addressing the loss of all AC and DC power, the operators of Units 1, 2 and 4 did not have specific instructions on how to deal with an SBO under these conditions. The operators and ERC staff started reviewing available options and establishing possible ways to restore power and thereby regain the ability to monitor and control the plant.

1.3.2. Sequence of events at Fukushima Daiichi Units 1–3

As explained above, at the time of the earthquake, Units 1–3 were operating at their rated power, while Units 4–6 were in planned outage modes. The sequence of events associated with these units were therefore different and are dealt with separately.

All information presented in this section is based on the reports cited in Refs [3, 4, 6, 7, 72] unless indicated otherwise.

The event sequences for each unit includes those events from other units if they affected or were relevant to the overall event in the multi-unit site. Therefore, the same occurrences are sometimes repeated for different units to show this interface.

For reference, Annexes I, II and III provide the sequence of events in tabular form. Significant events are analysed in detail in Technical Volume 2, Section 2.2, together with management of the accident as discussed in Section 2.5.

1.3.2.1. Unit 1

Fukushima Daiichi Unit 1 was a BWR/3-type reactor with a Mark I containment. As has been described in detail, in contrast to the other units, Unit 1 was equipped with isolation condenser (IC) systems for shutdown cooling at high pressure instead of the reactor core isolation cooling (RCIC) systems found on the other units (see Section 1.2.6).

When the Great East Japan Earthquake occurred at 14:46 on 11 March 2011, Unit 1 was operating at its rated electric power of 460 MW(e). The reactor water level was 950 mm, which corresponded to 4380 mm above the top of the active fuel (TAF), and the reactor pressure was 6.9 MPa (69 bar). The spent fuel pool (SFP) was fully filled with water at a temperature of 25°C.

11 March 2011

When the earthquake occurred, it triggered the acceleration sensors of Unit 1. The trip set points of 100 Gal vertical and 135 Gal horizontal [73] were exceeded in two of four sensors, initiating an automatic reactor scram at 14:46. All control rods were fully inserted automatically at 14:47. The shift team confirmed the reactor trip based on the decrease in reactor power and the insertion of the control rods, and reported to the on-site ERC at 15:02 that the reactor was subcritical. The reactor scram rapidly reduced the steam generation in the core, causing a drop in the reactor water level by 800 mm and a drop of reactor pressure by 0.85 MPa (8.5 bar). The level was recovered by continued feedwater addition.

Since it was an ‘earthquake of greater than 45 Gal’, the operators began to implement post-earthquake actions according to the event based AOP, ‘Natural Disaster Accident’, Section IV, Natural Disasters, Chapter 22 [20]. The Emergency Response Team was activated at the ERC located within the seismically isolated building. About one minute after the first shock of the earthquake, two workers witnessed the inflow of water into the fourth floor of the reactor building.[90]

From 14:46 to 14:47, the operators tried to switch the power for Units 1 and 2 to off-site power, but they were unsuccessful because the switchyard breaker had been damaged by the earthquake.

The LOOP meant that the emergency busbar lost power, with the result that the reactor protection system (RPS) lost power. This triggered a primary containment isolation signal (PCIS), which closed all the main steam isolation valves (MSIVs). The LOOP also stopped the heating, ventilating and air-conditioning (HVAC) system. In the SFP, which lost cooling and refilling capabilities upon the loss of off-site power, the temperature of the pool water started to increase due to decay heat.

Both of Unit 1's EDGs started automatically at 14:47, and AC power to the emergency busbar was restored. The operators began to implement 'Natural Disaster Accident' Section II, Turbine and Electrical, Chapters 12, 13 and 14 of the AOP to address the LOOP.

The closure of the MSIVs isolated the reactor from the steam/power conversion system, thus preventing, as designed, normal core cooling using the main condenser. As the reactor pressure increased due to decay heat, both IC systems automatically started, also as designed.

The two IC systems decreased the reactor pressure and coolant temperature so rapidly that the operators manually stopped both loops of the IC systems at 15:03, in order to prevent the cool down limit of 55°C/h, set by the plant's operational limits and conditions (OLCs), from being exceeded.

Because the HVAC had stopped as a result of the LOOP, the PCV temperature and pressure began to rise. The operators therefore manually started the two trains of the containment cooling system (CCS) at 15:05 and 15:11, respectively.

To maintain the RPV pressure within the prescribed range, the operators manually turned the 'Train A' IC system on and off three times between 15:17 and 15:34 by opening and closing the DC powered outboard (i.e. outside containment) isolation valve on the condensate return pipe.

At 15:27, about 40 minutes after the earthquake, the first tsunami wave reached the site. It exceeded 4 m but did not affect any essential systems.[91] However, between 15:36 and 15:37, the second tsunami wave flooded the site. The tsunami damaged the seawater pumps, resulting in the loss of ultimate heat sink (LUHS). The flooding incapacitated both EDGs that were located in the basement of the turbine building (TB). All AC power was lost at 15:37, and operators entered the symptom based EOP for an SBO condition. In accordance with Article 10 of the Nuclear Emergency Act, TEPCO declared a station blackout at 15:42.

The DC power panel in the basement of the TB was also inundated, and DC power was lost between 15:37 and 15:50.

As a result of the loss of DC power, the shift team could not monitor plant parameters such as the reactor pressure and the reactor water level; the team was also unable to check lamp indicators for the

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[90] The water is estimated to have come from the SFP on the fifth floor of the RB as a result of sloshing caused by the earthquake, and no available data show any leakages from the pipes connected to the RPV.

[91] At 15:29, some detectors at several monitoring points triggered an alarm on the 'high–high' set point of 430 nGy/h, which cleared later at 15:36. Meanwhile, more reliable monitors in that range at the same monitoring posts indicated a normal reading of 40 nGy/h.

operation status of major systems and components in the MCR of Units 1 and 2. All data recorders stopped, and the lights in the MCR gradually went out. Only the emergency lights on the Unit 1 side of the MCR remained on. Some of the most significant effects of the DC power loss were:

- Loss of reactor water level and pressure indications.
- Loss of valve status information for the IC systems.
- Loss of high pressure coolant injection (HPCI) activation and indication.
- Loss of SFP water temperature and level indications.

Since neither the status of the reactor nor the operability of the IC could be monitored, an incident according to Nuclear Emergency Act, Article 15, on 'ECCS cooling water injection function loss' was declared at 16:36, and the relevant government agencies were notified at 16:45.

The MCR operators moved to their SOPs. Accident Management Guidelines (AMGs) were implemented in the ERC upon the SBO and LUHS to identify a strategy for coping with the predicted degradation of the fission product barriers. The HPCI system was not available due to the loss of DC power. The residual heat removal (RHR) systems were also not available due to the flooding of the seawater pumps and the loss of AC power. Two options for injecting water into the reactor were identified, namely:

- The use of systems that could inject water directly into the reactors even at high pressures, such as the standby liquid control (SLC) system and the control rod drive (CRD) system, which required the restoration of AC power.
- The use of alternative equipment, such as mobile fire engines and the stationary diesel driven fire pump (DDFP) that could inject water at low pressures, which required depressurization of the reactors and alignment of the fire protection (FP) lines to inject water into the core.

For some time after the earthquake, frequent severe aftershocks and ongoing tsunami warnings made it impossible for the workers to leave protected buildings and/or approach lower plant site elevations. However, the ERC considered it necessary to check the condition of electrical equipment to assess the possibility of power restoration. To this end, a recovery team began a survey of off-site power equipment at around 16:00.

Meanwhile, the reactor water level indicators became available again[92]; the wide range (WR) monitor of the reactor water level indicated at 16:42 that the water level was −90 cm, which corresponded to 2530 mm above TAF. This was reported to the ERC. Consequently, at 16:45, the declaration under Article 15 was cancelled. At 16:56, the water level measurement went off-scale at the bottom range (i.e. −150 cm WR or 1930 mm above TAF), corresponding to a reactor water level loss rate of 2.6 m/h. At 17:07, the MCR informed the ERC that the reactor water level information was again unavailable and the Article 15 declaration was reissued. The relevant government parties were informed at 17:12.

At 16:55, a survey team was sent to activate the DDFP, but had to return to the MCR because of another tsunami warning.

At 17:12, the Site Superintendent ordered the review and preparation of water injection with fire engines in lieu of the injection of water through the fire protection (FP) system line as an alternative AM strategy.[93] Thus, the use of fire protection tanks and fire engines, which had been deployed after

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[92] The reason for the recovery is unknown.

[93] Injection via the fire engines was not defined as one of the AM measures.

the Niigata-Chuetsu-Oki earthquake in 2007 as a fire suppression measure, was considered. The plan was to establish an alternative water injection flow path via the FP, MUWC and CS system lines by manually opening valves in the turbine and reactor buildings. This could only be done, however, after the reactor pressure had been lowered sufficiently to make fire pump injection possible. Yet, no specific action to consider the use of fire engines was taken until the early morning of 12 March until the respective roles and responsibilities of the function teams for these 'first time' activities were clarified.

At 17:15, the engineering team of the station ERC estimated that the reactor water level would reach the TAF in one hour.

At 17:19, operators went into the basement of the turbine building (TB), pushed the fault recovery button on the FP control panel and, at 17:30, confirmed that the DDFP had started. They started to work on the line to connect the DDFP to the core spray system, partly by manually opening the motor operated valves in the RB.

About 2.5 hours after the loss of indications in the MCR, some of the indicator lamps of the isolation valves were found to be working and, on the control panel, showed the status of the valves as 'closed'. Since the isolation valves on the IC lines were designed to 'fail–close' on loss of DC power to the control circuit, and to 'fail-as-is' on loss of AC/DC power to the valve actuator(s), this corroborated the fact that the valves had closed at the time of DC power loss, rendering shutdown heat removal by the IC impossible thereafter. It became clear that the outboard isolation valves (on the condensate return as well as the steam supply lines) of the IC Train A were closed. As the latter valve had been open prior to the arrival of the tsunami, the operators realized that the isolation valves had failed-closed due to the loss of the electrical power supply to the instrumentation.

The shift team opened the outboard isolation valves from the MCR (remote-manually) at 18:18, taking the chance that the other isolation valves were in an open position. After opening the outer isolation valves of Train A, a small amount of steam was observed above the RB of Unit 1, suggesting the onset of IC operation. However, these indirect signs of an operating IC disappeared after a short time. As there were questions concerning the soundness of the IC system, and as it was not operating as expected, the outboard isolation valve in the condensate leg of the IC was remote-manually closed again at 18:25, which was not reported to the ERC.

After several reports from the on-site ERC on the status of Unit 1 and the other units, and following the approval of the Prime Minister, a nuclear emergency was declared by the Government of Japan at 19:03 on 11 March.[94] At 20:50, the Government of Fukushima Prefecture issued an evacuation order for residents within 2 km of the plant after evaluating the national nuclear emergency declaration and discussing the uncertainty concerning the status of the NPPs with TEPCO officials.

Given the continued unavailability of instrumentation and control, an operator entered the RB and read the RPV pressure locally as 7 MPa (70 bar) at 20:07. This pressure reading provided further evidence that the IC was not working.

Temporary lighting was partially re-established in the MCR by use of a mobile generator at 20:47.

Meanwhile, the line connecting the DDFP to the core spray system by manually opening the motor operated valves in the RB was completed at 20:50. However, the RPV pressure remained at 7.0 MPa

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[94] At the same time, the NERHQ, located at the Prime Minister's Office, was established, and the Prime Minister assumed responsibilities as the Director General, directing the national nuclear emergency response.

(70 bar), which was much too high for the maximum pump head of the DDFP (0.79 MPa (7.9 bar)). Without an operable depressurization system, injection via the DDFP was impossible.

At 20:50, an evacuation order was issued by the Governor of Fukushima Prefecture to all residents within 2 km of the power station.

Temporary batteries and cables were gathered and carried to the MCR of Units 1 and 2 in order to energize the DC powered indicators. After confirming the wiring layout by referring to electrical diagrams, batteries were connected to instrument panels, and DC power to some indicators was recovered. The reactor water level indicator was restored at 21:19 and initially indicated a water level of 200 mm above TAF.[95]

At 21:23, the Prime Minister, as the Director General of the Nuclear Emergency Response Headquarters, issued an order requiring the evacuation of all persons within 3 km of the site and sheltering for those within 3–10 km of the site.

Reactor cooling via the IC Train A was attempted again at 21:30, since alternative water injection into the RPV was still not possible, and the DDFP was operable providing a means to refill the shell (secondary) side of the ICs. At least initially, the formation of steam at the IC vent pipe was again visually confirmed but it soon ceased. During later inspection, the water inventory on the shell side of the IC was discovered to be at almost normal level. At the onset of the accident the filling level of the shell side of the IC had been about 80% in Trains A and B.[96]

Two operators went to the RB to check the reactor water level and the IC pool water level. When one of them tried to enter the RB, his personal dosimeter indicated that he received a dose of 0.8 mSv in about 10 seconds. The operators immediately left the RB and returned to the MCR to give their report at 21:51. Subsequently, a radiation protection team measured local dose rates of 1.2 mSv/h and 0.5 mSv/h in the TB in front of the northern and southern airlock doors to the RB, respectively. At 23:05, entry to the RB was restricted by the Site Superintendent because of the increasing radiation levels. This was an indication of the severity of the conditions at the Unit 1 reactor and of possible core damage.

Because of the cable connection that had been established between the mobile generator and the MCR, it was not possible to completely close the MCR door, and the dose rates in the MCR increased together with the other areas of the control building. As the dose rates in the Unit 1 side of the MCR increased, operators had to move periodically to the Unit 2 side of the control room.

A mobile generator that had been used for MCR lighting was connected to the DW pressure instrumentation at 23:50. The first measurement of the DW pressure since the loss of DC power showed that the pressure in the DW was 0.6 MPa (6 bar), exceeding the maximum design pressure of 0.528 MPa (5.28 bar), and that it was increasing.

12 March 2011

At 00:06, the Site Superintendent ordered preparations for venting of Unit 1 (and Unit 2) and a notice was issued at 00:49 identifying an ‘abnormal rise in primary containment vessel pressure’ in

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[95] The reliability of this measurement is questionable. It is likely that these water level indications resulted from the evaporation of the water in the reference leg of the water level measurement, prompting the operators to conclude that the reactor core was still submerged.

[96] After the accident, when the IC instrumentation was re-established on 3 April, as listed later in this section, the shell side water levels were determined to be 63% and 83% for Trains A and B, respectively.

accordance with Article 15 of the Nuclear Emergency Act. TEPCO informed the appropriate government agencies at 00:55 about the declaration of this Article 15 incident.

Completion of the 3 km zone evacuation was announced by the Government at 00:30 and re-confirmed at 01:45.

TEPCO informed the Prime Minister's Office, the Ministry of Economy, Trade and Industry (METI) and the Nuclear and Industrial Safety Agency (NISA) at 01:30 about the containment venting plans. Having received their agreement, TEPCO Headquarters ERC instructed the station ERC to start venting after it had been officially announced to the public at 03:00.

The crew that was dispatched at 01:25 to check the DDFP found out at 01:48 that the pump had not been working. After refilling the fuel tank and installing the temporary batteries carried for the pump, the attempts to start the pump failed and use of the DDFP for water injection proved to be impossible. The next strategy considered was the utilization of the station fire engines as an injection source for the reactor and the plans were initiated by the ERC at 02:03. The fire engines were to be connected to the injection port in the turbine building, which had been installed the previous year as a fire protection measure based on the experience of the Niigata-Chuetsu-Oki earthquake. The power recovery teams and the in-house fire brigade first had to clear access paths and mechanically open blocked truck bay shutters in order to gain access to the area where the fire protection system intake was located. At 02:10, the sea side of the TB was cleared sufficiently to allow access.

Meanwhile, at 02:24, the on-site ERC determined that the maximum stay time was not to exceed 17 minutes per person in the area where the venting preparation activities were to be conducted in order to remain below the dose limit for emergency personal of 100 mSv. This was based on the estimated dose rate of approximately 300 mSv/h in the area. The crew working on venting activities was advised to take potassium iodide (KI) tablets and to a wear breathing apparatus with a capacity of 20 minutes.

Reactor water level readings taken at 02:30 were 1300 mm and 530 mm above TAF in two different instrumentation channels, confirming that the reliability of those measurements was highly questionable. Around the same time, the DW pressure reached 0.84 MPa (8.4 bar) and then decreased to 0.8 MPa (8.0 bar) in the next 15 minutes, stabilizing between 0.7 MPa and 0.8 MPa (7.0 bar and 8.0 bar) afterwards.

Field observations at 02:55 reported to the ERC and the MCR that the Unit 2 reactor core isolation cooling (RCIC) was operating. This prompted the Site Superintendent to give priority to venting Unit 1 over Unit 2. However, when plans for primary containment vessel venting for Units 1 and 2 were announced to the public by METI and TEPCO at a press conference at 03:06, there was confusion about which unit would be prioritized.[97]

Connection to the FP system of Unit 1 was established at 03:30, and the injection of the contents of one fire engine into the reactor started around 04:00, about 12.5 hours after the SBO. Water injection from a single one-tonne truck continued intermittently for approximately 5.5 hours, with the truck having to return to the freshwater tank periodically to be refilled. At the same time, work on establishing a direct line from the tank continued. The operation of the fire engines and work to establish a direct line were interrupted periodically by the changing radiological conditions around the units.

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[97] Immediately before the press conference, the NISA Director General received the information that the RCIC at Unit 2 was operating. He recognized that Unit 1 would be prioritized. In contrast, the TEPCO Managing Director did not have this information and believed that the IC of Unit 1 was operating. He thought, therefore, that Unit 2 would be given first priority.

Dose consequence predictions and release estimates for the venting operation were prepared by TEPCO and provided to the Government at 04:01 in order to determine on-site and off-site radiological consequences from the venting.

At 03:45 on 12 March, an attempt to enter the RB to conduct radiation measurements was abandoned, when the team encountered ‘white fog-like’ steam upon opening the RB airlock door, although the radiation readings main gate measurements at 04:00 had not shown any anomaly. However, shortly afterwards, a drop in the containment pressure was recorded. The measurement at 04:19 on 12 March showed that pressure in the Unit 1 primary containment vessel had decreased since the last measurement (at 02:45) without any operator action and without an established vent path, indicating that some unintentional containment pressure relief had occurred through an unknown path. Subsequently, at 04:23, a significant increase was detected in the dose rate measurements at the main gate, namely 0.59 μSv/h compared with 0.069 μSv/h measured earlier at 04:00. This was also an indication of uncontrolled radioactive release from the primary containment, i.e. degraded confinement.

In response to these increased dose rates, the fire brigade working on water injection to the reactor had to evacuate the fire engine temporarily, halting freshwater injection. The MCR staff was equipped with high range (100 mSv) alarm pocket dosimeters (APDs) and full-face masks at 04:45 provided by the ERC, and TEPCO notified the Government about the increased radiation levels on the site at 04:55. In light of these increased dose rates and the contamination detected on workers coming back from outside activities, the ERC recommended, at 04:57, that workers performing outdoor task at the site should wear full face masks with charcoal respirators and full body suits. Radiation measurements began to be taken inside the seismically isolated building where the ERC was located. At 05:04, following up on the ERC’s recommendation, the shift superintendent issued a mandatory order for the MCR staff to wear full face masks with charcoal respirators. Unit 1 operators had also moved to the Unit 2 side of the MCR where the radiological conditions were less adverse.

The evaluation of deteriorating radiological conditions at the site, combined with the elevated containment pressure in Unit 1, prompted the Government to expand the evacuation zone. Accordingly, a 10 km zone evacuation order was issued at 05:44 on 12 March by the Government based on the information from the site that the Unit 1 PCV venting was delayed and that its pressure remained elevated, above its design pressure.

At 05:46, after an interruption of more than one hour, the fire brigade restarted injection of cooling water using the fire engine. The fire engine was refilled from the nearest FP tank and returned to the connection point six times until 09:15. In the meantime, a hose connection between the FP tank, the fire engine and the intake was established so that continuous water injection became possible, injecting about 15 m^3 until 09:30. Additional fire engines from the Japan SDF arrived between 06:00 and 07:00, and one fire engine came from the Kashiwazaki-Kariwa NPP at around 10:30. These additional fire engines were used to refill the FP tank used for Unit 1 by carrying water from the other FP tanks.

The legal order for manual venting of the Unit 1 PCV, issued by METI via telephone, was received at the station at 06:50.

The Prime Minister arrived at the Fukushima Daiichi site at 07:11 on 12 March to be briefed by the Site Superintendent, and he left the site at 08:04 after a one hour visit.

At 08:03, the order to start venting in one hour was issued by the Site Superintendent. At 08:37, the Fukushima Prefecture Government was informed that venting would start at 09:00, and it was agreed that the evacuation status would be confirmed before performing venting.

Upon confirmation of the completion of evacuation of Okuma Town, that was received from the Fukushima Prefecture authorities at 09:02, teams were activated to start manipulation of the valves in order to arrange the path for the venting of Unit 1's containment. The first of three teams of two workers left the MCR at 09:04 to conduct the necessary field work. They were to manually open the motor operated valve (MOV) and either one of the two air operated valves (AOVs) that were on parallel lines, in order to align for venting of the PCV. The commencement of venting activities was made public via the press at 09:05.

The task of the first team was to manually open the PCV MOV on the 2nd floor of the RB. After opening the valve by 25% at 9:15, the team retreated. The operators received radiation doses of around 25 mSv. The second team left the MCR at 09:24 to manually open the small bypass AOV located in the torus room in the basement of the RB. However, high radiation inside, exceeding the personal dose of 100 mSv[98], forced the team to abandon the mission and return to the MCR at 09:32. In parallel, the operators unsuccessfully tried to remote-manually open the small AOV from the MCR three times, at 10:17, 10:23 and 10:24, assuming that there would be adequate residual pressure in the instrument air system. However, a brief increase in the radiation reading at the main gate and monitoring points at 10:40 was noted, potentially indicating that some venting had occurred. This venting could not be confirmed, since there was no associated decrease in PCV pressure. Also, the radiation readings started decreasing at the main gate and at the other monitoring points after 11:15.

At 12:30, the recovery team transported a portable air compressor to a connection point of the instrumentation compressed air system on the outside of the RB to try to open the large isolation AOV, rather than the small AOV whose opening had been previously attempted.

At 14:00, the recovery team connected and started the compressor, and opened the large AOV on the PCV vent line. Operators confirmed the decreasing trend in PCV pressure at 14:30. Within the next 20 minutes, the pressure inside the PCV decreased from 0.75 MPa to about 0.58 MPa (7.5 bar to about 5.8 bar), indicating successful venting of the Unit 1 PCV. The successful venting operation was reported to government agencies at 15:18. Although there was no significant immediate change in the radiation measurements within the site boundaries, about one hour later, a radiation dose rate reading of approximately 1 mSv/h was recorded at 15:29 by one of the site monitors located near the site boundary to the north-west of Unit 1 (MP4, located at the north-west of Units 1–4 and west of Units 5-6).[99] Overall, the venting process took 14.5 hours, from the Site Superintendent's order around midnight to vent, owing to high radiation levels in the torus room which houses the SC where valves had to be manually manipulated and the lack of a compressed air supply to operate the valves.

On the parallel attempts to inject water into the reactor via the DDFP, the crew working on the DDFP that had been out of service since 01:48 reported at 12:53 on 12 March that the DDFP was restored and available. The pump was started at 12:59, but stopped again at 13:21 due to a ground fault of the motor.

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[98] A personal dose in excess of the 100 mSv limit received by one operator of the first team entering the torus room was reported to the Government at around 12:00.

[99] At 16:17, it was noted by the ERC that the radiation measurement taken at 15:31 near the main gate was 0.569 mSv/h; the authorities were notified at 16:27, since this value exceeded the legal reporting criterion of 0.5 mSv/h. The notification was corrected at 16:53, when it was realized that the radiation level measured at 15:29 was 1.015 mSv/h, i.e. after venting of Unit 1 (but before the explosion at Unit 1).

By 14:53, all the available fresh water in the FP tanks (80 m^3) had been injected into Unit 1, and the tank inventory had been almost completely depleted.[100] At 14:54, the Site Superintendent ordered the fire brigade to inject sea water into the reactor from the Unit 3 backwash valve pit, where seawater had collected after the tsunami, as it was the only available source of water at that time. The arrangements for seawater injection were completed in just over half an hour, by 15:30.

Also, by 15:30 on 12 March, a mobile 6.9 kV voltage power supply[101] to Units 1 and 2 using an undamaged transformer in Unit 2 was completed, and a low voltage grid for the supply of AC power to Unit 1 was re-energized via an undamaged power centre (P/C) of Unit 2. Energizing a motor control centre (MCC) of Unit 1 enabled the starting of the standby liquid control (SLC) system, which was used to inject feedwater into the RPV.

Nearly 24 hours after the SBO, temporary water and power provisions, the seawater injection lines and the 6.9 kV AC, were connected to Unit 1 to recover core cooling. However, within minutes of connection, an explosion in the Unit 1 RB damaged both of these arrangements before they could be put in use.

The Unit 1 explosion, at 15:36 on 12 March, caused extensive damage to the upper RB structure, which consisted of a steel framework with inserted steel plates. Although the explosion did not directly affect the primary containment structure (the PCV), the damage to the secondary containment, or reactor building (RB), was significant. The cause of the explosion was unknown to the plant staff, but it was suspected that it was ignition of hydrogen that had been released from the damaged Unit 1 core and had escaped from the PCV to the RB via an unknown path.

Additionally, the explosion caused serious damage to the alternative seawater injection line assembly and to cables of the emergency high voltage power supply. It also worsened the already challenging site conditions for emergency response activities, blasting the windows of the fire engines, injuring workers and causing locally high dose rates on the plant site due to contaminated rubble and scattered debris from the building materials. Consequently, the on-site ERC requested evacuation of staff from the areas in and around Units 1–4. Considering that radioactive gases had been also released through the same path that allowed hydrogen outside the PCV, the ERC also ordered the evacuation of the staff from two MCRs (Unit 1 and 2, and Unit 3 and 4), except for the three most senior staff.

At 15:29, radiation dose rates at a station monitoring post along the site boundary showed 1.015 mSv/h. It was confirmed at 16:17 that the radiation level measured near a monitoring post (MP4) was 0.569 mSv/h as of 15:31. This situation was deemed to fall under Article 15 of the Nuclear Emergency Act, and government agencies were notified (the notification was corrected when, at 16:53, it was discovered, that radiation levels at 15:29 had been 1.015 mSv/h, as noted above). Approximately three hours after the explosion in Unit 1 (four hours after venting of the Unit 1 containment), at 18:25 on 12 March, the Government extended the evacuation zone to 20 km.

Following the temporary evacuation of the Unit 1–4 area, lasting about two hours, the survey teams were redeployed at 17:20 and reported extensive damage to the seawater injection arrangement. After

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[100] Note that not all the injected water went into the RPV because the water injection by fire engines was through the FP, MUWC and CS lines and there were several branches in the MUWC line to provide water for pump and valve seals, gland steam evaporators, etc.

[101] Almost one hour after the SBO on 11 March, mobile power equipment (low and high voltage power supply vehicles) was dispatched to the Fukushima Daiichi and Fukushima Daini NPP sites. The first vehicle, from Tohoku Electric, arrived at around 22:00 on 11 March, i.e. nearly six hours after the SBO. More vehicles from other TEPCO and Tohoku Electric facilities and the Japan Self-Defense Forces arrived at the sites throughout the night. By 10:15 on 12 March, a total of 23 vehicles were at the site.

replacement of the damaged hoses, the fire engine pumps were started up and seawater injection into the RPV started at 19:04, from the Unit 3 backwash valve pit through the core spray line. Overall, between the end of freshwater injection and the start of seawater injection, the Unit 1 core was without cooling for nearly four hours.

After 20:45, boric acid was added to the sea water to address recriticality concerns.

By midnight, about 31 m^3 of sea water had been injected into the Unit 1 RPV.

13 March 2011

Seawater injection continued throughout the day on 13 March.

Early in the day, medical team leaders instructed all workers to take potassium iodide (KI) pills, making it mandatory for everyone under 40 years of age and optional for others.

At 13:37, measurement of the PCV pressure was re-established, having been lost after the hydrogen explosion the previous day. The measured pressure in the SC was around 0.6 MPa (6 bar) (0.595 MPa (5.95 bar) in the DW and 0.590 MPa (5.9) in the SC), slightly higher than before to the explosion. Measurements from 18:00 onwards indicated a decreasing trend in the SC pressure.

14 March 2011

At 01:10, the water in the Unit 3 backwash valve dropped below the suction level of the temporary hoses so that injection of sea water into the reactor coolant systems of Unit 1 (and Unit 3) had to be halted. After the intake hose was lowered deeper into the pit, the remaining pit water was reserved for injection into Unit 3 as a priority, and Unit 1 core cooling was postponed until the pit could be refilled. Refilling of the backwash valve pit started at 09:05 with seven tanker trucks from the Japan SDF, each with a capacity to transport five tonnes of water. After nearly two hours of refilling the pit, the seawater injection into Unit 1 was ready to be resumed at 11:01, when all activities had to stop because of the explosion in Unit 3. This damaged the hoses and fire engines around the Unit 3 backwash valve pit, including two fire engines forming a line to pump water directly from the ocean into the pit, and necessitated a temporary evacuation of workers from the outside areas.

The on-site ERC was informed at 14:04 by TEPCO Headquarters that it was agreed with the nuclear regulator, NISA, to increase the dose limit for emergency workers to 250 mSv.

The work to re-establish the seawater injection line, this time directly from the ocean, was started again after a break of two hours. Again, priority was given to restoring seawater injection into Unit 3 when the line was established. At around 20:00 on 14 March, seawater injection into the Unit 1 RPV resumed, using a new fire engine to pump water directly from the sea. Overall, this series of events caused a 19 hour suspension of water injection into Unit 1.

15 March 2011

At 06:14 on 15 March, the sound of an explosion was heard on the site and tremors were felt in the common MCR of Units 1 and 2. This was followed by a drop in the Unit 2 SC pressure, which reached atmospheric pressure at 06:30. In light of the possibility of failure of the Unit 2 PCV, all plant personnel including the Unit 1 MCR staff were ordered to temporarily evacuate to the seismically isolated building where the ERC was located. Subsequently, all personnel, with the exception of those required for monitoring and emergency restoration, were instructed by the Site Superintendent to go to a ‘radiologically safe location’. Approximately 650 people understood this order to be a site evacuation and evacuated to the Fukushima Daini NPP. An estimated 50–70[102] staff, including the Site Superintendent, remained at the Fukushima Daiichi ECR. The relevant government agencies were informed by the on-site ERC of the evacuation at 07:00.

About two hours later, white smoke (or steam) was observed being released from the Unit 2 reactor building near the fifth floor. A radiation dose rate measurement of nearly 12 mSv/h was recorded at the main gate at 09:00 on 15 March, the highest measurement since the beginning of the accident. Because of the high radiation levels, an order was issued by government authorities, two hours later at 11:00, requiring all residents within a 20–30 km radius of the Fukushima Daiichi NPP to take shelter indoors.

16 March to May 2011

Between 17 and 20 March, temporary power cables were laid to Units 1 and 2. At 15:46 on Sunday 20 March, almost exactly nine days after the SBO, an auxiliary transformer of Units 1 and 2 was connected to the external grid, and temporary off-site power was restored to Unit 1 (and 2) through this AC power system, ending the Unit 1 SBO.

On 23 March, a fire engine pump was connected to the RPV feedwater system and seawater injection started at 02:30. This replaced the previous seawater injection via the RPV spray line.

At 11:30 on 24 March, lighting was restored to the common MCR of Units 1 and 2.

On 25 March, the water injected into the reactor was switched from sea water to fresh water and on 29 March, the fire engine pumps were replaced by electrical pumps powered by a diesel generator, to pump fresh water into the reactor.

In order to replenish the water in the Unit 1 SFP to ensure that the spent fuel was not exposed, spraying of sea water by concrete pump trucks was performed between 13:03 and 16:04 on 31 March.[103]

When the IC instrumentation was re-established on 3 April, the shell side water levels were determined to be 63% and 83% for Trains A and B, respectively, indicating that the IC was not utilized after the tsunami.

In order to avoid the possibility of futher hydrogen explosions, it was decided to purge the PCV with nitrogen. Therefore, a temporary nitrogen supply was connected to the DW inert gas supply system, and nitrogen injection started on 7 April.

TEPCO issued an action plan on 17 April 2011, the Roadmap towards Restoration from the Accident at Fukushima Daiichi Nuclear Power Station [23]. The roadmap included measures to be taken for: the establishment of stable cooling of the reactors and spent fuel; reduction and monitoring of radioactive releases; control of hydrogen accumulation; and prevention of return to criticality. These actions were implemented in the nine months following the accident.

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[102] As noted by different investigation reports, the exact number of staff is not certain [4, 6]. It is also noted that the staff who evacuated to Fukushima Daini started to return to the site on the same day.

[103] Spraying the SFP with concrete pump vehicles was performed again on 14 May, this time using fresh water, and repeated almost weekly until an available plant system, namely the spent fuel pool cooling and cleanup (FPC) system, was first utilized on 29 May and continued to be used thereafter.

The roadmap established two conditions that would define the end of the accident state, or 'cold shutdown state'[104]: achievement of significant suppression of radiological releases and steady decline of radiation dose rates; and achievement of target values for certain plant parameters as prescribed in the roadmap.

On 17 and 18 April, remote controlled robots were used to check the conditions at ground level within the RBs of Units 1 to 3. Inside the Unit 1 RB, the temperature was 29°C and the humidity was approximately 50% on 26 April [74].

An air filtration system was installed on 5 May to lower the concentration of radioactive aerosols within the RB of Unit 1. The air contamination declined from 4.8 Bq/cm^3 on 26 April to 0.02 Bq/cm^3 on 7 May, and the airlock to the RB was opened at around 20:00 on 8 May.

During 9 May, 7 TEPCO employees, 2 NISA inspectors and 21 contractors entered the Unit 1 RB to check radiation levels, construct temporary shielding and install temporary lighting. In the following days, the pressure transmission lines, used for RPV pressure and water level measurement, were refilled. After refilling the lines, it was determined that the reactor water level was lower than the active core height. This measurement provided the first firm evidence, supported by temperature measurements, that the RPV had failed. Recalibration of the SC pressure measurement showed that the previously recorded pressure measurements could be considered reliable.

The Government and TEPCO announced on 19 July that the first condition had been achieved in Units 1–3 and on 16 December 2011 that the second condition had been achieved for these units. This announcement officially brought the 'accident' phase of events at the Fukushima Daiichi NPP Unit 1 to a close.[105] However, some unstable plant conditions continued, such as fluctuations in temperature, which had been explained as being caused by instrumentation failures, or fluctuations in the measurement of fission products. More stable plant parameters were achieved between March and April 2012, while post-accident management efforts continued as listed in Section 1.6.

1.3.2.2. Unit 2

Fukushima Daiichi Unit 2 was a BWR/4-type reactor with a Mark-I containment.

When the Great East Japan Earthquake occurred at 14:46 on 11 March 2011, Unit 2 was operating at its rated thermal power of 2381 MW(th). The reactor water level was 1150 mm, which corresponded to 5320 mm above TAF, and the reactor pressure was 0.7 MPa (70 bar). The spent fuel pool (SFP) was fully filled with water at a temperature of 26°C.

11 March 2011

When the earthquake occurred, it triggered the acceleration sensors of Unit 2, initiating an automatic reactor scram at 14:47. All control rods were fully inserted automatically, and the shift team reported the reactor trip to the ERC at 15:01 and confirmed that the reactor was subcritical. The reactor scram caused a drop of the reactor water level by 1000 mm, which was recovered by feedwater, and a drop of reactor pressure by 0.6 MPa (6 bar).

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[104] The term 'cold shutdown state' was defined by the Government of Japan at the time specifically for the Fukushima Daiichi reactors. Its definition differs from the terminology used by the IAEA and others.

[105] According to the criteria set by the Government of Japan at the time.

From 14:46 to 14:47, the shift team tried to switch the power house load of Units 1 and 2 to off-site power but this was unsuccessful because the switchyard breaker was damaged by the earthquake.

Due to the loss of all off-site power, the emergency busbar lost power, with the result that the RPS lost power. This initiated a primary containment isolation signal (PCIS), which caused all the MSIVs to close.

Both EDGs started automatically at 14:47, restoring AC power to the emergency busbar.

Following the MSIV closure, the shift team started the reactor core isolation cooling (RCIC) manually at 14:50, as required by procedures, but it stopped automatically at 14:51 because the RPV water level had reached the high level set point (+1485 mm, corresponding to 5655 mm above TAF, namely 'L-8').

The reactor pressure increased due to decay heat after the reactor isolation (i.e. the MSIV closure) until 14:52, when safety relief valve (SRV) 'F' started to open at 7.54 MPa (75.4 bar) and close at 7.2 MPa (72 bar), thus maintaining the reactor pressure by cycling. The reactor water level decreased as steam was released through the SRV into the suppression pool.

The shift team manually reactivated the RCIC at 15:02. The temperature of the suppression pool increased as the steam was discharged from the SRV and the RCIC turbine. The operators activated the SC spray mode of the residual heat removal chain (i.e. the RHR and RHRS systems) at 15:25 to cool down the SC. At 15:28, the RCIC stopped again automatically at the high level set point, and the operators restarted it at 15:39.

In the SFP, which lost cooling and refilling capabilities upon the loss of off-site power, the temperature of the pool water started to increase due to decay heat.

Meanwhile, at 15:27, the first tsunami wave reached the site but did not impact any essential plant systems.

The second tsunami wave arriving between 15:36 and 15:37 flooded the plant site, resulting in a series of events. The tsunami damaged the seawater pumps, resulting in the loss of ultimate heat sink (LUHS). Seawater entered the basement levels of the buildings. The water cooled EDG located in the basement of the TB failed at 15:37 because of flooding of the EDG body. The other EDG, which was air cooled and located away from the ocean on the ground floor of the shared auxiliary facility (common spent fuel pool building), was not flooded. However, the metal clad switch gear (M/C) and the power centre (P/C) of that EDG were located below ground level in the basement of the common SFP building; hence, they were flooded, and subsequently failed at 15:41. This loss of backup AC power resulted in an SBO. The incident, in accordance with Article 10 of the Nuclear Emergency Act, was declared by TEPCO at 15:42, and plant operators entered symptom based EOP for SBO condition.

Furthermore, the DC power panel in the basement of the TB was also inundated, and so DC power was also lost during this time. With the failure of DC power, all alarm and status indicators in the MCR started to blink and then went out, the lighting went off and the alarm sounds ceased.

In the short period of RCIC operation prior to the loss of DC power, the RCIC injected water at up to 31 litres per second into the RPV, thereby causing a rise in the RPV water level [1].

After the loss of DC power, the operators were no longer able to confirm whether water injection into the RPV was taking place. Therefore, at 16:36, an incident 'ECCS cooling water injection function loss' according to the Nuclear Emergency Act, Article 15, was declared. The MCR operators moved to their SOPs, and the team in the on-site ERC consulted the Accident Management Guidelines (AMGs) in order to identify a strategy for coping with the predicted degradation of the fission product barriers.

As mentioned earlier, the heat removal capability for the SFP had already been lost following the LOOP. The additional loss of DC power meant that operators could no longer monitor the water temperature and levels in the SFP.

In the absence of procedures addressing the loss of all AC and DC power, the operators did not have specific instructions on how to deal with an SBO under these conditions. The MCR and ERC staff started reviewing available options and establishing possible ways to restore power and thereby regain the ability to monitor and control the plant.

At 17:12, as part of an accident management (AM) strategy, the Site Superintendent ordered a review and the preparation for water injection using fire engines. This was seen as an alternative AM measure, in addition to injection by the DDFP through the FP, make-up water condensate (MUWC) and LPCI system lines. It was decided to line up the alternative system to Unit 1 first, because its radiation levels were increasing more rapidly than those of Unit 2. Thus, the Unit 2 line-up work started later, at around 21:00.

At 17:35, operators found that indicators on the trip channel were still alive and showing a stable reactor water level at 80%. The shift supervisor, therefore, reported to the station ERC that the reactor water level was stabilized at 80%.[106]

In spite of frequent aftershocks and ongoing tsunami warnings, recovery teams were dispatched at 16:00 and at 18:00 to survey the station power supply facilities. Following visual inspection, the team reported to the MCR at 20:56 that all M/Cs were inoperable but some P/Cs were available.

After several reports from the on-site ERC on the status of Units 1 and 2, and following the approval of the Prime Minister, a nuclear emergency was declared by the Government of Japan at 19:03 on 11 March. At 20:50, the Government of Fukushima Prefecture had issued an evacuation order for residents within 2 km of the plant after evaluating the national nuclear emergency declaration and discussing the uncertainty concerning the status of the NPPs with TEPCO officials.

Although partial lighting was re-established in the MCR at 20:47, the critical indications, such as reactor water level and the status of the RCIC, remained out of service. The operators had no direct indications of conditions in the reactor or whether the core cooling system was running or not. Without any indications of operation of the RCIC system and core pressure and temperature, the operators assumed the worst case scenario that the RCIC system was not operating and that the Unit 2 core was heating up. Assuming the RCIC was not operating, the reactor water level was calculated to fall below TAF and expose the fuel within approximately one hour. At 21:01, the on-site ERC informed government authorities that the Unit 2 core, without any cooling, was predicted to become uncovered at around 21:40. Upon this information, at 21:23, the Prime Minister’s Office issued and evacuation order for residents within 3 km. The inhabitants within the 3–10 km zone around the site were also instructed to take shelter indoors.

As has been mentioned before, after the connection of temporary batteries to instrument panels, DC power to some indicators was recovered. At 21:50, the reactor water level measurement was

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[106] Power to those indicators was later lost and, as of 18:12, the reactor water level could no longer be confirmed.

temporarily re-established and indicated a level of 3400 mm above TAF. This indicated that the RCIC was running, but this could not be controlled.[107]

At 22:00 a mobile high voltage power supply vehicle arrived on-site but could not be connected due to the damaged station electrical equipment.

The manual alignment of the FP injection line (via the MUWC and LPCI system lines), which had started at around 21:00, was completed in the RB. Flooding prevented access to the TB basement, so operation of the DDFP was confirmed by the smoke observed to be coming from its exhaust.

12 March 2011

Preparation for the required containment venting commenced at 00:06. Both Unit 1 and 2 containment venting plans were provided to the Prime Minister's Office, METI and NISA and were approved at 01:30.

At 01:20, it was discovered that the DDFP had stopped working, since the previously observed exhaust smoke was no longer visible.

Although flooding prevented access to the RCIC room, at 02:10 on 12 March, a team was able to enter the room in the RB where the RCIC instrumentation panel was located. The readings taken there verified that the RCIC was still functioning.[108] This was reported to the MCR and the station ECR at 02:55 and served to clarify the previously unknown condition of Unit 2's core cooling about 11 hours after the loss of monitoring in the MCR.

Meanwhile, the condensate storage tank (CST), for reactor water injection (via the RCIC) was being depleted. At the same time the SC water level was increasing to levels to initiate actions to prevent overfill. Upon low level indication in the CST, it was decided to switch the RCIC pump suction leg from the CST to the SC. The team was dispatched at 04:20 and switch of lines was accomplished at 05:00. As the RCIC was continuing to cool the Unit 2 core, the Site Superintendent ordered that priority be given to preparations for the PCV venting of Unit 1, as discussed earlier.

The measurement of Unit 1's containment pressure at 04:19 on 12 March showed that pressure in the containment had decreased since the last measurement (at 02:45) without any operator action and without an established vent path, indicating that some unintentional containment pressure relief had occurred through an unknown path. Furthermore, the radiation levels measured at the main gate around 04:23 showed an increase.[109] Combined with the unexpected decrease in the Unit 1 PCV, this indicated to the staff in the common MCR of Units 1 and 2 and the ERC of some uncontrolled radioactive release from the Unit 1 PCV.

The ERC provided, at 04:45, high range APDs and full-face masks to the MCR staff, and the relevant government organizations were notified at 04:55 about the increased site radiation levels. As the site wide and the MCR dose rates increased, the shift superintendent for Units 1 and 2 required at 05:04 that the MCR staff wear full face masks with charcoal respirators. Unit 1 operators in the MCR had also periodically moved to the Unit 2 side where the radiological conditions were less adverse.

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[107] The reliability of level measurement was questionable.

[108] However, the RCIC could not be controlled because of the lack of DC power to operate the system.

[109] An increase of around ten-fold (0.000 069 mSv/h measured at 04:00 versus 0.000 59 mSv/h at 04:23).

At 05:44, the evacuation of a 10 km zone order was issued by the Government, based on the information from the site that the Unit 1 PCV venting was delayed and the PCV pressure in Unit 1 remained elevated well above its design pressure.

At 14:00, the large AOV of the PCV vent line was opened and the Unit 1 PCV venting occurred, as confirmed by the decreasing pressure measurements at 14:30 and 14:50. Although there was no significant immediate change in the radiation measurements within the site boundaries, about one hour later, a radiation dose rate reading of approximately 1 mSv/h was recorded at 15:29.

By 15:30 on 12 March, to restore temporary AC power, a mobile 6.9 kV voltage power supplies[110] to Units 1 and 2 using an undamaged transformer in Unit 2 was completed, and a low voltage grid for supply of AC power to Unit 1 was re-energized via an undamaged power centre (P/C) of Unit 2.

The explosion that occurred at 15:36 on the service floor of the Unit 1 RB damaged the newly installed high voltage cable. The blast probably also opened the blowout panel on an RB service floor wall of Unit 2.

The explosion also worsened the already challenging site conditions for emergency response activities, blasting the windows of the fire engines, injuring workers and causing locally high dose rates on the plant site due to contaminated rubble and scattered debris from the building materials. Consequently, the on-site ERC requested evacuation of staff from the areas in and around Units 1–4. Considering that radioactive gases had been also released through the same path that allowed hydrogen outside the Unit 1 PCV, the ERC also ordered the evacuation of the staff from two MCRs (Units 1 and 2, and Units 3 and 4), except for the three most senior level staff.

At 15:29, radiation dose rates at a station monitoring post along the site boundary showed 1.015 mSv/h. It was confirmed at 16:17 that the radiation level measured near a monitoring post (MP4) was 0.569 mSv/h as of 15:31. This situation was deemed to fall under Article 15 of the Nuclear Emergency Act, and government agencies were notified of ‘abnormal rise in the site boundary radiation dose rate’. Approximately three hours after the explosion in Unit 1 (four hours after venting of the Unit 1 PCV), at 18:25 on 12 March, the Government extended the evacuation zone to 20 km.

Although immediate venting of Unit 2 was not considered necessary, at 17:30, the Site Superintendent requested considerations for venting to be started before the radiological conditions would worsen upon the site wide degradation of radiological conditions.

13 March 2011

On the morning of 13 March, at 08:10, operators entered the RB and manually opened the MOV on the PCV vent line to 25%. Complete opening of the AOV was deferred until the actual time when venting would need to be carried out.

As the conditions for maintaining the relevant fundamental safety functions in Units 1 and 3 became more difficult, at 10:15, the Site Superintendent ordered venting of the Unit 2 PCV by opening the large SC vent AOV. This order was intended to take advantage of relatively favourable radiological conditions by manually operating valves in the Unit 2 RB before any deterioration in line with the site

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[110] Almost one hour after the SBO on 11 March, mobile power equipment (low and high voltage power supply vehicles) was dispatched to the Fukushima Daiichi and Fukushima Daini NPP sites. The first vehicle, from Tohoku Electric, arrived at around 22:00 on 11 March, i.e. nearly six hours after the SBO. More vehicles from other TEPCO and Tohoku Electric facilities and the Japan Self-Defense Forces arrived at the sites throughout the night. By 10:15 on 12 March, a total of 23 vehicles were at the site.

wide trend.[111] The AOV opening was accomplished in 45 minutes, at 11:00, but venting did not occur because the pressure inside the Unit 2 containment was lower than the set burst pressure of the rupture disc, 0.528 MPa (5.28 bar). In order to continuously maintain the venting path, instrumentation air was needed to keep the large SC vent open necessitating connection of a portable compressor.[112]

At 12:05, the Site Superintendent also ordered precautionary preparations for seawater injection into Unit 2 in case the unit's RCIC should fail. For this purpose, fire engines were to be connected to the FP lines of Unit 2 to inject water from the backwash valve pit of Unit 3, if needed. By the late afternoon, the fire brigade completed a seawater injection line to Unit 2. However, the ERC decided to prioritize water injection to Units 1 and 3, and the fire engine pumps were kept on standby.

Meanwhile, batteries gathered from various vehicles were connected to the SRV control panels in the MCR at 13:10, in order to allow RPV depressurization to be carried out if low pressure injection was needed.

At 14:15, after a radiation level of 0.905 mSv/h had been measured near one of the monitoring points, an 'abnormal rise in the site boundary radiation dose rate' incident according to the Article 15 of the Nuclear Emergency Act (radiation levels exceeding 0.500 mSv/h) was announced.

14 March 2011

The portable compressor, delivered from the Fukushima Daini NPP at 01:52, was connected to the air tank of the instrument air system in the TB and started to supply air after 03:00 in order to keep the large isolation AOV SC vent valve open.

At 04:30, a reinstated SC pressure monitor indicated that the SC pressure was 0.467 MPa (4.67 bar), suggesting that the pressure increase had slowed down and stabilized. As it was still below the rupture disc pressure, venting did not start.

At 11:00, the alternative seawater injection line assemblies for Units 1, 2 and 3 were completed but were kept on standby for Unit 2 as the reactor core isolation cooling (RCIC) system was thought to be still functional, while the injection to Units 1 and 3 was to resume.

At 11:01, an explosion occurred in the upper part of the Unit 3 RB. The explosion and the ejected building debris damaged fire engines and fire hoses located around the backwash valve pit of Unit 3. After a temporary evacuation of the plant site, recovery work to establish the seawater injection setup started at 13:05. However, due to scattered debris and high local radiation levels on-site, the backwash valve pit was no longer usable as a water source.

After the explosion, the large isolation AOV on the Unit 2 vent line was discovered to be closed and could not be reopened. The explosion in Unit 3 seemed to cause the valve to close, which affected the previously set up Unit 2 containment venting path, resulting in the loss of Unit 2 PCV venting capability.

Observing the reactor pressure and water level readings at 12:30 and 13:30, and comparing them to earlier readings, showed that the level was decreasing and the pressure was increasing. The unit

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[111] Between 05:30 and 10:50 on 13 March, neutrons were detected about 1 km away from the RBs of Units 1–4 near the main gate, indicating a possible breach of the PCV, although the source of the neutrons was unknown.

[112] Portable compressors were requested through teleconferencing with TEPCO Headquarters at 22:22. They were dispatched from the Fukushima Daini and Kashiwazaki-Kariwa NPPs. A portable compressor was delivered later at 01:52 on 14 March from the Fukushima Daini NPP for Unit 2 venting arrangement.

operators and the on-site ERC inferred from this that the Unit 2 RCIC system had failed. As a result, a ‘loss of reactor cooling functions’ report as defined in the regulations[113] [18] associated with the Nuclear Emergency Act [19] was issued for Unit 2 at 13:25 and the government agencies were notified at 13:38.

The measured reactor water level continued to drop, and it was estimated (at 13:25) that the level would reach TAF at around 16:30; priority was therefore given to water injection efforts. The alternative water injection line to the reactor through the FP line via two fire engines was completed at 14:43. However, water injection was not possible without first depressurizing the RPV.

Last measured at 12:30, the suppression pool was near or at saturation conditions at 0.486 MPa (4.86 bar) and 149.3°C. The ERC, concerned about high PCV pressure and saturated conditions in the SC, hesitated to depressurize the RPV, as the PCV response to the mass and energy release from the RPV to the PCV could adversely affect the PCV’s integrity. Therefore, the depressurization of the RPV was postponed until the containment venting line was re-established. This also postponed the water injection that would require depressurization.

The on-site ERC was informed at 14:04 by TEPCO Headquarters that it was agreed with nuclear regulator, NISA, to increase the emergency worker exposure dose limit to 250 mSv.

A revised estimation at 15:57 indicated that the reactor water level would reach TAF (uncovering the core) at around 17:30, based on the presumed time of the loss of the RCIC system. By 16:00, a containment vent path had not yet been re-established, and it was clear that achieving a successful venting was going to take some time. With uncovering the core predicted to be imminent, it was decided at 16:28 to depressurize the RPV by release through the SRV to the SC, to enable water injection, whilst recognizing the potential adverse impact on the confinement as a result of the release of steam from the reactor into the containment as there was no venting path to ensure PCV integrity in case of further over pressurization.

The first attempt to open the SRV from the switch in the MCR at 16:34 failed.[114] After several further unsuccessful attempts with five different SRVs, operators opened an SRV at 18:02. Additional SRVs had to be opened, before the RPV pressure dropped to about 0.65 MPa (6.5 bar) at 19:03 (from about 7 MPa (70 bar) at 16:34), which was below the fire engine pump discharge pressure. During this pressure relief, there was no apparent increase in the PCV pressure. On the other hand, the rapid pressure drop caused the water inside the RPV to flash to steam and, without make-up water injection, the water level continued to drop.[115]

Seawater injection could have started immediately after depressurization of the RPV, but the fire engine chosen for the injection ran out of fuel and stopped. After refuelling, two fire engines were started at 19:54 and 19:57, respectively, and seawater injection into Unit 2 RPV via the FP system could begin.[116]

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[113] Cabinet order in reference to the Nuclear Emergency Act.

[114] As the work to open the SRV was ongoing, the shift crew heard noises that sounded like steam relief around the SRV area.

[115] Due to flashing of the water in the measurement pipes, the reactor water level measurement after the depressurization cannot be considered reliable. Thus, the magnitude of core uncovery, i.e. partial or complete, is not known. TEPCO estimates that the core was completely uncovered.

[116] Note that not all the injected water went into the RPV because the water injection by fire engines was through the FP, MUWC and LPCI lines and there were several branches in the MUWC line to provide water for pump and valve seals, gland steam evaporators and so on.

Meanwhile, re-establishing the PCV vent path continued. After confirming that the air tank was not empty and the outlet valve was open, it was suspected that the solenoid had failed by grounding, preventing the large SC vent AOV to open. Therefore, opening the small bypass SC vent AOV was also pursued and, by successful excitation of the solenoid, the valve was deemed to have opened at around 21:00.[117] As the PCV pressure remained below the bursting pressure of the rupture disk, the venting still did not start.

At 20:30, the RPV pressure started to rise again, exceeding 1.0 MPa (10 bar) at 21:00. Two more SRVs were opened, so that the RPV pressure started to drop at 21:20. The RPV pressure rose repeatedly afterwards, and water injection was considered to have been interrupted.

At 21:55, the containment atmospheric monitoring system (CAMS) — radiation monitoring equipment inside the PCV — was restored and its readings showed significantly elevated radiation levels in the DW and SC compared with the earlier readings at 15:15, prior to the CAMS going off-line. The radiation level increase was 5000-fold (from 1.08 mSv/h to 5360 mSv/h) in the containment atmosphere (the DW) and 40-fold (from 10.3 mSv/h to 383 mSv/h) in the SC section of the containment. Additionally, neutrons had been detected between 21:00 on 14 March and 01:40 on 15 March, by a mobile radiation monitor near the main gate (approximately 1 km away from the RBs of Units 1, 2 and 3). The measured neutron dose rates were 0.01–0.02 μSv/h.[118]

In the next three to four hours, more SRVs were opened to allow water to be injected into the Unit 2 reactor; hence, the containment pressure continued to increase due to mass and energy addition to the SC. However, the Unit 2 venting could not be accomplished.

Also, both the reactor pressure and the DW pressure continued to increase, and by 22:50, the measurements showed a reactor pressure of 1.923 MPa (19.23 bar) and a DW pressure of 0.54 MPa (5.4 bar). Since this DW pressure exceeded the design pressure, it constituted an incident of ‘unusual rise of pressure in containment vessel’ under Article 15 of the Nuclear Emergency Act as declared at 22:50 by the on-site ERC. The government agencies were notified at 23:39.

There was a mismatch between the pressure trends in the SC, in which the pressure remained between 0.3 MPa and 0.4 MPa (3–4 bar), and in the DW, where the pressure increased to 0.74 MPa (7.4 bar) by 23:40. The DW continued to over pressurize while SC pressure remained below rupture disc burst pressure. In order to protect the confinement function and permit venting (PCV pressure relief) as soon as possible, TEPCO staff at the on-site and off-site ERCs agreed to vent directly from the DW by remote-manually opening the small DW bypass AOV from the MCR. It was recognized that this would increase radioactive releases to the environment without suppression pool’s scrubbing of radioactive isotopes. However, it was also not possible to open the valves on the DW vent path and consequently Unit 2 venting could not be accomplished.

15 March 2011

At 00:01, the DW vent bypass AOV was opened, but venting did not occur, although it is believed that the valve was open for a few minutes. The DW pressure remained close to 0.74 MPa (7.4 bar), while the reactor pressure increased from 0.753 MPa (7.53 bar) at 00:05 to 1.923 MPa (19.23 bar) at 00:45.

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[117] Later, at 23:25, it was confirmed that the bypass AOV had not opened.

[118] It was thought by TEPCO that the neutrons came from the spontaneous fission of actinides that were released following core damage in one of the three reactors, probably from Unit 2 [5].

Opening further SRVs caused the reactor pressure to drop to 0.73 MPa (7.3 bar), at which it remained for some time before increasing again to 0.775 MPa (7.75 bar) at 02:22. At the same time, the DW pressure also increased slightly to 0.77 MPA (7.7 bar) at 02:45.

At 04:17, the relevant government agencies were notified that depressurization of the RPV and the PCV had not been fully effective.

At 06:14, the sound of an explosion was heard on site, and tremors were felt in the MCR. This was followed by a drop in the Unit 2 SC pressure indication, which went off scale. The MCR initially reported to the ERC that the indicated SC pressure was at nearly atmospheric pressure, as zero bar was displayed in the MCR indicator at 06:30, inferring potential loss of the confinement function. After re-checking the readings, however, it appeared that the DW pressure was still at 0.73 MPa (7.3 bar) and the SC pressure went off scale.

This information indicated a possible containment vessel failure and the possibility of uncontrolled releases from Unit 2. On this basis, the on-site ERC ordered all personnel in all the units to temporarily evacuate to the seismically isolated building where the on-site ERC was located. At about the same time as the event associated with the Unit 2 SC, an explosion in the upper part of the Unit 4 RB was observed by the evacuating personnel.[119]

After corroborating the damage and failure of the Unit 2 SC (PCV), as well as the rising radiation levels, all plant personnel were ordered to evacuate temporarily to the seismically isolated building where the ERC was located. Subsequently, all personnel, with the exception of those required for monitoring and emergency restoration were told by the ERC to move to a 'radiologically safe location', resulting in approximately 650 people understanding this order as a site evacuation and evacuating to the Fukushima Daini NPP. Relevant government agencies were informed of the evacuation at 07:00, with an estimated 50–70 staff, including the Site Superintendent, remaining at the Fukushima Daiichi site.

Only a limited amount of data and plant parameters were recorded between the evacuation and the return of operators to the MCR. These included DW pressure measurements of 0.73 MPa (7.3 bar) at 07:20 and 0.155 MPa (1.55 bar) at 11:25, and a dose rate measurement at the main gate of 11.93 mSv/h was recorded at the main gate at 09:00 on 15 March, the highest measurement since the beginning of the accident and the government agencies were notified at 09:18.

At 08:25, white smoke (or steam) was observed being released from the Unit 2 RB near the fifth floor.

Given the increased radioactive releases, the Prime Minister issued an order at 11:00, requiring residents within a 20–30 km zone around the Fukushima Daiichi NPP to take shelter indoors.

16 March to May 2011

On 18 March, four workers entered the ground floor of Unit 2, where they encountered high temperature and high humidity and received a dose of about 3 mSv during their stay of approximately 14 minutes [75].

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[119] It is reported in the event investigations that the Site Superintendent became aware of the Unit 4 explosion when it was reported to him at 08:11, when the evacuation personnel arrived in the ERC. Also, the evacuating personnel of the MCR for Units 3 and 4 reported scattered debris around Unit 4, and damage to the RB of Unit 4 on the fifth floor. Later seismic analyses indicated that the explosion originated from a location inside Unit 4.

On Sunday 20 March, an auxiliary transformer of Units 1 and 2 was connected to the external grid, and temporary off-site power was restored to Units 1 and 2 at 15:46. Almost exactly nine days after the SBO, off-site power was restored to Unit 2 through this temporary AC power system, ending the SBO.

Between 23 and 25 March, water injection to the reactors was switched from sea water to borated fresh water, and on 24 March lighting was re-established in the MCR. On the following day, the fire pump was replaced by a stationary motor driven pump [74].

Unlike in Units 1, 3 and 4, the Unit 2 RB was still covering the Unit 2 SFP, and consequently the spray method for replenishing pool water could not be used for Unit 2.

On 2 April, contaminated water was discovered to be flowing from the TB into the sea via the trench for power cables near the seawater intake channel of Unit 3. The high activity of the water (^{134}Cs/^{137}Cs: 1.8×10^9 Bq/kg, ^{131}I: 5.2×10^9 Bq/kg) indicated that this water originated from within the PCV of Unit 2. However, it was unclear why the water in the TB of Unit 2 had a much higher concentration of fission products than the water in the TBs of the other units [76].

On 3 April, the power supply to the pumps supplying water to Units 1–3 was switched to off-site power.

On 4 April, the Government of Japan issued permission for TEPCO to discharge 10 000 tonnes of low level contaminated water into the ocean in order to provide storage facilities for the highly contaminated water found in the Unit 2 TB basement.

The leakage of highly contaminated water to the ocean was stopped on 6 April by injecting concrete and polymer hardener into the soil surrounding the trench. On 21 April, the amount of released activity via this water leakage was determined to about 4.7×10^{15} Bq.

A survey of the RB ground floor by remote controlled robots started on 17 April 2011.

RPV temperature measurements were restored after 20 April. The temperature sensor at the RPV support skirt (restored on 30 April) showed temperatures in the range of 250–300°C.

The Government and TEPCO announced on 19 July that the first condition of the Roadmap towards Restoration from the Accident at Fukushima Daiichi Nuclear Power Station [23] had been achieved in Units 1–3, and on 16 December 2011 that the second condition had been achieved for these units. This announcement officially brought the ‘accident’ phase of events at the Fukushima Daiichi NPP Unit 2 to a close.[120] However, some unstable plant conditions continued, such as fluctuations in temperatures, which had been explained as being caused by instrumentation failures, or fluctuations in the measurement of fission products. More stable plant parameters were achieved between March and April 2012, while post-accident management efforts continued as listed in Section 1.6.

1.3.2.3. Unit 3

Fukushima Daiichi NPP Unit 3 was a BWR/4-type reactor with a Mark-I containment.

When the Great East Japan Earthquake occurred at 14:46 on 11 March 2011, Unit 3 was operating at its rated thermal power of 2381 MW. The reactor water level was about 1150 mm, which

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[120] According to the criteria set by the Government of Japan at the time.

corresponded to 5320 mm above TAF, and the reactor pressure was about 0.71 MPa (71 bar). The SFP was fully filled with water at a temperature of 25°C.

11 March 2011

When the earthquake occurred, it triggered the acceleration sensors of Unit 3, initiating an automatic reactor scram at 14:47. All control rods were fully inserted automatically, and the shift team confirmed at 14:54 that the reactor was subcritical. The reactor scram caused a drop of the reactor water level by 1200 mm, which was recovered by feedwater, and a drop of reactor pressure by 0.7 MPa (7 bar).

Because it was an 'earthquake of greater than 45 Gal', the operators began to implement post-earthquake actions according to the AOP, 'Natural Disaster Accident', Section IV, Natural Disasters, Chapter 22. The Emergency Response Team was activated at the ERC.

Due to loss of all off-site power, the emergency busbar lost power with the result that the RPS lost power. This initiated a PCIS, which caused all the MSIVs to close. Both EDGs started automatically at 14:48, restoring AC power to the emergency bus bar.

The reactor pressure increased due to decay heat after reactor isolation (i.e. the MSIV closure) until 14:52, when safety relief valve (SRV) 'C' started to open at 7.54 MPa (75.4 bar) and close at 7.2 MPa (72 bar), thereby maintaining the reactor pressure by cycling. The reactor water level decreased as steam was released through the SRV into the SC. The SRVs continued to cycle to maintain the reactor pressure.

The shift team started the RCIC system manually at 15:05, as required by procedures. It stopped automatically at 15:25, when the RPV water level reached the high level set point (+ 1485 mm corresponding to 5655 mm above TAF, namely 'L-8').

In the SFP, which lost cooling and refilling capabilities upon the loss of off-site power, the temperature of the pool water started to increase due to decay heat.

The first tsunami wave reaching the site at 15:27 had a run-up height of 4–5 m and did not impact any essential plant systems. However, the second tsunami wave, with a run-up height of 14–15 m, flooded the plant site between 15:36 and 15:37, resulting in a series of events. The pumps for seawater systems were flooded and damaged, leading to the loss of ultimate heat sink (LUHS). Furthermore, sea water flowed into the RB, TB and other buildings. The two EDGs and associated M/Cs in the basements of the TB and the control building (CB) were flooded and lost their function, resulting in a total loss of AC power at 15:38. Station blackout (SBO) occurred and was declared by TEPCO at 15:42, and operators entered the symptom based EOP for an SBO condition.

After RCIC system stopped and SRVs continued to relieve RPV pressure, the reactor water level started to decrease again, and the shift team manually reactivated the RCIC system at 16:03. Unlike in Units 1 and 2, the flooding affected DC power systems partially, and the DC power remained available in Unit 3 for some time. The operators in the MCR were able to remote-manually start and control the RCIC system, using residual DC power and so ensured continuing, adequate core cooling. Monitoring of relevant plant parameters, such as water level and pressure inside the RPV, was possible at Unit 3. Chart recorders in the MCR continued recording plant data.

As the core cooling depended on the limited capacity of the station batteries, the operators tried to minimize the usage of DC power. This included disconnecting lighting and non-essential instrumentation at the MCR. Further, to avoid power consuming valve activations of the RCIC, resulting from automatic shutdown at high reactor water levels and automatic restart at low water levels, the operators manually adjusted its RPV water injection rate to keep the reactor water level nearly constant. This was done by suitably distributing the pump discharge flow of the RCIC into the RPV and, via a test line, back into the CST.

At 21:27, the electrical lighting of the MCR of Unit 3 was restored through the use of a mobile generator. The operation of the RCIC and cycling of SRV activation transported decay heat from the RPV into the SC, causing a continuous temperature increase of the water in the SC. The DW pressure started to increase during the evening, exceeding 0.2 MPa (2 bar) by midnight.

12 March 2011

The SBO response that had been executed in accordance with the procedure had to be modified when the RCIC system ceased to operate at 11:36 on 12 March, after nearly 20.5 hours of continuous operation, and water injection into the RPV was consequently lost. Reactor pressure was between 7.4 MPa and 7.7 MPa (74 and 77 bar) at the time. The operators unsuccessfully tried to restart the RCIC several times.[121]

The SC pressure had, meanwhile, also increased to around 0.4 MPa (4 bar) due to the SRV and RCIC system operations, and the operators started the DDFP at 12:06 remote-manually (i.e. from the MCR) to provide an alternative SC spray to cool down the SC, with the result that the SC pressure stabilized [77].

Without core cooling, the water in the reactor continued to boil and evaporate, and with continuous SRV cycling, the reactor water level continued to decrease. At 12:35, the water level eventually reached the point (the ‘reactor water level low’ signal corresponding to 2950 mm above TAF) at which the high pressure coolant injection (HPCI) system — an emergency core cooling system — activated automatically. This system started and automatically maintained the reactor water level in the predetermined range. To avoid repeated stops and starts of the HPCI, which would have utilized much of the limited DC power remaining, the operators took manual control of the system by controlling the water injection rate into the RPV using the test line in accordance with the SBO procedure. Since the capacity of the HPCI is much larger than that of the RCIC system, the HPCI turbine consumed much more steam from the reactor.

At 15:36 on 12 March, an explosion occurred on the service floor of the Unit 1 RB, causing damage to the upper building structure and injuring workers and locally high dose rates due to contaminated debris. Consequently, the on-site ERC requested evacuation of staff from the areas in and around Units 1–4, including the common MCR of Units 3 and 4, except for the three most senior level staff.

Meanwhile, although the relatively stable pressure inside the PCVs obviated the need for immediate venting, the Site Superintendent ordered, at 17:30, preparations to start for PCV venting of Units 2 and 3. This decision was based on consideration of the relatively less harsh radiological conditions in the buildings as the site wide radiological conditions were deteriorating quickly.

Given the combined effects of water injection and steam consumption of the large capacity HPCI system, the reactor pressure decreased significantly, to around 1.0 MPa (10 bar) at 19:00. At low

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[121] The operators reset the RCIC system turbine steam stop valve in the MCR and restarted the RCIC system, but it shut down immediately after the restart. They went into the RCIC room and confirmed locally that the stop valve was normal. They tried to restart the RCIC system again, but failed. There are two kinds of trip mechanisms: the electrical trip, which can be reset at the MCR control panel, and the mechanical trip, which needs additional recovery work in the RCIC system room. It is estimated that the trip of the RCIC system was caused by the electric trip detecting high discharge pressure because it was possible to reset only from the MCR.

reactor pressure, the inlet steam pressure of the HPCI turbine decreased to less than its designed range, causing the HPCI turbine rotational speed to fall below its specified operating range. The discharge pressure of the HPCI pump, therefore, gradually decreased, approaching the RPV pressure. This caused the operators to become concerned about reliability of the HPCI system now getting near the limits of the operational range.

At 20:36, the reactor water level monitor was lost due to depletion of the available 24 V DC batteries. It was restored at 03:51 on 13 March using batteries delivered from the Hirono Thermal Power Station.

13 March 2011

After 14 hours of continued operation of the emergency HPCI system, the concern about the reliability and possible failure of the HPCI turbine, which was by then operating at low reactor steam pressure, increased. The concern related to the possibility of turbine damage and creation of a release path from the reactor vessel resulting in an uncontrollable release of radioactively contaminated steam, directly outside PCV. This concern was heightened when the turbine did not automatically stop, as it was designed to, when the reactor pressure decreased below the automatic shutoff pressure of 0.8 MPa (8 bar) at 02:00 and reached 0.79 MPa (7.9 bar) at 02:30. This should normally have caused the automatic isolation of the HPCI, but it did not. The operators, in agreement with members of the ERC, therefore decided to stop the HPCI and switch the core cooling function from the HPCI to the alternative means of injection, DDFP.[122] The operators thought this could be achieved without interruption of core cooling, since the reactor pressure was already below that of the diesel driven fire pump and could be kept low by the use of SRVs.

A team was sent to the RB in order to verify the operation of the DDFP, which at this time was utilized to spray and depressurize the SC, and switch the DDFP connection from the SC spray line to the RPV injection line.

At 02:42, the HPCI was shut down remote-manually from the MCR.[123] The reactor pressure was measured as 0.68 MPa (6.8 bar) at the time. The shift team then proceeded to attempt to depressurize the reactor by opening SRVs at 02:45 and 02:55 from the MCR. However, the SRVs did not open although the valve status in the MCR indicated that they were functional[124] and the reactor pressure started to increase, reaching 0.87 MPa (8.7 bar) at 03:00. In parallel with attempts to open the SRV, the shift team started the DDFP. Although the discharge pressure of the DDFP reached 0.71 MPa (7.1 bar) by 03:05, it did not exceed the reactor pressure and so no water injection into the reactor was possible. By 03:44, the reactor pressure reached 0.42 MPa (4.2 bar).

Faced with this setback, the operators tried to restart the HPCI to revert to injection via the HPCI system at 03:35, but the restart attempts in the next 45 minutes were unsuccessful.[125] Between 03:37 and 05:08, they also unsuccessfully tried to local-manually activate RCIC (i.e. from the RCIC room). The reactor pressure continued to increase and exceeded 7.0 MPa (70 bar) by 04:30. Without any remaining system capable of injecting water into the RPV to cool the reactor, a ‘loss of reactor cooling function’ incident under Article 15 of the Nuclear Emergency Act was declared at 05:10 and

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[122] This decision was not communicated to the Site Superintendent.

[123] Note that it was possible that the flow rate into the RPV with the HPCI had decreased before it was shut down.

[124] It is estimated that the battery capacity was enough to display the status indicator lamps, but not enough to operate the SRVs [78].

[125] It was presumably due to the fading DC power supply.

was reported to the government agencies at 05:58. Without core cooling, the Unit 3 reactor continued to heat up in the following hours.

After the loss of core cooling, an alternative water injection method to cool the Unit 3 core utilizing the fire engines was considered and the work began at 05:21 to establish a line for injecting seawater into the Unit 3 core from the Unit 3 backwash valve pit through the FP lines. Also, the fire engines located at the Unit 5–6 complex and an additional fire engine from the Kashiwazaki-Kariwa NPP (which was on standby at Fukushima Daini NPP) were dispatched.

In view of the deteriorating conditions without core cooling and projected containment heat up and pressurization by the use of SRVs to depressurize the reactor for cooling water injection, the Site Superintendent also ordered preparations for venting, at 05:15, by completing the Unit 3 containment venting path up to the rupture disk. Earlier, at 04:52, the operators had unsuccessfully attempted to excite the solenoid of the SC vent valve using the small portable generator that had been utilized for the MCR lighting. Upon receipt of the venting order, a team entered the torus room in the basement of RB, where the valves for venting were located. On investigation, the team discovered that instrument air provided by the air cylinder, needed to operate the large SC AOV, was not available, since there was no pressure in the tank. Replacement of the air cylinder with another available instrument air tank in the vicinity of the torus room began at 05:23.

Since the vent path had not been established, the on-site ERC decided to change the DDFP injection to SC spray line to control the pressure increase in the containment. The DDFP, that was previously aligned but had been unable to inject to the reactor, was changed back to the SC spray injection at 05:08.

At 06:00, a fire engine located at the Unit 5–6 complex was confirmed functional and was dispatched to Unit 3. An additional fire engine, requested earlier from off-site resources earlier, left Fukushima Daini NPP at 06:00. It arrived in the Fukushima Daiichi NPP at 06:30, and was directed to the Unit 3. A seawater injection line was completed by 07:00 with water intake for the fire engines changed to Unit 3 backwash valve pit from the fresh water FP tank, However, its use was postponed by the Site Superintendent as a result of a communication from TEPCO headquarters with directions to continue to inject fresh water, rather than sea water, as long as fresh water was available.[126] As a result, the injection line was changed back to the borated freshwater source. The efforts to reduce the reactor pressure below the fire engine pump pressure required the activation of the pressure relief valves. This was achieved by use of DC batteries from cars, which were collected in the common MCR of Units 3 and 4. In parallel, the efforts to establish temporary AC power to the SLC system for high pressure injection continued.

Meanwhile, the SC spray injection had not sufficiently supressed the containment pressure and the SC continued to heat up. As the containment venting became necessary to discharge heat, the ERC requested the expedited alignment of the vent path while minimizing the containment pressure increase. At 07:39, directed by the ERC, the shift team proceeded to switch containment spray line from SC to DW for containment pressure suppression and at 07:43 DW spraying by the DDFP injection started. The DW spray stabilized the containment pressure, while the teams worked on the

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[126] A division director in the off-site ERC at TEPCO Headquarters who attended a meeting in the Prime Minister's Office earlier asked the Site Superintendent on the telephone whether there was any fresh water available. He informed the Site Superintendent of the views of meeting participants, who were inclined to continue freshwater injection as long as possible. The Site Superintendent interpreted this communication as a directive not to inject sea water as long as fresh water was available.

containment vent line. At 08:35 the operators opened manually the MOV in the RB to about 15%.[127] The venting line assembly was completed and kept open up to the rupture disc near the ventilation stack after 08:41. However, the pressure inside the containment vessel was lower than the pressure needed to burst the rupture disc, and so no containment venting occurred.

The established vent line and the stabilized containment pressure prompted the on-site ERC to stop the DW spray injection and use the DDFP for core injection. Between 08:40 and 09:10, the injection alignment was changed from the DW spray line to the alternative core injection line. As the AC power had not yet been restored to the high pressure injection system, the only injection method was DDFP or fire engines that required depressurization of the RPV.

The recovery team used batteries gathered from cars to actuate the SRVs from the MCR for reactor depressurization. As efforts continued to reduce the reactor pressure by opening an SRV, the operators in the MCR observed a drop in the reactor pressure at 09:08, although the opening of SRV was not confirmed by valve status indicators.[128] Upon the rapid RPV depressurization, borated freshwater injection into the reactor started through the FP line via the two fire engines at 09:25.[129] Overall, the Unit 3 core had remained without cooling for nearly six hours.

Along with this depressurization of the reactor, there was a pressure surge in the primary containment, confirming a discharge from the RPV to the PCV. This incidental depressurization of the RPV resulted in a surge in the SC pressure to over 0.63 MPa (6.3 bar), exceeding the maximum design pressure of the containment vessel, and eventually causing the rupture disc to burst at 09:20. Consequently, the containment pressure dropped rapidly, and the ERC judged that Unit 3 PCV venting had started. The venting of the Unit 3 containment was short lived when a valve on the vent line closed presumably because of the lack of sufficient air supply to keep it open.[130]

As the freshwater injection into the Unit 3 reactor from the FP tank via the fire engines continued for nearly three hours, available fresh water in the tanks was depleted at 12:20. As a result, the Site Superintendent decided to inject sea water into the Unit 3 reactor. The fire engines were repositioned, and seawater injection from the backwash valve pit of Unit 3 started nearly one hour later, at 13:12.

On the afternoon of 13 March, the site radiological conditions deteriorated.[131] At 14:15, an 'abnormal rise in the site boundary radiation dose rate' was declared, upon a radiation level measurement of 0.905 mSv/h at one of the site monitoring posts near the site boundary, in accordance with Article 15 of the Nuclear Emergency Act. At 15:28, dose rates exceeded 12 mSv/h at the Unit 3 side of the

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[127] The operators had some concerns about the PCV buckling under negative pressure. Thus, they opened the valve 15%, instead of 25% as defined in the procedures and implemented in Units 1 and 2.

[128] The valve status indicators did not conclusively show whether or not the valves were in the open position as the indication lamps of two of the SRVs showed erratic behaviour. The reason of the RPV depressurization is estimated that the ADS was activated with a false signal. The establishment of the pump discharge pressure of the RHR or the CS was necessary to activate the ADS, and the increase of SC pressure might satisfy the condition because the RHR pump was then directly connected to the SC even though the pump itself did not function.

[129] Not all of the injected water may have reached the reactor because of back flows into the various branches in the pipe lineup.

[130] As discovered two hours after venting started, at 11:17. It is unknown how long the valve remained in an open position. In the following 6.5 hours, various attempts were made to open the valve but these were hampered by the high dose rate within the RB. At 17:52, the compressed air system was restored by the use of a mobile compressor, and the valve was kept open afterwards.

[131] Between 05:30 and 10:50 in the morning, neutrons were detected about 1 km away from the reactor buildings of Units 1-4 near the main gate although the source of the neutrons was unknown. The measured neutron dose rates were 0.01–0.02 μSv/h.

common MCR of Units 3 and 4, causing the shift team to move to the Unit 4 side. At 14:31, the radiation dose rate exceeded 300 mSv/h at the north side and 100 mSv/h at the south side RB doors.

The on-site ERC inferred from these dose levels that radioactive gases had escaped from the Unit 3 reactor, which in turn meant that hydrogen had also escaped. Mindful of the possibility of a hydrogen explosion similar to the one at Unit 1, the Site Superintendent decided, at 14:45, to temporarily evacuate the workers from the common MCR of Units 3 and 4 and from the areas in the vicinity of Unit 3.

The evacuated areas also included the Unit 3 backwash valve pit area, halting the activities for water injection. The evacuation order was lifted at 17:00, and workers returned to the Unit 3 backwash valve pit area to continue the activities for water injection and venting.

14 March 2011

As the injection of sea water from the Unit 3 backwash valve pit continued into Monday 14 March, the water in the pit fell to such a low level that injection into Unit 3 (and Unit 1) had to be halted at 01:10. After the intake hose was lowered deeper into the pit, the remaining water was reserved for injection into Unit 3, which resumed two hours later.[132]

In the following hours, the Unit 3 containment pressure was found to be increasing and the reactor water level indication continued to decrease. By 06:20, the DW pressure reached 0.47 MPa (4.7 bar) and the reactor water level indicators went off-scale, indicating to the operators, for the first time, that the core was uncovered. From around 06:30 until 06:45, the Site Superintendent ordered an evacuation of all workers because of concern about a possible hydrogen explosion in Unit 3, halting the Unit 3 backwash valve pit area refilling activities.

The DW pressure reached 0.52 MPa (5.2 bar) at 07:00, dropped to 0.5 MPa (5 bar) at 07:20, and remained at around that pressure. The Site Superintendent decided to resume the work of establishing a seawater injection line to the backwash valve pit and withdrew the evacuation order at 07:30.

At 11:01, an explosion in the upper part of the Unit 3 RB destroyed the building structure above the service floor. The explosion also injured workers, caused damage to hoses and fire engines around the Unit 3 backwash valve pit and required the temporary evacuation of the workers in the outside areas. The explosion happened about one hour after the Unit 3 backwash valve pit levels had been restored and at a time, when Unit 1 seawater injection was getting ready to be restarted, interrupting the injection of water into Units 2 and 3 and further delaying the seawater injection into Unit 1. The work to re-establish the seawater injection line was started again after a break of two hours. Again, priority was given to restoring seawater injection into Unit 3 when the line was established.

At 11:02, reactor pressure was measured as 0.391 MPa (3.91 bar) and 0.385 MPa (3.85 bar) at Trains A and B, respectively. The DW pressure was 0.48 MPa (4.8 bar), and the SC pressure was 0.47 MPa (4.7 bar). These measurements were reported to the on-site ERC and it was inferred that both the Unit 3 RPV and the PCV were stable.

At 13:05, work began to re-establish a seawater injection line, this time directly from the ocean since the damage caused to the fire engines and hoses by the Unit 3 explosion had damaged the previous injection line from the pit beyond repair.

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[132] Unit 1 core cooling was postponed until the pit could be refilled.

Injection of seawater directly from the ocean to the reactor was started at 15:30 under the high radiation levels owing to the highly contaminated debris scattered by the Unit 3 explosion.

At 19:20, water injection had to be stopped, because a fire engine ran out of fuel, but it was restarted at 19:54. Water injection was interrupted again from 21:14 until 02:30 on 15 March in order to allow water injection into Unit 2.

15 March 2011

At 06:14, an explosion was heard on the site and tremors were felt in the common MCR of Units 3 and 4. Report from Unit 2 to the on-site ERC was indicating potential loss of the confinement function and the possibility of uncontrolled releases from Unit 2. On this basis, the on-site ERC ordered all personnel in all the units, including in Unit 3, to temporarily evacuate to the seismically isolated building. At about the same time as the event associated with the Unit 2, an explosion in the upper part of the Unit 4 RB was observed by the evacuating personnel.[133]

Subsequently, all personnel, with the exception of those required for monitoring and emergency restoration, were instructed by the Site Superintendent to go to a ‘radiologically safe location’. Approximately 650 people understood this order as a site evacuation and evacuated to the adjacent Fukushima Daini NPP, while an estimated 50–70 staff, including the Site Superintendent, remained at the Fukushima Daiichi ECR. The relevant government agencies were informed by the on-site ERC of the evacuation at 07:00.

A radiation dose rate measurement of nearly 12 mSv/h was recorded at the main gate at 09:00 on 15 March, the highest measurement since the beginning of the accident. Because of the high radiation levels, an order was issued by government authorities two hours later, at 11:00, requiring all residents within a 20–30 km radius of the Fukushima Daiichi NPP to take shelter indoors.

16 March to May 2011

On 15 March 2011, the TEPCO Nuclear Line circuit breaker was energized, and five days later, the 480 V emergency low voltage switchboard (P/C 4D) was energized.

A remote visual inspection from a helicopter to address concerns about the status of the SFP was conducted on the afternoon of Wednesday 16 March. The inspection was not conclusive as to sufficiency of the water to cover the fuel assemblies in the Unit 3 SFP, making its replenishment a high priority.

The first supply of water to the Unit 3 SFP was accomplished between 09:30 and 10:00 on 17 March, when helicopters dropped seawater. Fresh water was sprayed by water cannon trucks later on the same day between 19:05 and 20:07.

Spraying into the pools continued daily in March, using water cannon and fire engine trucks or concrete pump vehicles, to ensure that the spent fuel was not exposed.[134]

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[133] On the basis of the activity data and location in the charcoal filters of the standby gas treatment system (SGTS), it can be assumed that a gas flow from Unit 3 via its common chimney pipes into Unit 4 occurred, transporting sufficient hydrogen to account for the resulting explosion and building damages.

[134] Starting on 23 March, an available plant system, the FPC, was also utilized in the following months in addition to the spraying by vehicles.

At around 15:55 on 21 March, grey smoke coming from the roof of the RB was observed. The smoke continued until the next day and then stopped.

On 22 March, MCR lighting was restored at 10:45.

At around 16:20 on 23 March, black smoke coming from the RB was observed. Two observations at 23:30 on the same day and 04:50 on 24 March confirmed that the smoke stopped.

At 06:02, on 25 March, reactor water injection was changed from sea water to fresh water.

On 26 March, more than 14 days after the SBO, temporary off-site power to Unit 3 was restored.

Freshwater injection to the reactor from fire trucks was transferred to electrical pumps powered by a diesel generator at 08:30 on 28 March.

The Government and TEPCO announced on 19 July that the first condition of the Roadmap towards Restoration from the Accident at Fukushima Daiichi Nuclear Power Station [23] had been achieved in Units 1–3 and on 16 December 2011 that the second condition had been achieved for these units. This announcement officially brought the ‘accident’ phase of events at the Fukushima Daiichi NPP Unit 3 to a close.[135] However, some unstable plant conditions continued, such as fluctuations in temperatures, which had been explained as being caused by instrumentation failures, or fluctuations in the measurement of fission products. More stable plant parameters were achieved between March and April 2012, while post-accident management efforts continued as listed in Section 1.6.

1.3.3. Sequence of events for the Fukushima Daiichi units in the outage (Units 4–6)

If not indicated otherwise, all information in this sequence of events can be found in the reports cited in Refs [3, 4, 6].

1.3.3.1. Unit 4

Unit 4 had been shut down for the planned refuelling outage since 30 November 2010. The reactor was disassembled, with the head removed at the time of the earthquake. The cavity gates were installed, isolating the SFP from the upper refuelling pools. All fuel assemblies had been transferred from the core to the SFP. In total, 1331 spent fuel assemblies and 204 new fuel assemblies were stored inside the SFP, having an estimated decay heat of 2.26 MW by 11 March. The SFP temperature was 27°C at the time of the earthquake.

11 March 2011

The earthquake damaged the open-air switchyards of Units 3 and 4, preventing recovery of the power supply via the main grid.

This LOOP initiated startup of the air cooled EDG to supply emergency power. The second EDG was unavailable due to maintenance outage at the time of the earthquake.

The SFP cooling and make-up water pump was not supplied by emergency AC power from the EDGs and, consequently ceased to function on the LOOP. As the SFP lost cooling and refilling capabilities

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[135] According to the criteria set by the Government of Japan at the time.

upon the LOOP, the temperature of the pool water started to increase due to decay heat.[136] Alternative SFP cooling would have been possible via the residual heat removal system (RHR), which was supplied with power by the EDG. However, switching from RHR cooling to SFP cooling would have required manual actions, which had not taken place before the arrival of the tsunami.

At 15:27, the first tsunami wave arrived at the station but did not impact any essential plant systems. Between 15:36 and 15:37, the second tsunami wave arrived and damaged the seawater pumps, resulting in the loss of ultimate heat sink (LUHS). It flooded the TB basement, damaging the water cooled EDG, which was located on the first basement floor. The air cooled EDG was located on the first floor of the common fuel pool building and was not damaged by the tsunami. However, the associated regular and emergency metal-clad switch gear and power centres (M/C and P/Cs) located in the basement of the common fuel pool building and the basement of the TB were all damaged by the tsunami. On the other hand, the regular and emergency P/Cs associated with the water cooled EDG that were located on the first floor of the TB were not damaged.

Consequently, all AC power was lost and Unit 4 was under SBO conditions. Because of the SBO, the EOPs for ‘loss of all AC power’ [20] were initiated. A ‘specific event’, as defined in the regulations [18] associated with the Nuclear Emergency Act [19], was declared on the basis of a ‘station blackout’, due to the loss of all AC power supplies for longer than 5 minutes. Consequently, the relevant off-site agencies were informed in accordance with the requirements of the Nuclear Emergency Act.

The DC battery equipment, which was also located below ground in the TB, also suffered extensive water damage due to inundation. Consequently, DC power was gradually lost in Unit 4 during the first 10–15 minutes of the flooding. The additional loss of DC power meant that operators could no longer monitor the water temperature and levels in the SFP.

As the SFP lost cooling and refilling capabilities, the temperature of the pool water continued to increase due to decay heat without means to monitor the pool level and temperature.

13 March 2011

At 11:50, a water temperature of 78°C was measured inside the SFP of Unit 4, a rise of 51°C since the cooling function was lost after the tsunami on 11 March.

14 March 2011

At 04:08, the temperature in the SFP was measured as 84°C.

A team that was dispatched to check the status of the Unit 4 SFP at 10:30 on 14 March, just before the Unit 3 explosion, encountered high radiation levels, at the door of the Unit 4 RB and could not enter the building.

15 March 2011

At 06:14, an explosion was heard on the site and tremors were felt in the common MCR of Units 3 and 4. Report from Unit 2 to the on-site ERC was indicating potential loss of the confinement

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[136] The SFPs are filled with water providing radiation shielding and removal of heat from the nuclear fuel located there. However, without cooling, the pool water would heat up and eventually start evaporating. If this situation continues without refilling, the cooling of fuel stops when the water level falls and exposes the fuel. Overheating and exposure causes damage to the fuel and the release of radionuclides.

function and the possibility of uncontrolled releases from Unit 2. On this basis, the on-site ERC ordered all personnel in all the units, including Unit 4, to temporarily evacuate to the seismically isolated building. At about the same time as the event associated with the Unit 2, an explosion in the upper part (around the fourth floor) of the Unit 4 RB was observed by the evacuating personnel[137]. The explosion destroyed large parts of the building structure and internal components on the third, fourth and fifth floors. The damage on the fifth floor was first confirmed at 06:55 on the fifth floor, and all relevant agencies were informed at 07:55. There were neither eyewitnesses nor images of the explosion, and the noise it had generated was first ascribed to a possible explosion in the suppression pool of Unit 2.[138]

All personnel, with the exception of those required for monitoring and emergency restoration, were instructed by the Site Superintendent to go to a ‘radiologically safe location’. Approximately 650 people understood this order as a site evacuation and evacuated to the adjacent Fukushima Daini NPP, and an estimated 50–70 staff, including the Site Superintendent, remained at the Fukushima Daiichi ECR.

A radiation dose rate measurement of nearly 12 mSv/h was recorded at the main gate at 09:00 on 15 March, the highest measurement since the beginning of the accident. Because of the high radiation levels, an order was issued by government authorities, two hours later at 11:00, requiring all residents within a 20–30 km radius of the Fukushima Daiichi NPP to take shelter indoors.

At 09:38, a fire was reported on the north-west part of the Unit 4 RB. It was observed later that this fire had self-extinguished at 11:00.

The ERC recovery team tried to enter the RB at 10:30 in order to confirm the state of the SFP regarding to a reported fire, but abandoned the attempt because the dosimeter displayed a maximum rate of 1000 mSv/h upon opening the RB door.

16 March to May 2011

Another fire was reportedly observed on the fourth floor at around 05:45, but not confirmed upon investigation half an hour later.

A remote visual inspection from an SDF helicopter to address concerns about the status of the Unit 3 and 4 spent fuel pools was conducted on the afternoon of Wednesday 16 March. The inspection confirmed that there was sufficient water in the Unit 4 spent fuel pool to cover the fuel assemblies.

Between 08:21 and 09:40 on 20 March, the Japan SDF started to spray fresh water into the SFP using a fire engine. This operation was repeated between 18:30 and 19:46 on the same day and between 06:37 and 08:41 the next morning. By 21 March, approximately 250 m^3 of fresh water had been sprayed into the pool.

On the morning of 22 March, use of a concrete pumping truck to spray sea water into the SFP of Unit 4 was started and continued on daily basis for the next three days. Injection of water via the FPC system commenced on 25 March, and the level in the skimmer surge tank was observed to be rising, indicating that the SFP level was restored.

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[137] On the basis of the activity data and location in the charcoal filters of the standby gas treatment system (SGTS), it can be assumed that a gas flow from Unit 3 via its common chimney pipes into Unit 4 occurred, transporting sufficient hydrogen to account for the resulting explosion and building damages.

[138] Later seismic analyses by TEPCO showed that there had been no explosion inside Unit 2 and ascribed the noise to the explosion in Unit 4.

On 26 March, more than 14 days after the SBO, temporary off-site power to Unit 4 was restored.

The MCR lighting was restored at 11:50 on 29 March.

The water level inside the SFP was measured by means of a concrete pumping truck to be 2100 mm above fuel assemblies on 12 April. Ten days later, water level measurement, again using a concrete pumping truck, displayed a water level of 1700 mm above the fuel. The decrease in water level was attributed to the result of the minimum amount of water being sprayed into the SFP and the evaporation of water by the decay heat of the stored fuel.

On 27 April, the water level in the skimmer surge tank rose from 4300 mm to 6050 mm, indicating a restored SFP level. Also, the water level in the reactor well was measured for the first time since the accident, showing 1800 mm above fuel assemblies. As the water level within the SFP dropped due to evaporation in the following days, fresh water was added intermittently to compensate for this loss by the concrete pump trucks spray.

The inspections conducted on 27 April and 7 May showed that the fuel was still adequately stored inside the fuel racks and the pool gate was in sound condition despite the debris that had fallen into the SFP during the explosion in Unit 4.

The water temperature measurements at the end of April were around 90°C.

Starting on 9 May, hydrazine was added to the cooling water in order to prevent corrosion.

1.3.3.2. Unit 5

Fukushima Daiichi Unit 5 was a BWR/4-type reactor with a Mark I containment.

At the time of the earthquake, at 14:46 on 11 March, Unit 5 had been in cold shutdown condition for routine inspections since 3 January 2011. The fuel for the new operation cycle was placed inside the core with all control rods inserted as a beginning of cycle RPV pressure leak test was being conducted. The pressure vessel head was therefore closed and RPV was filled with water and being pressurized by the control rod drive (CRD) pump. The reactor water temperature was 90.6°C and the reactor pressure was around 7.25 MPa (72.5 bar). The PCV cover was open with the lid removed.

As a prerequisite for the pressure test, the relief (depressurization) function of the SRVs was restricted as they were disabled (locked)[139], although their automatic overpressure protection function was still available. Also, the MSIVs outside the containment had also been left open while the inside containment isolation valves were closed.

11 March 2011

All off-site power to Units 5 was lost at 14:49 due to the earthquake damage. Both water cooled EDGs started up automatically and provided emergency AC power to the safety systems. The reactor pressure initially dropped to 5.0 MPa (50 bar) following the loss of power supply to the CRD pump due to loss of off-site power (LOOP), but rose again due to the decay heat of the fuel, but it was well below the levels to activate the SRVs.

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[139] The depressurization function of the SRVs were locked prior to the earthquake by removal of the fuses on the MCR control panel for remote operation and deactivation the nitrogen supply lines in order to prevent the operator error of inadvertent opening of an SRV during the pressure leak test.

In the SFP, which lost cooling and refilling capabilities upon the LOOP, the temperature of the pool water started to increase due to decay heat.

When the tsunami hit the station between 15:36 and 15:37, both EDGs became inoperable because of water damage to the associated seawater pumps for component cooling. Also, all regular and emergency high voltage switchboards became inundated by the flood and were therefore rendered inoperable, resulting in an SBO at 15:40.

The lights on the Unit 5 side of the common MCR of Units 5 and 6 ceased to function, with only the emergency lighting operational.

Both trains of the DC power supply, located in the CB, were still operable and powered by DC batteries after the tsunami, supplying the monitoring instruments including the reactor pressure (narrow and wide range) and the reactor water level (narrow range) indicators. The AC powered shutdown range reactor water level indicator was not available owing to the LOOP. The reactor water level monitored by the DC powered narrow range water level indicator indicated the water level of at least 1500 mm above TAF.

As it was in the cold shutdown mode at the time of earthquake, the Unit 5 reactor was not generating enough steam to drive the turbines of the RCIC (or HPCI) system to run their pumps, so residual heat removal by high pressure coolant injection systems was not possible. The low pressure systems were also not operational: The residual heat removal (RHR) system ceased to function due to the loss of AC power supply to its pumps as well as the pumps of the residual heat removal and cooling seawater (RHRS) system; and, the make-up water condensate (MUWC) system was inoperable because its associated condensate transfer pump was no longer supplied with the required AC power. Furthermore, the FP system had been unavailable before the earthquake due to maintenance.

The MUWC system had an air cooled condensate transfer pump and did not require water cooled component cooling, and the shift team was more experienced in its use than other alternatives to be restored and aligned. The operators, therefore, decided on the pursuing low pressure core injection by the MUWC system, interconnected to the RHR system, which required the restoration of AC power and reactor depressurization[140]. Accordingly, activities to restore AC power using the available interconnecting line[141] to the operating EDG in Unit 6 were started.

Since it was not possible to reduce the reactor pressure using the SRVs as their relief function was disabled, alternative depressurization options were explored. At 21:00, depressurization of the reactor was attempted by discharging water via the RCIC and HPCI steam lines as well as via the HPCI exhaust line. Both methods were unsuccessful in reducing the reactor pressure, and the reactor continued to heat up and pressurize owing to the decay heat.

12 March 2011

The SRV automatically opened, as designed for the over pressurization protection safety function, when the RPV pressure rose to the activation pressure at 01:40 on 12 March, approximately 10 hours after the SBO. The SRVs continued to automatically open and close intermittently, maintaining the pressure between 8.1 MPa and 8.3 MPa (81 bar and 83 bar). The reactor had continued to heat up and

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[140] The MUWC condensate transfer pump had a maximum discharge pressure of 0.98 MPa (9.8 bar), which necessitated a significant reduction of the reactor pressure to allow water injection to take place.

[141] Cross-tie lines had been installed at the Fukushima Daiichi NPP nearly a decade earlier as a design enhancement for accident management.

re-pressurize, in the absence of heat removal measures, prompting the need to expedite the power restoration and reactor depressurization efforts.

The work to supply power to instrumentation switchboards in the common Units 5 and 6 control building was conducted between 03:00 and 05:00. Temporary cables were laid from the Unit 6 instrumentation switchboard located in the basement of the Unit 5 TB, connecting the emergency AC power from the Unit 6 EDG. Subsequently, the AC powered shutdown range reactor water level indication became functional, confirming the water level prior to discharge from the RPV for depressurization.

For depressurizing the reactor, the on-site ERC and the MRC staff decided to use the nitrogen operated head vent nozzle (a small valve at top of the RPV) as an alternative method to depressurize the reactor because DC power was available from the 250 V emergency batteries for this purpose. The solenoid valve in the nitrogen supply line was opened at 05:00 on 12 March. Later, at 06:06, approximately 14.5 hours after the SBO, the vessel head vent nozzle was remotely opened. The reactor pressure dropped below the MUWC pump discharge pressure, ready for injection upon restoration of MUWC and RHR systems. Reactor pressure was down from 8.3 MPa (83 bar) to approximately to 0.2 MPa (2 bar) by 06:30.

Although the nozzle was left open to continue to depressurize the water filled RPV, the reactor pressure had gradually risen above discharge pressure of the MUWC pump as work continued to restore power to the pump from the Unit 6 EDG. When the pressure was approximately 1.5 MPa (15 bar) at around 07:31, the operators tried an alternative method to depressurize the reactor, via the RHR piping, but this method did not have notable effect on the reactor pressure.

Meanwhile, the laying of cable to connect power between Unit 5 and the operating EDG in Unit 6 was completed and the associated circuit breaker was closed at 08:13 connecting Unit 5 to Unit 6 emergency AC power supply. This supplied some power to be distributed to some Unit 5 equipment nearly 16.5 hours after the SBO. Installation of temporary power cables among the Unit 5 equipment, as well as between Unit 5 and Unit 6 continued throughout the day.

At 14:42, air filtration of the common MCR of Units 5 and 6 was restored for maintaining MCR habitability when the emergency ventilation system was manually started upon restoration of power from Unit 6 EDG.

Meanwhile, the 250 V DC batteries were depleted by around 16:52 on 12 March.

13 March 2011

A concern was raised regarding the water level in the Unit 5 SFP at 12:00 on 13 March, since the SFP water temperature had been displaying a constant value of 26°C. The shift supervisor explained that the water level had dropped below the temperature gauge (located 11.2 m above the SFP floor), resulting in the gauge displaying the ambient air temperature. This led to the application of alternate SFP make-up methods using the RHR interconnection.

Additional power cables among the Unit 5 equipment and between the Unit 5 and Unit 6 equipment were installed, restoring power to other Unit 5 equipment. After connecting the power supply to the Unit 5 low voltage power panel from the Unit 6 EDG, power was supplied to the Unit 5 MUWC system's condensate water transfer pump at 20:54. The pump was manually started and the MUWC–RHR interconnecting pipe valves and the RHR discharge valves were remotely opened at around 21:00, establishing a reactor water injection route via one train of RHR 53 hours after the SBO. However, water injection to the reactor did not occur, since the reactor pressure had gradually risen and exceeded the injection pressure.

The power supply to the SGTS also became available and the system was started up at 21:01, maintaining negative pressure within the Unit 5 RB in support of the confinement function.

14 March 2011

As the reactor pressure increased and remained higher than the MUWC pump injection pressure, the operators tried another alternative method to depressurize the reactor, via the main steam line. This method also did not have notable effect on the reactor pressure. In response, it was decided to use an SRV as the remaining effective option for depressurization.

To operate the SRV required reassembly of the fuses that had been removed from the MCR control panel prior to the earthquake to prevent inadvertent operation from the MCR during the pressure leak test. It also required manual opening of the nitrogen supply line inside the PCV.

After the restoration of SRV's 'A' function (i.e. the fuse in the MCR control panel was installed and a nitrogen line in the PCV was manually opened), SRV 'A' was remote-manually opened at 05:00, using the DC power supplied by the batteries. The reactor vessel pressure decreased to 0.9 MPa (9 bar) at 05:20. The water level which was 2200 mm above TAF prior to SRV opening, as measured at 05:00, dropped to 950 mm above TAF after the opening of SRV.

After reactor depressurization, the operators remotely opened the RHR Train B discharge valve and water injection to the reactor from the CST started at 05:30 on 14 March, over two and a half days after the SBO. The reactor water level increased to 2000 mm above TAF by 06:10 validating successful water injection into the reactor via the alternative system.

Using the accident management interconnection pipes, the MUWC system was also used to restore SFP cooling and make-up starting at 09:27. The operators locally opened the valves on the fourth floor of the RB and remotely (from the MCR) operated other valves needed to inject water into the SFP from the MUWC system via the RHR and FPC systems. Upon the water injection, the indicated SFP water temperature increased from 32.5°C to 48°C at 09:58. The water temperature gauge was therefore believed to be covered with water again and water injection was halted around 10:00. Later, when the operators went to the fifth floor of the Unit 5 RB, they visually noted that the SFP water level decreased again, the SFP pool water make-up by MUWC–RHR–FPC injection was repeated between 14:35 and 15:08.

16 March 2011

In order to maintain the SFP temperature, the ERC instructed MCR operators at 21:00 on 16 March to bleed and feed the SFP water. For this, SFP water was to be extracted to the SC[142] via the RHR system, while simultaneously injecting water from the MUWC system via the RHR and FPC systems, and the SFP water exchange started at 22:16 to prevent further increase in the SFP water temperature.

17 March 2011

The SFP water exchange continued until 05:43 on 17 March. During this process the SFP water temperature increase was successfully limited to 0.2°C.

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[142] The capacity of the SC to perform its pressure suppression capability while taking SFP inventory was evaluated and confirmed.

At 11:00 on 17 March, one of the two RHR pumps on one RHR system train was deemed to be functional but did not have AC power to operate. Since flooding damaged the high voltage power panel inside the basement of Unit 5 TB, power could not be provided to the Unit 5 RHR pump via that panel. As a result, temporary power cables were laid connecting to the Unit 6 high voltage power panel (M/C) on 18 March to power Unit 5 RHR pump.

18 March 2011

On 18 March, the water cooled EDG of Unit 6 and its auxiliary systems were confirmed to be functional, but the component water cooling had to be provided for its operation. As the RHRS pumps were damaged by the tsunami and inoperable, the on-site ERC decided to use a mobile submersible pump to provide seawater cooling to the RHR system heat exchanger. The pump was procured and power to the pump and its control panels was supplied by a mobile high voltage generator when cables were connected on 18 March.

19 March 2011

After connecting pressure resistant hoses from the mobile submersible pump to the RHR system piping, the submersible pump was started at 01:55 on 19 March, providing component cooling including the water cooled EDG of Unit 6. The water cooled EDG was started at 04:22 on 19 March, and subsequently, AC power was supplied to Unit 5 via temporary cables from the Unit 6 water cooled EDG (Fig. 1.3–2). The RHR pump on the functional train of RHR system was started at 04:56.

Upon the availability of RHR system trains, the alternative RHR system arrangement was set for SFP water cooling mode and put in service at 05:00 on 19 March and continued into the next day.

Meanwhile, in order to avoid the accumulation of hydrogen, drilling holes in three parts of the RB roof was completed on 18 March.

20 March 2011

The alternative RHR system in the SFP water cooling mode was able to cool the SFP water temperature from 68.8°C, when the system was put in service, to 35.2°C in nearly one day. The ERC then decided to switch the cooling provided by the alternative RHR system from SFP cooling (the FPC mode) to reactor shutdown cooling (the SHC mode). After configuring the RHR for reactor cooling[143] by realigning the valves remote-manually from the MCR or local-manually in the RB, Train A of the RHR system started up in SHC mode at 12:25.

Unit 5 was the first Fukushima Daiichi NPP unit to reach cold shutdown mode. After the RHR system was put into service at 12:25 on 20 March to provide core cooling, the reactor temperature decreased below 100°C in approximately two hours. Therefore, Unit 5 was placed in the cold shutdown mode at 14:30 on 20 March 2011, nearly nine days after the beginning of the accident.

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[143] The RHR system was used to cool the reactor and the SFP on an alternating basis after 20 March.

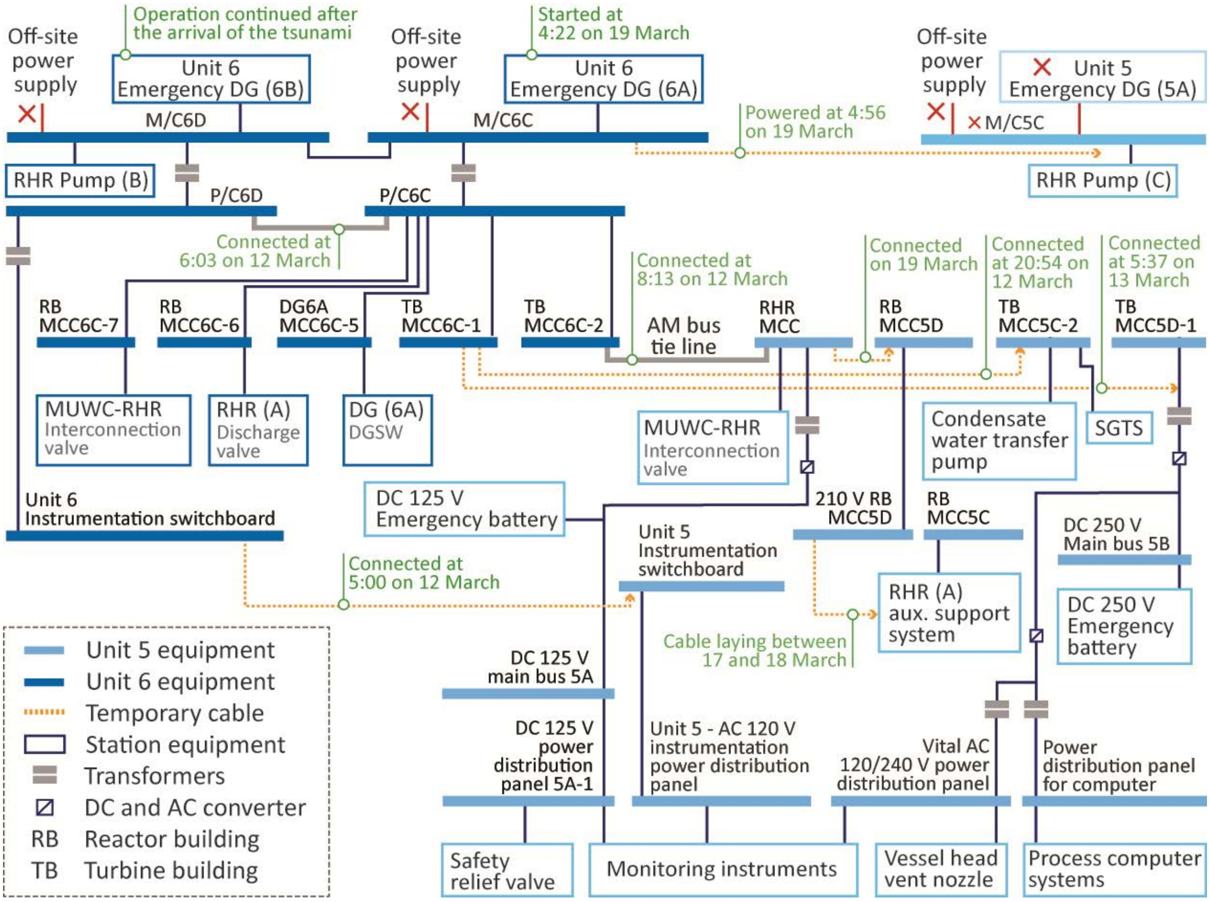

FIG. 1.3–2. Restoration of power for Units 5 and 6 [3].

1.3.3.3. Unit 6

Fukushima Daiichi Unit 6 was a BWR/5-type reactor with Mark II containment.

At the time of the earthquake, at 14:46 on 11 March, Unit 6 had been in outage mode since 14 August 2010. The reactor was in cold shutdown condition, with the fuel loaded and all control rods fully inserted into the core. The RPV head and the PCV cover were closed. The pressure vessel vent pipe[144] was left open and the MSIVs outside the containment had also been left open while the inside containment isolation valves were closed.

The reactor pressure was at atmospheric level, the reactor water temperature was 26°C and the SFP water temperature was 25°C. At the time of the earthquake, the 'upset range water level indicator' displayed a value of 1400 mm, which corresponded to the water level of 5596 mm above TAF.

11 March 2011

All off-site power to Unit 6 was lost at 14:49 due to earthquake damage. Upon the LOOP event due to the earthquake, two water cooled EDGs and one air cooled EDG started up automatically and provided emergency AC power to the safety systems.

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[144] A pipeline that is connected to the RPV head in order to extract steam (or non-condensable gases) from the RPV when the reactor is not in shutdown condition.

In the SFP, which lost cooling and refilling capabilities upon the occurrence of the LOOP, the temperature of the pool water started to increase due to decay heat.

Because it was an ‘earthquake of greater than 45 Gal’, the operators began to implement post-earthquake actions according to Chapter 22 of the AOP, ‘Natural Disaster Accident’, Section IV, Natural Disasters. The Emergency Response Team was activated at the ERC. The operators also began to implement ‘Natural Disaster Accident’ Section II, Turbine and Electrical, Chapters 12, 13 and 14 of the AOP to address the LOOP.

When the tsunami hit the station between 15:36 and 15:37, the water cooled EDGs shut down (at 15:36) because of the damage inflicted to the seawater pumps, as well as the damage to the associated power panels and switchboards. However, the air cooled EDG, located on the first floor in the diesel generator building (DG building) did not suffer either water damage or loss of cooling (since it was air cooled). Its associated power panels had also not suffered water damage from the inundation. Therefore, the associated emergency high voltage switchboard on the first basement level inside the RB was still available for emergency power supply. Therefore, the operators continued with their AOPs for responding to the earthquake and LOOP.

The DC power equipment was also functional. Due to the loss of emergency AC power supply after the failure of the water cooled EDG, the power supply was switched over to one train of DC power supply. As the air cooled EDG was still operating, the Unit 6 side of the common MCR of Units 5 and 6 was still functioning.

The relatively low decay heat of Unit 6 and initial low reactor pressure meant that there was some time available to implement alternative methods for coolant injection and that there was no immediate need for reactor depressurization.

Pumps B and D of the low pressure heat removal system, RHR, were still supplied with emergency AC power, but the system itself was inoperable due to severe tsunami damage to the pumps of the RHRS. This also impacted the fuel pool cooling and cleanup (FPC) system, the high pressure core spray (HPCS) system and its associated components.

However, the condensate transfer pump of the MUWC system was still available, as it was powered by the air cooled EDG as an alternate reactor water make-up and heat removal at low pressure.

Train B of the standby gas treatment system (SGTS), also powered by EDG 6B, continued to function after the tsunami hit the station and negative pressure was maintained inside the RB.

The shift supervisor in consultation with the ERC decided to utilize the MUWC system for coolant water injection until the RHR system could be restored. In order to allow water injection via the MUWC–RHR piping, two valves on the RHR train had to be aligned. These valves were no longer supplied with emergency power since the water cooled EDG had ceased to function. However, by interconnecting the associated power panel, these valves could be remotely operated from the MCR.

12 March 2011

The restoration of power to Unit 6 systems (and cross-connecting the operating EDG to Unit 5) in order to supply power to instrumentation switchboards in the common Units 5 and 6 control building was conducted between 03:00 and 05:00.

The work associated with electrical system connection to operate the valves to align MUWC-RHR system for core cooling started at 06:03 on 12 March.

At 14:42, air filtration of the common MCR of Units 5 and 6 was restored for maintaining MCR habitability when the emergency ventilation system was manually started upon restoration of power from the operating EDG.

13 March 2011

A concern was raised regarding the Unit 6 SFP level at 12:00 on 13 March since the SFP water temperature had been displaying a constant value of 18°C. The shift supervisor elaborated that the water level had dropped below the temperature gauge (located 11.2 m above the SFP floor) resulting in gauge displaying the ambient air temperature. This prompted plans to arrange SFP make-up, in addition to the reactor from the MUWC system via the RHR and FPC systems.

Following the manual start of the MUWC condensate transfer pump at 13:01 on 13 March, water injection to Unit 6 core started at 13:20 and continued intermittently afterwards.

14 March 2011

Using the accident management interconnection pipes, the MUWC system was also used to restore SFP cooling and make-up at 14:13, when, after ensuring the cooling of Unit 5 SFP, the operators manually opened valves on the fifth floor of the Unit 6 RB and also remotely operated valves from the MCR to inject water into the Unit 6 SFP via the FPC. Upon the injection of water, the indicated SFP water temperature increased from 21.5°C to 50.5°C at 15:03 when water injection was stopped. At this point, it was assumed that the water level had again risen above the temperature gauge.

For the reactor core cooling, intermittent water injection continued on 14 March. At 21:30, when the water level[145] decreased to 1800 mm, the water injection was repeated and the restored the reactor water level to 3000 mm by 21:55. With the intention of maintaining a high water level, operators controlled the level just below the main steam line nozzle.

15 March 2011

The installation of an alternative emergency power supply from Unit 6 to Unit 5 has been described in the previous section. Starting on 15 March, the operators conducted inspection to verify the functionality and operability of the water cooled EDGs and its auxiliary systems.

16 March 2011

In order to maintain the SFP temperature, the ERC instructed MCR operators at around 13:00 on 16 March to bleed and feed the SFP water. For this, SFP water was to be extracted to the SC via the RHR system, while simultaneously injecting water from the MUWC system via the RHR and FPC systems. In order to circulate the SFP water, and therefore control the rise in the water temperature, the shift team operated the FPC pump between 13:10 and 21:44 utilizing the power supply from the air cooled EDG. During this period, the SFP water temperature increase was halted. This recirculation operation was stopped in order to avoid heat transfer from the uncooled pump to SFP water.

17 March 2011

The operators checked the functionality and operability of the water cooled EDGs and its auxiliary systems by visual inspection. The inspections also addressed the concerns regarding the rotation of

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[145] Shutdown range reactor water level indicator

DGSW pump shaft as its shaft could be stuck. The inspection team reported to the on-site ERC that the water cooled EDG and its auxiliary systems were operable. As result, the ERC developed a plan for RHR restoration for Units 5 and 6 based on the fact that both EDGs were available and operable.

The TEPCO RHR system recovery team developed a plan to use a mobile submersible pump in the RHRS instead of the damaged RHRS pumps. The installation of an alternative RHR system assembly began in the early morning of 17 March. Simultaneously, attempts were made to clear earthquake and tsunami debris from the Unit 6 site to allow the alternative RHR restoration work to be carried out. Installation of the two procured submersible pumps in place of the damaged RHRS pumps continued throughout 17 March and the next day.

18 March 2011

At 17:00, in order to avoid the accumulation of hydrogen, drilling holes in three parts of the RB roof was completed.

The DG seawater pump was restored and activated at 19:07.

19 March 2011

After connecting pressure resistant hoses from the mobile submersible pump to the RHRS piping, the Unit 5 submersible pump was started at 01:55 on 19 March, providing component cooling including the water cooled EDG of Unit 6, and the second EDG was started at 04:22.

Power to the two submersible pumps, that were installed to replace the damaged the pumps of Unit 6 RHRS, and their control panels was supplied by a mobile high voltage generator when cables were connected at 21:26 on 19 March.

Upon the availability of RHR system trains, starting earlier at 11:00, alignment of the RHR Train A in the SFP cooling (FPC) mode was conducted, and SFP cooling was started at 22:14 on 19 March and continued into the next day.

20 March 2011

The operation alternative RHR system in SFP water cooling mode cooled the SFP water temperature from 67.5°C, when the system was put in service, to 27.5°C at 17.00 on 20 March.

The ERC then decided to switch the cooling provided by alternative RHR system from SFP cooling (FPC mode) to the reactor shutdown cooling (SHC mode) after switching the operating mode of the Unit 5 RHR system. To avoid the backflow of water from the reactor into the SFP cooling mode line, the shift team stopped the RHR system at 16:26. After configuring the RHR for reactor cooling by realigning the valves remote-manually from the MCR, the RHR was started in SHC mode to inject water into the reactor at 18:48.

After the RHR system was put into service at 18:48 on 20 March to provide core cooling, the reactor temperature decreased below 100°C in less than an hour. Therefore, Unit 6 was placed in the cold shutdown mode at 19:27 on 20 March 2011, little more than nine days after the beginning of the accident.

1.3.4. Sequence of events in the common spent fuel pool

At the Fukushima Daiichi site, there is a large shared pool to store fuel assemblies from all units, called the common spent fuel pool, located in a separate common pool building as a shared auxiliary facility. It has been in service since October 1997, and at the time of the earthquake there were 6375 spent fuel assemblies stored in it.

Two air cooled EDGs associated with Units 2 and 4 were installed on the first floor of the common pool building. These EDGs themselves did not suffer direct water damage. However, their associated power panels which were installed on the basement floor of the shared auxiliary building, lost function when the basement flooded.

On 21 March, water was sprayed over the pool after the water temperature had risen to 61°C [79]. On 23 March, via a temporary line, water from SC surge tank A was injected into the common pool by a fire engine. On the next day, 24 March, common pool cooling was carried out using the FPC system and the SFP auxiliary unit cooling system pump. Power was supplied to the alternative cooling system on 24 March after off-site power had been restored to the Fukushima Daiichi site. The water temperature in the common pool had risen to 73°C by this time.

1.3.5. Sequence of events for the dry cask storage facilities

The dry cask storage facility at the Fukushima Daiichi site started operation in August 1995. It is located between Units 1 and 4, and Units 5 and 6. The storage casks are cooled by natural convection.

At the time of the earthquake, there were 408 spent fuel assemblies stored in nine dry storage casks (five large dry storage casks and four medium dry storage casks) in the cask storage building. After the earthquake, the entire nuclear power plant site, including the dry storage area, lost off-site power and an SBO occurred when the tsunami hit. The tsunami inundated the storage area floor and also carried a large amount of sea water, sand and scattered debris inside. Each cask was bolted to the floor and therefore did not move from its position. Subsequent inspections by TEPCO found neither significant damage to the casks themselves nor elevated radiation levels and the cooling of the casks by natural convection was not affected. The integrity of the casks was verified by leak tests [17].

1.3.6. Sequence of events for the Fukushima Daini Units

The Fukushima Daini site hosts four BWR/5 reactors with Mark II containments. Prior to the earthquake, all four units were operating at rated thermal power, off-site power was being supplied by three of four lines (one line was undergoing maintenance), all 12 EDGs (the number includes the HPCS-DGs) and all emergency core cooling systems were operable.

11 March 2011

When the earthquake occurred, all units automatically shut down due to the seismic instrumentation trip. Two of the three available off-site power sources were lost, but off-site power was maintained by the remaining line.

Approximately 35 minutes after the earthquake, the first tsunami wave reached the site, flooding the heat exchanger buildings, which were housing the seawater pumps and motors at the seawater intakes of all four units, and the EDG areas.[146] The flooding resulted in a loss of ultimate heat sink (UHS) at Units 1, 2 and 4.

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[146] Unlike the Fukushima Daiichi NPP units, Fukushima Daini units had their seawater pumps and motors (of the RHRC, the RHRS and the emergency equipment cooling water (EECW) systems) and their PCs housed, i.e. relatively protected, in the 'heat exchanger buildings'.

The first tsunami wave also flooded main buildings including the RB and TB of Unit 1, the TB of Unit 3, and the SBs for Units 1 and 2, and Units 3 and 4.

Operators began reactor depressurization of all four units using the SRVs to control pressure and the RCIC systems to maintain the reactor coolant system inventory. This operation transferred the decay heat from the reactors to the water in the suppression pools.

At Unit 3, Train A of the RHR equipment was inoperable due to flooding, but the Train B equipment remained operable, including the UHS. This allowed the operators to take the unit to cold shutdown less than 24 hours after the tsunami reached the station.

ERC personnel knew that the critical issue was re-establishing core cooling capabilities to Units 1, 2 and 4. This required restoration of the residual heat removal and cooling seawater (RHRS) system and residual heat removal and cooling (RHRC) system functions. The temporary cables needed to supply power to the equipment were transported to the site by helicopter and trucks. The cables were installed to supply power from the radioactive waste (referred to as 'radwaste') building, Unit 3 heat exchanger building B, and mobile power supply trucks to the motors of the RHR system and RHRC pumps for Units 1, 2 and 4. Approximately 9 km of temporary cable were installed. Some pump motors had to be replaced on Units 1 and 4. Replacement motors were airlifted in by the SDF and were also transported from the Kashiwazaki-Kariwa NPP.

12 March 2011

By 05:00, the reactor pressure in all four units had been reduced to the point where low pressure alternate injection using the MUWC systems could be initiated and the RCIC systems were isolated. Both the RCICs and the SRVs had transferred reactor decay heat into the SCs. Since there was no alternative means for decay heat removal, SC temperatures on Units 1, 2 and 4 exceeded 100°C by 06:07, resulting in the inoperability of the SCs. After deliberation, the ERC directed the MCR to perform SC cooling by injecting MUWC cooling water into the SCs using the FCS drain line. MUWC was also used to spray the DW and the SC in order to suppress PCV pressure increase. As work continued to restore the RHRS at Units 1, 2 and 4, it was decided to align the PCV vents in all four units in case they were needed.

By 12:15, the Unit 3 reactor water temperature that had been lowered by the RHR system decreased below 100°C and the reactor was placed in cold shutdown. At 13:38, a second off-site power line was restored.

13 March 2011

On 13 March, a third off-site power source was restored, and at Unit 1 the seawater cooling pump for Train B RHR equipment was manually started at 20:17, followed by the Train D RHR equipment cooling pump at 21:03.

14 March 2011

Beginning in the early morning, RHR was sequentially restored to Units 1, 2 and 4. At Unit 1, by 10:15 the SC temperature had been reduced to less than 100°C, which restored the pressure suppression function, and by 17:00 the reactor was in cold shutdown when the reactor temperature decreased below 100°C. At Unit 2, by 15:52 the SC temperature had been decreased to less than 100°C and by 18:00 the reactor was in cold shutdown.

15 March 2011

At Unit 4, by 07:15 the reactor water temperature was reduced to below 100°C and the reactor was in cold shutdown. At 17:43, the fourth and final off-site power source was restored.

1.3.7. Site to site event comparison

In addition to the Fukushima Daiichi site, four other nuclear power plant sites on the east coast of Japan were impacted by the earthquake and tsunami. These sites are Higashidori, Onagawa, Fukushima Daini and Tokai Daini. Given that all of the reactors at these sites are BWRs but the plant response varied, it is illuminating to review each reactor's response in order to consider the factors which allowed some to cope better than others.

1.3.7.1. Higashidori nuclear power plant

The Higashidori site is home to one BWR/5 reactor with a Mark I containment. The reactor was undergoing a planned refuelling/maintenance outage at the time and the core had been removed from the reactor and placed into the SFP. When the earthquake struck, all three off-site power supply lines were lost. One of the facility's two EDGs had been removed from service and was undergoing routine planned maintenance, but the remaining EDG was operable, and it started and provided power to its associated safety systems. There was no onsite damage reported as the result of either the earthquake or tsunami. Off-site power was restored later on 11 March.

1.3.7.2. Onagawa nuclear power plant

There is one BWR/4 and two BWR/5 reactors at the Onagawa site, all of which have Mark I containments. Onagawa Units 1 and 3 were operating at full power when the earthquake struck; Unit 2 was in the beginning stages of a reactor startup.

The earthquake rendered four of the five off-site power supply lines inoperable, but off-site power was maintained by the remaining line. The first tsunami wave arrived at the site approximately 45 minutes after the earthquake. Onagawa experienced a tsunami with a 13 m run up height. Even though the site elevation 'dropped' from 14.8 m to 13.8 m as a result of the earthquake, the elevation was still adequate to prevent the site from being inundated. There was, however, significant tsunami induced flooding at Unit 2, as described below.

When the earthquake struck, Unit 1 tripped due to the seismic instrumentation, and both EDGs started but did not connect to their electrical loads since off-site power was available. Approximately 10 minutes after the earthquake, there was a failure of the unit's startup transformer due to earthquake induced damage to the high voltage circuit breakers. Loss of the startup transformer resulted in a Unit 1 LOOP, but the EDGs were available and provided power to their associated safety systems. The operators started the RCIC system to provide reactor coolant system make-up and used the SRVs to depressurize the reactor to the point that the RHR system could be used to provide decay heat removal. Cold shutdown was achieved shortly after midnight on 12 March. The startup transformer was restored to service at 02:05 on 13 March, which re-established off-site power to the unit.

Unit 2 was in the early stages of a reactor startup, but the reactor was not critical. When the earthquake struck, the seismic instrumentation system initiated a reactor trip. As a result, the unit immediately transitioned to cold shutdown since the reactor coolant temperature was only 78°C. The unit's EDGs automatically started, but remained in a standby mode since off-site power was available.

Unit 2 experienced significant flooding when the tsunami caused seawater to flow through penetrations in the seawater intake pump pit floor. The water flowed through a pipe/cable tray trench into the reactor auxiliary building area basement, which flooded the Train B RCW heat exchanger and pump room and the HPCW heat exchanger and pump room, ultimately causing the shutdown of the Train B EDG and the HPCS DG. Train A safety systems were not affected by the flooding.

At Unit 3, the reactor tripped due to the seismic instrumentation and both EDGs started but did not connect to their electrical loads since off-site power was available. The operators started the RCIC system to provide reactor coolant system make-up and used the SRVs to depressurize the reactor to the point that they could use the RHR system to provide decay heat removal. Unit 3 was in cold shutdown at 01:17 on 12 March.

1.3.7.3. Fukushima Daini nuclear power plant

As described in Section 1.3.6, off-site power was maintained at the site after the earthquake by one remaining off-site source, but tsunami flooding resulted in the loss of the UHS at Units 1, 2 and 4.

The operators were successful in depressurizing the reactors using the SRVs and using the RCIC systems to maintain RCS inventory, but both the SRVs and the RCIC systems transferred heat from the reactors to the water in the SCs. With no decay heat removal capability, DW pressures climbed and the SC water temperatures on Units 1, 2 and 4 increased to the point where they became inoperable.

ERC personnel recognized that the critical issue was establishing decay heat removal for Units 1, 2 and 4. Based on equipment observations, the ERC prioritized inspection/maintenance of selected equipment in the heat exchanger buildings. This included replacing selected pump motors on Units 1 and 4 and installing approximately 9 km of temporary cables to route power from operable power panels and/or mobile generators to the required pumps.

Beginning in the early morning of 14 March, decay heat removal was sequentially restored to Units 1, 2 and 4. By 18:00, the Unit 1 and 2 reactors were in cold shutdown, followed by Unit 4 at 07:15 on 15 March.

1.3.7.4. Tokai Daini nuclear power plant

The Tokai Daini NPP site hosts one operating BWR-5 reactor with Mark II containment.

Prior to the earthquake, the Tokai Daini NPP unit was operating at full power. In response to the earthquake, the reactor automatically shut down due to the seismic instrumentation trip. All three off-site power sources were lost and all three EDGs started automatically. The first tsunami wave reached the site about 30 minutes after the earthquake. Ultimately, tsunami induced flood waters inundated one pump bay containing seawater pumps, which in turn caused the loss of one of the EDGs and its associated electrical loads. The other pump bay had been upgraded to be watertight and did not flood. The remaining EDGs provided power to the ECCS, which maintained core cooling. One off-site power supply source was restored at 19:37 on 13 March, and the reactor reached a state of cold shutdown at 12:40 on 15 March.

1.4. RADIONUCLIDE INVENTORY AND RELEASES

Radionuclides escaped from the cores of Fukushima Daiichi NPP Units 1, 2 and 3 as a result of failures of the fuel, cladding, and RPV and/or associated systems. These radionuclides were subsequently released to the environment either in a controlled manner, i.e. by venting of the primary containment vessel (PCV), or in an uncontrolled manner as a consequence of damage and failure of the PCV and RB during the accident sequence.

It is important to quantify the amount, type, distribution, dispersion, direction, and settlement of these radionuclides to be able to predict the public health and environmental consequences of the radiological release, as will be discussed in detail in Technical Volume 4, and to plan and implement remediation and recovery, as discussed in Technical Volume 5. There were limited radiation measurements made at and around the Fukushima Daiichi NPP during the accident[147], as well as larger scale atmospheric and oceanic measurements afterwards which continue up to the present day. Many organizations around the world continue to apply computational methods to model and describe the total releases into the atmosphere and the marine system from the Fukushima Daiichi NPP units.

Data on the initial radionuclide inventories in the cores of Fukushima Daiichi Units 1–3, and the release fractions of radiologically significant radionuclides, are essential for personal radiation dose and environmental consequence assessments. Their release mechanisms, paths, times and durations can be derived from knowledge of the event sequence. Information on the atmospheric and oceanic dispersion of radionuclides provides information necessary for the protection of people and the environment.

In this section, the initial radionuclide inventories of the Fukushima units at the time of the accident and those at the supposed start time of core degradation are provided. The fission product release mechanisms and the atmospheric, oceanic and terrestrial dispersion pathways are discussed. The principal features and main results of these analyses are also compared with Chernobyl accident releases.

To date, it is considered that there was no radioactive release from the SFPs at Units 1–4, because no voiding and fuel heat-up occurred during the accident and no damaged fuel was found after the accident. For this reason, the inventories of the SFPs at Units 1–4 are not provided and only core inventories of, and releases from, Fukushima Daiichi NPP Units 1–3 are discussed.

1.4.1. Fukushima Daiichi Units 1–3 radionuclide core inventories at the time of accident

The exact amount of each radionuclide in any reactor core at any given time is not precisely known. However, the inventory of isotopes can be calculated from knowledge of the core type and dimensions, the fuel enrichment and the reactor power history.

When comparing different inventory calculations for the Fukushima Daiichi NPP reactors the following points need to be noted:

- The composition and enrichment of the uranium/plutonium oxide fuel (MOX fuel) used at the Fukushima Daiichi NPP reactors is not publicly available due to security and commercial restrictions. Therefore, the inventory has to be calculated based on the known parameters (Table 1.4–1) [64, 65, 80], supplemented by assumptions derived and justified from similar fuel types (Table 1.4–2).
- The power history of Fukushima Daiichi Units 1–3 was made available publicly by JNES in 2011 [81]. The differences in the assumptions about power histories and fuel enrichment are linked to the unavailability of specific data for the cores of Units 1–3 when the early estimates were performed. When the average core burnups of the Units 1–3 cores became available, after the plant computer calculations and the operator logs [64, 65, 80] were disclosed by TEPCO, they provided a method for directly validating the power history used in the calculations.

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[147] The Fukushima Daiichi NPP was not equipped with instrumentation scaled to record fission product releases in such severe accidents. Even if sufficient electric power had been available during the accident, the measurement range of the normal exhaust air screening equipment would have been greatly exceeded for data collection.

- Later calculations used more detailed information about the time at power and the cooling times, and the number of fresh fuel assemblies loaded into the core in each refuelling cycle, as well as the MOX fuel composition, which were published in a 2012 JAEA report (in Japanese) [82]. Although these data cannot be considered as exact in the absence of TEPCO's confirmation and concurrence, it is deemed to be sufficient to validate the properties and power histories used in the different calculations.
- Comparison of the initial core inventory from various calculations, using different methods and codes, gives confidence to the validity of the input assumptions. The majority of the fuel inventory calculations for Fukushima Daiichi NPP Units 1–3 utilized the ORIGEN family codes [83, 84] as their calculation method. A cross-comparison analysis was performed by JAEA with ORIGEN2 and SWAT codes [82]. IBRAE RAN made its calculation with the BONUS code [85, 86].

Table 1.4–1 presents the parameters of the six Fukushima Daiichi cores and Table 1.4–2 gives a summary of the input and assumptions used for estimating the radioactive inventories of Units 1–3.

TABLE 1.4–1. PARAMETERS OF THE FUKUSHIMA DAIICHI REACTOR CORES [64, 65, 80]

Fukushima Daiichi Unit		1	2	3	4	5	6
Reactor type		BWR/3	BWR/4				BWR/5
Full core power (MW(th))		1380	2381	2381	2381	2381	3293
Condition before earthquake		Operating	Operating	Operating	Refuelling outage (core off-loaded)	Refuelling outage (shutdown pressure test)	Refuelling outage (cold shutdown)
Core power at the time of accident (MW(th))		1380	2381	2381	0	Decay heat	Decay heat
Typical cycle length		~13 months					
Average reload batch size (No. of assemblies)		~100	~137	~137	~137	~137	~191
Core effective power days at the time of the accident (day)		~140	~80	~130	—	—	—
Fuel assembly (No. of assemblies in the core)		400	548	548	548	548	764
High burnup 8 × 8 fuel assemblies	Number	68	—	—	—	—	—
	Enrichment (Avg., w/o)	3.4	—	—	—	—	—
	Burnup (GW·d/t)	39.5 (Avg.) 50.0 (Max.)	—	—	—	—	—
9 × 9 fuel (A type) assemblies	Number	—	—	516	—	—	—
	Enrichment (Avg., w/o)	—	—	3.8	—	—	—
	Burnup (GW·d/t)	—	—	45.0 (Avg.) 55.0 (Max.)	—	—	—

TABLE 1.4–1. PARAMETERS OF THE FUKUSHIMA DAIICHI REACTOR CORES [64, 65, 80] (cont.)

Fukushima Daiichi Unit		1	2	3	4	5	6
9 × 9 fuel (B type) assemblies	Number	332	548	—	—	548	764
	Enrichment (Avg., w/o)	3.6	3.8	—	—	3.8	3.7
	Burnup (GW·d/t)	45.0 (Avg.) 55.0 (Max)	45.0 (Avg.) 55.0 (Max)	—	—	45.0 (Avg.) 55.0 (Max.)	45.0 (Avg.) 55.0 (Max.)
8 × 8 MOX fuel assemblies	Number	—	—	32	—	—	—
	Enrichment (Avg., w/o)	—	—	1.1–1.2 [U] 2.7–5.3 [Pu]	—	—	—
	Burnup (GW·d/t)	—	—	33.0 (Avg.) 40.0 (Max.)	—	—	—
Fuel rod active length (m)		3.66	3.71				

Note: MW(th): Megawatt (thermal); GW·d/t: gigawatt-day per tonne; w/o: weight percentage.

TABLE 1.4–2. SUMMARY OF INPUT AND ASSUMPTIONS USED IN THE CALCULATIONS OF INVENTORY OF RADIONUCLIDES IN THE CORES OF UNITS 1–3

Input/assumption	Kirchner et al., 2012 [84]	JAEA [82]	IBRAE RAN [87]	PNNL [83]
Code used	ORIGEN-ARP	ORIGEN2	BONUS	ORIGEN-ARP
Units modelled	Average core representing Units 1–3	Units 1–3 with specific core parameters	Units 1–3 with specific core parameters	Average core representing Units 1 and 3
Fuel type	GE-11 9 × 9	Unknown	—	GE 8 × 8
U-235 enrichment (%)	3.8	3.7	3.7	4.0
Pu-239 enrichment (%)	0	1.68	1.68	0
Power density (Units 1–3), MW/t HM	25.0	20.0/25.3/25.3	20.0/25.3/25.3	25.0
Irradiation history	Assumed: 5 × 360 days; Downtimes: 4 × 30 days	Realistic	Realistic, only last downtime is considered	Assumed: 3 × 400 days
Assumed power density distribution in the core	Kq = 1 Average over the core	Kq = var Linear across fuel groups at each cycle linear over cycles in each fuel group	Kq = 1 Average over the core	Kq = 1 Average over the core
Average core burnup (Units 1–3), GW·d/t HM	26.7	25.8/23.1/21.8	21.9/20.3/19.7	30
Average core burnup by operator logs (Units 1–3), GW·d/tHM	25.779 (Unit 1)/23.05 (Unit 2)/21.812 (Unit 3) [64, 65, 80]			

Note: t HM: metric tonnes of heavy metal; GW·d: gigawatt-days.

By way of example, the results of all the calculations of the inventory of Unit 2 are shown in Table 1.4–3 and summarized in Fig. 1.4–1.

TABLE 1.4–3. FUEL INVENTORY (Bq) CALCULATED FOR THE UNIT 2 CORE IN DIFFERENT ANALYSES [82-84, 87]

Nuclide	Kirchner et al., 2012	JAEA	IBRAE RAN	PNNL*
Am-241	3.4E+14	4.35E+14	Not calculated	3.37E+14
Am-243	2.2E+13	2.97E+13	Not calculated	2.50E+13
Ba-140	4.2E+18	4.35E+18	4.27E+18	4.30E+18
Ce-144	3.1E+18	2.31E+18	2.37E+18	3.36E+18
Cm-242	6.5E+16	8.94E+16	Not calculated	7.18E+16
Cm-244	1.5E+15	3.21E+15	Not calculated	1.69E+15
Co-60	3.9E+16	3.61E+12	Not calculated	Not calculated
Cs-134	2.6E+17	2.76E+17	2.49E+17	2.97E+17
Cs-136	9.4E+16	8.17E+16	5.83E+16	1.03E+17
Cs-137	3.0E+17	2.55E+17	2.29E+17	3.36E+17
H-3	1.5E+15	1.25E+15	Not calculated	1.70E+15
I-129	6.9E+10	7.47E+10	6.73E+10	Not calculated
I-131	2.4E+18	2.34E+18	2.71E+18	2.45E+18
La-140	4.5E+18	4.43E+18	4.28E+18	7.76E+18
Np-239	3.9E+19	4.32E+19	4.58E+19	Not calculated
Pu-238	3.9E+15	4.57E+15	Not calculated	4.24E+15
Pu-239	9.1E+14	8.83E+14	9.57E+14	8.39E+14
Pu-240	1.3E+15	1.04E+15	7.66E+14	1.37E+15
Pu-241	2.6E+17	2.81E+17	3.28E+17	2.74E+17
Pu-242	3.1E+12	3.41E+12	Not calculated	Not calculated
Ru-103	3.4E+18	3.00E+18	2.92E+18	3.50E+18
Ru-106	1.0E+18	8.71E+17	8.31E+17	1.15E+18
Sr-89	2.4E+18	2.21E+18	2.23E+18	2.44E+18
Sr-90	2.4E+17	1.91E+17	1.73E+17	Not calculated
Te-129m	1.1E+17	7.06E+16	5.88E+16	1.14E+17
Te-132	3.3E+18	3.36E+18	3.63E+18	3.67E+18
U-235	1.1E+11	7.16E+11	1.49E+11	Not calculated
U-238	1.1E+12	1.11E+12	1.11E+12	Not calculated
Zr-95	4.0E+18	3.40E+18	3.47E+18	4.12E+18

* PNNL in Ref. [83] indicated that the results were for Unit 3. However, they are presented here as for Unit 2 because the corresponding input data are a better match for the Unit 2 core.

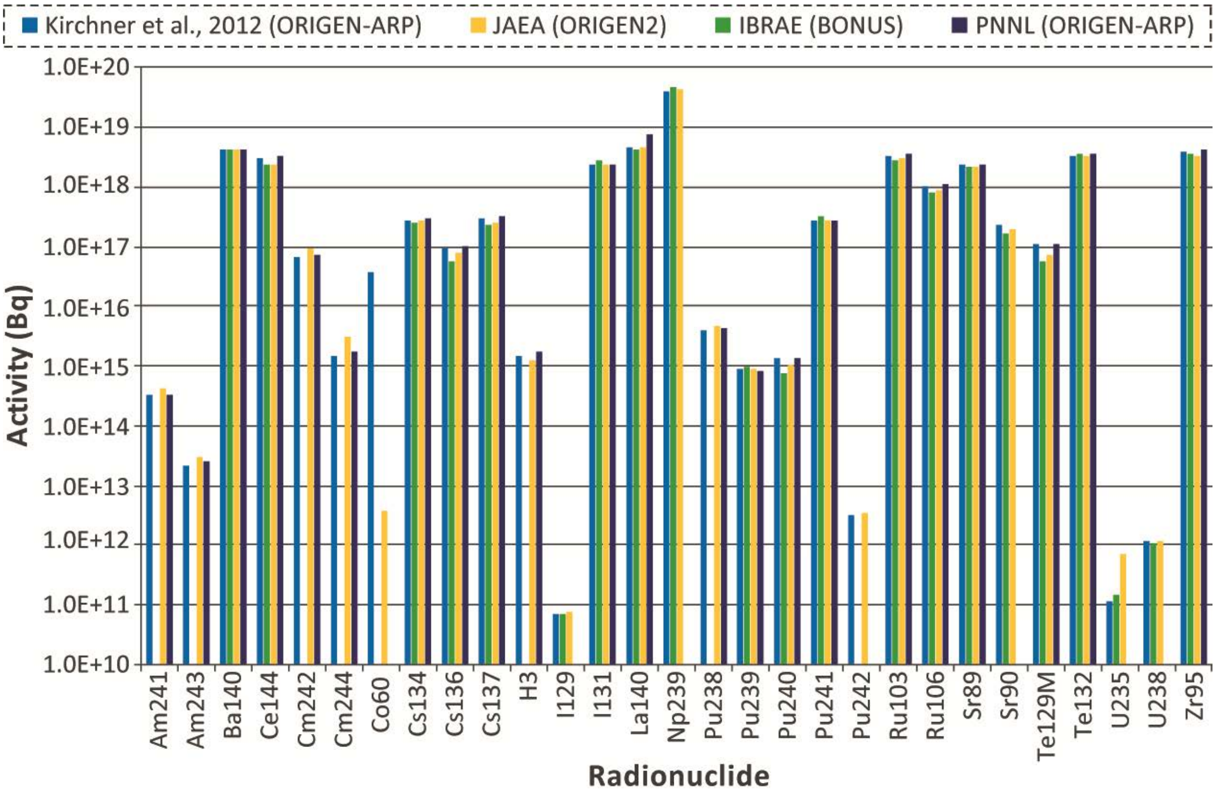

FIG. 1.4–1. Comparison of calculated activity of major radionuclides for the Unit 2 core [82-84, 87].

Tables 1.4–4 and 1.4–5 present the comparison of calculated inventories for Units 2 and 3 at two points in time: the time of reactor shutdown and the approximate time of core damage. It should be noted that, based on the current understanding of the accident progression, core degradation and major atmospheric releases occurred some 4–5 hours after Unit 1 tripped, some 70–80 hours after Unit 2 tripped and some 40–50 hours after Unit 3 tripped. At such times after reactor shutdown the shortest lived nuclides would have already decayed, so the tables only list those nuclides that have a half-life of at least 1 hour and which are major contributors to the radiological consequences.

TABLE 1.4–4. RADIONUCLIDE INVENTORY (IN Bq) IN THE UNIT 2 CORE AT DIFFERENT TIMES [82, 83, 87]

Nuclide	At time of scram			72 h after scram	
	JAEA (ORIGEN)	IBRAE RAN (BONUS)	PNNL (ORIGEN-ARP)	JAEA (ORIGEN)	IBRAE RAN (BONUS)
Cs-134	2.76E+17	2.49E+17	2.97E+17	2.76E+17	2.48E+17
Cs-136	8.17E+16	5.83E+16	9.59E+16	6.98E+16	4.97E+16
Cs-137	2.55E+17	2.29E+17	3.36E+17	2.55E+17	2.29E+17
I-131	2.34E+18	2.71E+18	2.16E+18	1.87E+18	2.15E+18
I-133	4.90E+18	4.91E+18	Not calculated	4.58E+17	4.60E+17
Te-132	3.36E+18	3.63E+18	2.69E+18	1.76E+18	1.92E+18
Te-127	1.74E+17	1.90E+17	1.85E+17	1.16E+17	1.34E+17
Te-127m	1.21E+16	2.62E+16	3.37E+16	1.23E+16	2.62E+16
Ba-140	4.35E+18	4.27E+18	3.98E+18	3.70E+18	3.63E+18
Sb-125	1.65E+16	1.52E+16	2.17E+16	1.65E+16	1.52E+16
Nb-95	2.88E+18	2.98E+18	4.14E+18	2.91E+18	3.00E+18
Sr-89	2.21E+18	2.23E+18	2.4E+18	2.12E+18	2.14E+18
Sr-90	1.91E+17	1.73E+17	Not calculated	1.91E+17	1.73E+17
La-140	4.43E+18	4.28E+18	4.28E+18	4.09E+18	3.99E+18
Zr-95	3.40E+18	3.47E+18	4.06E+18	3.30E+18	3.35E+18
Pu-238	4.57E+15	Not calculated	4.24E+15	4.60E+15	Not calculated
Pu-239	8.83E+14	9.57E+14	8.39E+14	8.90E+14	9.57E+14
Pu-240	1.04E+15	7.66E+14	1.37E+15	1.04E+15	7.66E+14
Pu-241	2.81E+17	3.28E+17	2.74E+17	2.81E+17	3.28E+17
Ag-110m	6.41E+15	Not calculated	3.89E+15	6.34E+15	Not calculated
Kr-85	3.11E+16	3.11E+16	3.42E+16	3.11E+16	3.10E+16
Xe-131m	2.57E+16	2.94E+16	Not calculated	2.53E+16	2.90E+16
Xe-133	4.67E+18	5.06E+18	4.54E+18	3.74E+18	4.02E+18
Xe-133m	1.37E+18	1.50E+17	Not calculated	8.11E+16	5.79E+16
Rb-86	4.50E+15	Not calculated	Not calculated	4.02E+15	Not calculated
Te-125m	5.38E+15	3.11E+15	4.72E+15	5.40E+15	3.12E+15
Tc-99m	3.88E+18	3.91E+18	3.27E+18	1.99E+18	2.02E+18
Mo-99	4.43E+18	4.46E+18	3.4E+18	2.08E+18	2.09E+18
Nb-95m	3.03E+16	2.06E+16	4.7E+16	3.02E+16	2.05E+16
Sb-124	7.91E+14	Not calculated	Not calculated	7.65E+14	Not calculated
Sn-123	1.33E+15	2.06E+15	3.11E+15	1.31E+15	2.03E+15
Sn-125	1.03E+16	2.18E+16	Not calculated	8.28E+15	1.75E+16
Ag-111	1.07E+17	1.02E+17	Not calculated	8.11E+16	7.71E+16
I-132	3.43E+18	3.70E+18	2.76E+18	1.81E+18	1.98E+18
Sm-151	8.87E+14	1.00E+15	1.02E+15	8.99E+14	1.01E+15
Np-239	4.32E+19	4.58E+19	Not calculated	1.80E+19	1.90E+19
Cm-244	3.21E+15	Not calculated	1.69E+15	3.21E+15	Not calculated
U-237	1.32E+18	Not calculated	1.35E+18	9.73E+17	Not calculated
Eu-156	3.21E+17	9.87E+16	3.38E+17	2.81E+17	8.70E+16
Y-90	1.95E+17	1.72E+17	2.75E+17	1.93E+17	1.73E+17
Pm-147	4.19E+17	3.89E+17	6.2E+17	4.21E+17	3.92E+17
Cm-242	8.94E+16	Not calculated	7.18E+16	8.89E+16	Not calculated
Ru-106	8.71E+17	8.31E+17	1.15E+18	8.66E+17	8.26E+17
Ru-103	3.00E+18	2.92E+18	3.41E+18	2.84E+18	2.77E+18
Ce-144	2.31E+18	2.37E+18	3.36E+18	2.30E+18	2.35E+18

TABLE 1.4–5. RADIONUCLIDE INVENTORY (IN Bq) OF UNIT 3 CORE AT DIFERENT TIMES [82, 87]

Nuclide	At time of scram		72 h after scram	42 h after scram
	JAEA (ORIGEN)	IBRAE RAN (BONUS)	JAEA (ORIGEN)	IBRAE RAN (BONUS)
Cs-134	2.52E+17	2.34E+17	2.51E+17	2.34E+17
Cs-136	8.18E+16	5.62E+16	6.99E+16	5.12E+16
Cs-137	2.41E+17	2.21E+17	2.41E+17	2.21E+17
I-131	2.33E+18	2.72E+18	1.86E+18	2.39E+18
I-133	4.90E+18	4.91E+18	4.57E+17	1.25E+18
Te-132	3.37E+18	3.65E+18	1.76E+18	2.52E+18
Te-127	1.78E+17	1.95E+17	1.20E+17	1.64E+17
Te-127m	1.33E+16	2.74E+16	1.34E+16	2.74E+16
Ba-140	4.35E+18	4.27E+18	3.69E+18	3.88E+18
Sb-125	1.57E+16	1.47E+16	1.57E+16	1.47E+16
Nb-95	3.26E+18	3.25E+18	3.28E+18	3.26E+18
Sr-89	2.35E+18	2.36E+18	2.26E+18	2.30E+18
Sr-90	1.81E+17	1.67E+17	1.81E+17	1.67E+17
La-140	4.42E+18	4.27E+18	4.08E+18	4.15E+18
Zr-95	3.68E+18	3.69E+18	3.56E+18	3.62E+18
Pu-238	5.53E+15	Not calculated	5.56E+15	Not calculated
Pu-239	1.04E+15	1.10E+15	1.05E+15	1.10E+15
Pu-240	1.36E+15	1.11E+15	1.36E+15	1.11E+15
Pu-241	3.15E+17	4.10E+17	3.15E+17	4.10E+17
Ag-110m	5.99E+15	Not calculated	5.94E+15	Not calculated
Kr-85	2.95E+16	2.99E+16	2.95E+16	2.99E+16
Xe-131m	2.60E+16	2.96E+16	2.55E+16	2.95E+16
Xe-133m	1.40E+17	1.50E+16	8.23E+16	8.61E+16
Xe-133	4.67E+18	5.06E+18	3.74E+18	4.59E+18
Rb-86	4.35E+15	Not calculated	3.89E+15	Not calculated
Te-125m	5.00E+15	2.95E+15	5.01E+15	2.96E+15
Tc-99m	3.86E+18	3.91E+18	1.99E+18	2.76E+18
Mo-99	4.42E+18	4.45E+18	2.08E+18	2.87E+18
Nb-95m	3.29E+16	2.20E+16	3.28E+16	2.20E+16
Sb-124	7.99E+14	Not calculated	7.72E+14	Not calculated
Sn-123	1.39E+15	2.14E+15	1.37E+15	2.12E+15
Sn-125	1.06E+16	2.24E+16	8.53E+15	1.97E+16
Ag-111	1.12E+17	1.07E+17	8.50E+16	9.09E+16
I-132	3.43E+18	3.72E+18	1.81E+18	2.59E+18
Sm-151	9.08E+14	1.03E+15	9.21E+14	1.04E+15
Np-239	4.30E+19	4.44E+19	1.79E+19	2.66E+19
Cm-244	2.71E+15	Not calculated	2.71E+15	Not calculated
U-237	1.28E+18	Not calculated	9.38E+17	Not calculated
Eu-156	3.12E+17	1.02E+17	2.73E+17	9.54E+16
Y-90	1.85E+17	1.66E+17	1.83E+17	1.66E+17
Pm-147	4.07E+17	3.80E+17	4.10E+17	3.82E+17
Cm-242	1.04E+17	Not calculated	1.03E+17	Not calculated
Ru-106	8.48E+17	8.16E+17	8.43E+17	8.14E+17
Ru-103	3.25E+18	3.15E+18	3.08E+18	3.06E+18
Ce-144	2.27E+18	2.29E+18	2.26E+18	2.28E+18

1.4.2. Radionuclide release mechanisms

1.4.2.1. Release from the cores to the RPVs

Fukushima Daiichi NPP Units 1, 2 and 3 experienced core meltdowns and radionuclides were released from the cores to the RPVs. With increasing fuel burnup, a certain fraction of the fission products migrate out of the fuel material into the gas space between the fuel pellets and the cladding tubes [88, 89]. Roughly 5–15% of the core inventory of noble gases, iodine and caesium are located in these gas gaps. In an accident when the core overheats, the fuel cladding fails and the contents of this gap are released to the RPV.

As the RPV pressurization is controlled by SRV cycling, from the outset of core degradation some radionuclides (mainly the noble gases) will be carried by steam to the SC pool of the PCV.

As the core degradation proceeds, leading eventually to melting of the core material, the fission products initially trapped within the nuclear fuel become volatile and released from the core material. The time and amount of release of the different fission product elements depends on their respective volatilization temperatures, as follows:

- Highly volatility elements like the noble gases, i.e. xenon (Xe), krypton (Kr), caesium (Cs), iodine (I), or tellurium (Te) and relevant chemical compounds of these elements, are released completely from the core in the early phase of core degeneration, when the core is still inside the RPV.
- Medium volatility elements like strontium (Sr) and barium (Ba) are released from the core during the in-vessel phase as well as during the ex-vessel phase. These medium volatile fission products dominate the release during the accident phase after RPV failure.
- Low volatility elements like zirconium (Zr), niobium (Nb), and the actinides (U, Pu, Np, Am) and their oxides, have a boiling point well above the temperatures reached in a core melt, and so only trace amounts of them are released. When the RPV fails and the core material falls into the reactor pit, the core melt no longer contains significant amounts of volatile fission products. Thus, the release of highly volatile fission products is expected to be low in this late phase of a core melt accident.

1.4.2.2. Transport to the PCV

After the fission products are released from the overheated reactor core, the noble gases, as well as the fission product vapours are transported by flows of gas or steam into cooler regions of the primary containment vessel (PCV). The fission product vapours start to condense to form small airborne particles (aerosols). These aerosols and the noble gases are then further transported by flows of gas or steam until they are either retained (e.g. by condensation, plate-out, scrubbing, etc.) inside the PCV or released into the environment through PCV leaks. The presence of very hot, high pressure steam in the RPV can create a number of possible leak paths, such as through the flanges of the SRVs or the seals of the recirculation pumps, for the other radionuclides to escape into the dry well and the SC of the PCV. While a fraction of the fission products released from the reactor core will be trapped in the water of the pressure suppression pool the remainder may be dispersed within the PCV and eventually released from the PCV to the outside atmosphere by either a controlled or an uncontrolled route. Finally, when high temperature core melt causes the RPV to fail, the molten debris is released directly to the RPV in the ex-vessel configuration.

Units 1–3 at Fukushima Daiichi NPP experienced radionuclide release both by steam transport from the RPV and by ex-vessel phenomena [7].

1.4.2.3. Release to the environment from the PCV

Those aerosols not trapped within liquid or on surfaces of structures, may be released from the PCV into the environment. Three different release paths can be distinguished at the Fukushima Daiichi nuclear power plant:

- Design leakage. In the Fukushima Daiichi containment design, the maximum design leakage was 0.5 vol. % per day at the design pressure. These leakages cause contamination of the reactor building (RB) relatively soon after the occurrence of core damage. This limits personnel access to the RB and thus hinders recovery actions. The RB is essentially a conventional structure with a design in-leakage of about 100 vol. % per day at a 5×10^{-5} MPa (0.5 mbar) sub-atmospheric pressure (the normal sub-pressure during power operation). Due to this low leakage rate, the aerosols escaping the PCV could remain for a long time inside the RB and a large fraction could settle out within that building, providing that the sub-atmospheric pressure could be maintained. To further reduce aerosol release from the RB, a filtered ventilation system keeps the building below the atmospheric pressure. Systems for maintaining sub-atmospheric pressure and filtered ventilation were inoperable due to loss of AC power.
- Containment venting. If there is an uncontrollable pressure buildup in the PCV, it can fail due to overpressurization. Therefore, the Fukushima Daiichi NPP units were equipped with a dedicated venting system to depressurize the PCV in a controlled manner. In Japan, the underlying philosophy was to vent as late as possible (or not vent until it is inevitable) in order to delay or prevent direct release of radioactive material to the public and the environment. As explained in Section 1.3, after the accident internal pressure rose rapidly in the PCVs of Units 1–3, and so the operators attempted to vent on several occasions, with mixed success. During venting of the PCV radioactive products were released unfiltered to the environment through the vent stacks. When venting took place from the SC, it is estimated that much of the vent gases were scrubbed within the water pool, resulting in a relatively lower release compared with the case where venting took place directly from the DW.
- Containment failure. The PCV can fail due to pressure buildup, by experiencing temperatures in excess of design values, or by transient phenomena such as hydrogen explosions. In the design of the Fukushima Daiichi nuclear power plant, PCV nitrogen inerting was used to prevent hydrogen combustion. The containment was designed to withstand an internal pressure and periodically tested at 115% of the design pressure. In addition to overpressure failure, the PCV can also fail if temperatures above design lead to failure of PCV penetrations, especially by thermal decomposition of the organic sealing materials. Venting or failure of the PCVs in three Fukushima Daiichi NPP units resulted in gas and steam escaping from the PCV and entering the RB. This gas/steam flow also transported a large volume of hydrogen into the building, resulting in hydrogen accumulation and several explosions that caused severe damage to the structure. Furthermore, this leakage released significant amounts of radioactive airborne aerosols into the building, and eventually into the environment.

1.4.2.4. Postulated atmospheric release pathways during the accident

Source term analyses indicate that the major releases that contributed most to the radiological consequences on Japanese territory occurred on 15 March. They were probably related to the release of activity from Unit 2 due to core melting and subsequent loss of PCV integrity early in the morning, or to PCV venting at Unit 3 that can be deduced from TEPCO information about operator actions and pressure drop readings in the DW after 16:00. Other large peaks of activity release are thought to have occurred in the afternoon on 12 March (explosion at Unit 1), at noon on 14 March (explosion at Unit 3), and late at night on the same day (probably due to venting of Unit 3).

However, Fig. 1.4–2 demonstrates that there is not an obvious correlation between the events thought to have produced the significant releases to the atmosphere and the dose rate measurements made by TEPCO during the accident at the measurement points (MP) shown in Fig. 1.4–3. Some dose rate peaks do not coincide with any event and some events seem to have had no impact on the dose rates.

Unit	Symbol in Fig.	Time of occurrence	Event
1	1a	12.03.2011 14:00	Venting No. 1
	1b	12.03.2011 15:36	Explosion
2	2a	14.03.2011 21:00	Venting No.1 or PCV leakage
	2b/4a	15.03.2011 06:15	Loud sound in torus room
	2c	15.03.2011 11:25	DW pressure drop
3	3a	13.03.2011 09:20	Venting No. 1
	3b	13.03.2011 12:30	Venting No. 2
	3c	13.03.2011 20:30	Venting No. 3
	3d	14.03.2011 05:20	Venting No. 4
	3e	14.03.2011 11:01	Explosion
	3f	14.03.2011 16:00	Venting No. 5
	3g	15.03.2011 16:05	Venting No. 6
	3h	16.03.2011 02:00	Venting No. 7
	3i	17.03.2011 21:30	Venting No. 8
	3j	18.03.2011 05:30	Venting No. 9
	3k	20.03.2011 11:25	Venting No.10
4	4a	15.03.2011 06:15	Explosion

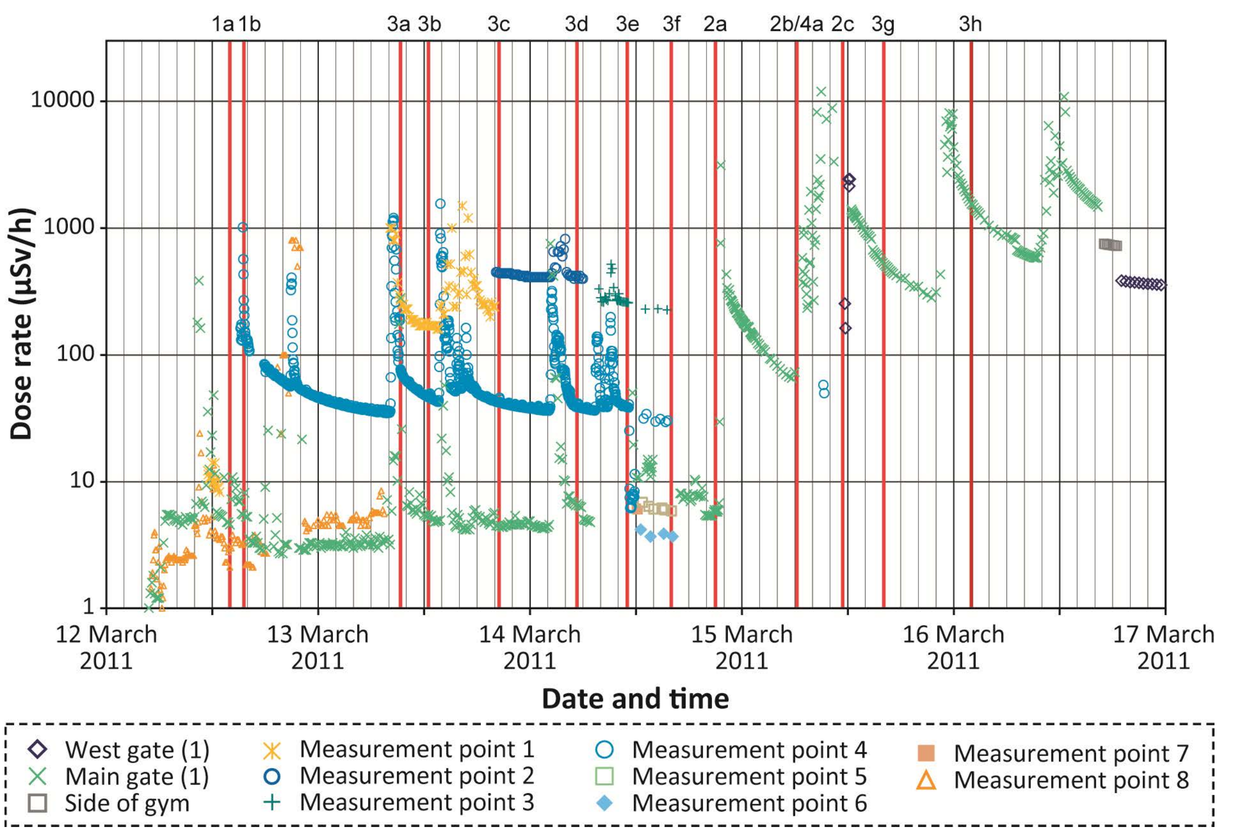

FIG. 1.4–2(a). Graph of dose rates measured at the Fukushima Daiichi site between 11 and 17 March 2011 (the vertical red lines indicate the major events registered during the accident).

Unit	Symbol at Fig.	Time of occurrence	Event
3	3i	17.03.2011 21:30	Venting No. 8
	3j	18.03.2011 05:30	Venting No. 9
	3k	20.03.2011 11:25	Venting No. 10

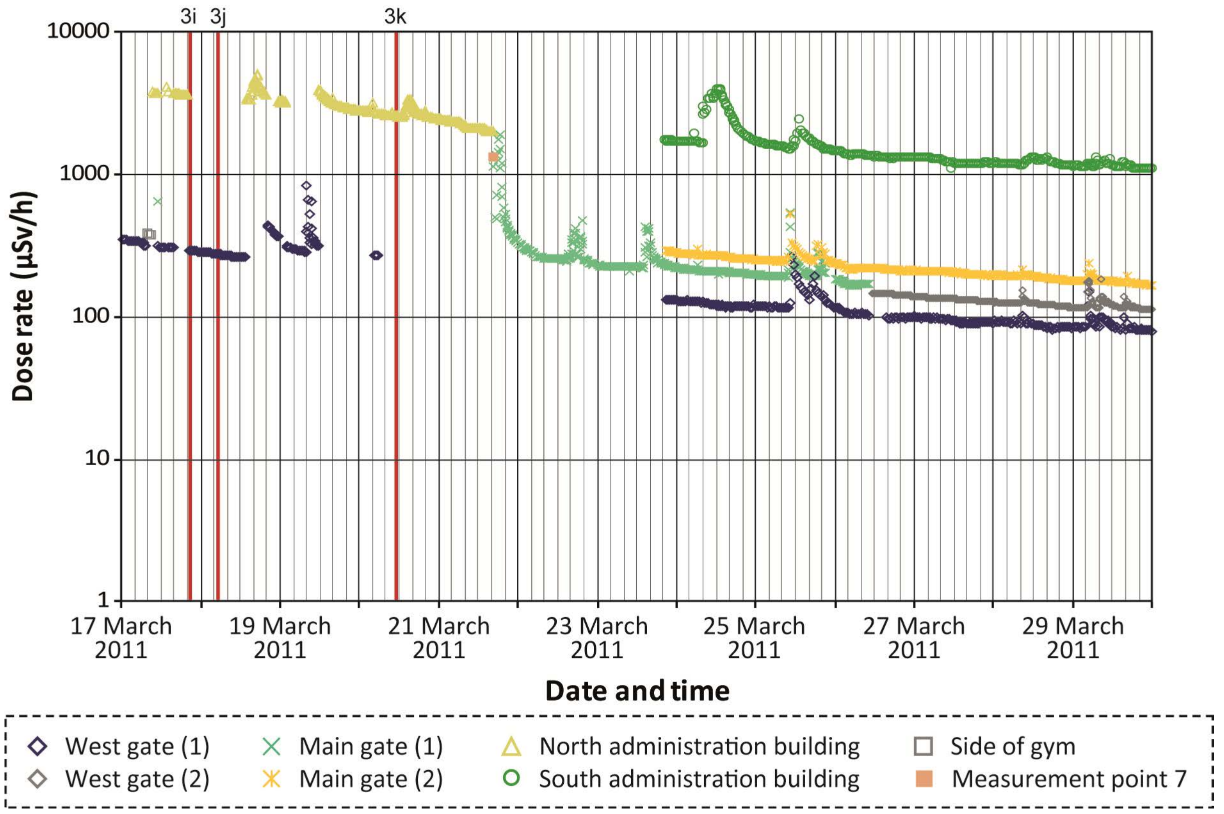

FIG.1.4–2(b). Graph of dose rates measured at the Fukushima Daiichi site between 17 and 30 March 2011 (the vertical red lines indicate the major events registered during the accident).

FIG. 1.4–3. Location of monitoring points at the Fukushima Daiichi site.

The first increase in dose rate at the site was measured near the main gate and the measuring point MP8 at 04:00–05:00 on 12 March. At around 10:00, the dose rate increased sharply at the same location. This can be correlated to Unit 1 SC venting, as multiple attempts to open the valves in the ventilation line were reported by TEPCO. However, the success of these attempts is unknown. The other postulated path besides venting could be a PCV leakage.

At 14:00, the PCV was vented at Unit 1 but it did not have a large impact on the dose rate readings available at this time. However, the first value measured at MP4 was about 0.16 mSv/h, well above the background level observed at the main gate and MP8. An abrupt peak of dose rate (~1 mSv/h) was measured near MP4 few minutes before the explosion at 15:36 at Unit 1, and explosion itself did not reveal any dose rate increase among readings available. The reason of this is currently unclear. Later, between 20:00 and 21:00, another release occurred and the dose rate increased to 0.4–0.6 mSv/h at MP4 and MP8. The cause of this release is not clear from the data.

On the next day, 13 March, the PCV at Unit 3 was vented at 09:20, giving a release confirmed by measurements made at the main gate measuring points MP4 and MP1 and by observation at the top of the vent stack by the live cameras. An identical peak was produced by another Unit 3 venting that was performed at 12:30, which was also accompanied by smoke coming from the vent stack. The success of the third Unit 3 venting at 20:30 is still questionable because it did not produce any dose rate change. Also, no events were observed at 02:00 on 14 March, when the dose rate increased at MP2, MP4 and the main gate.

The fourth venting operation at Unit 3 on 14 March (05:20) does not strictly coincide with the time of the peak (07:30–09:00) either. The explosion at Unit 3 (11:01) seems to have had a rather small effect on the measured dose rates, which only rose to 0.05 mSv/h at the main gate. A much larger reading (3 mSv/h) was registered at the main gate after the venting of Unit 2 PCV at 21:00 (success of venting is not confirmed). That event was followed by a drop in pressure in the SC, and an increase in pressure in the DW. The inconsistency in pressure changes in two connected parts of the PCV has not yet been explained, and it raises doubts about the efficiency of the venting as a postulated path of Unit 2 PCV leakage.

Neutrons were detected between 05:30 and 10:50 on 13 March by a mobile radiation monitor near the main gate which is around 1 km away from the RBs of Units 1–3. The measured neutron dose rates were between 0.01 μSv/h[148] and 0.02 μSv/h. Neutrons were also detected between 21:00 on 14 March and 01:40 on 15 March near the main gate. The measured neutron dose rates were again 0.01–0.02 μSv/h. These could indicate the core damage and inventory release from Unit 3 and Unit 2, respectively, following the loss of cooling function.

Early in the morning on 15 March, a loud sound came from the Unit 2 torus room, followed by a pressure drop first in the Unit 2 SC and a few hours later in the Unit 2 DW, which was confirmed by operators. About at the same time an explosion occurred at Unit 4. As a result, the dose rate reached a maximum value at the main gate of nearly 12 mSv/h. A large release to the Unit 2 reactor building compartments took place, followed by leakage to the atmosphere. This was confirmed by live camera images of an intensive steam flow through the orifice left in the Unit 2 reactor building wall by a previously broken blow-out panel.

On the evening of 15 March, the dose rate rose again to about 10 mSv/h at the boundary of the site, although there were no major events at around that time (21:00–22:00). A Unit 3 venting had taken place much earlier, at 16:05. The same inconsistency is seen at 09:00–10:00 on 16 March when the

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[148] The lowest detectable limit of the neutron monitor.

level of 10 mSv/h was reached for a third time. There were no venting operations near that time, the closest being at 01:55 which, in any event, was not considered to have been successful.

In the following days, there were no more large releases, and dose rates did not exceed 1 mSv/h, with the average value being 0.35 mSv/h. In the north administrative building a background dose rate of 3 mSv/h was recorded, due to the deposition of radioactive material that was released earlier on 15 March. Venting operations were attempted several times at Unit 3 [90], but there is no clear evidence that they were successful or led to radioactive releases.

On 21 March, at 16:00–18:00, another fluctuation in the dose rate (~2 mSv/h) was registered near the main gate. This may have been related to the emission of smoke for a long time from the reactor buildings at Unit 3 (at 15:55) and Unit 2 (at 18:22).

After 21 March, the measurements showed a steady decline in the dose rates at the site, with some minor peaks. On 24 and 25 March, at around 13:00, the dose rate at the south side of administrative building increased twice to 4 mSv/h and 2.5 mSv/h, respectively. The second increase was also registered at the west and the main gates.

Further discussion of radiological release and their consequences is provided in Technical Volume 4, Section 4.1.

1.4.3. Amount of radionuclides released

The amount of radionuclides released, also called the ‘source term’, comprises radionuclides released from the cores and confining structures into the environment during and after the accident at the Fukushima Daiichi NPP. In this section, the radionuclide release is given either as a percentage of the core inventory, or in becquerels (Bq) or peta becquerels (PBq) (= 10^{15} Bq).

While the radioactive noble gases are diluted in the atmosphere, the aerosols formed and dispersed from the nuclear accident sooner or later deposit on surfaces. The isotopic composition of the deposit is relevant in two respects. On the one hand, it can give valuable information about core degradation and the mechanisms of fission product generation and release. On the other hand, it plays a vital part in the assessment of the radiological consequences for the environment as different radioactive isotopes and elements contribute differently to these consequences.

Gamma spectroscopic measurements of the deposition were analysed in various countries [91, 92] and radioactive isotopes of the following elements were detected: iodine, caesium, tellurium, lanthanum, antimony, technetium, barium and silver (I, Cs, Te, La, Sb, Tc, Ba and Ag).

1.4.3.1. High volatility elements

Isotopes of the elements iodine and caesium dominated the activity deposited on the ground by at least one order of magnitude, followed by the tellurium isotope, ^{132}Te [92]. The dominance of these elements originates from their low vapour pressure, which results in their virtually complete release from the nuclear fuel during a core meltdown.

1.4.3.2. Medium volatility elements

The deposited activity of the medium volatile barium (as isotope ^{140}Ba) lies about two to three orders of magnitude below Cs and/or I activity. Assuming a full release of Cs from the reactor core, this indicates a Ba release from the nuclear fuel of below 1%. Other medium volatile elements, such as antimony (Sb) and niobium (Nb), show similar release fractions [92]. The release of medium volatile fission products is therefore much lower than observed after the Chernobyl accident [93].

Of special scientific interest was the unexpectedly low release of ^{95}Nb, as it had been assumed previously that the chemical compound Cs_2XxO_4 (with Xx = early transition elements) contributed significantly to the fission product release from the nuclear core of a light water reactor. However, if this assumption were correct, a release of the early transition elements in the order of tens of per cent would have been expected, i.e. two to three orders of magnitude higher than observed.

The strontium isotopes ^{89}Sr and ^{90}Sr decay via beta decay, practically without emitting gamma radiation, making them invisible to gamma spectroscopy. Therefore, the strontium contamination was measured by radiochemical analysis which showed that the release of strontium was three to four orders of magnitude less than the release of caesium [94].

1.4.3.3. Refractory elements

In the gamma spectra of the deposited material, only the low volatile lanthanum isotope ^{140}La was detected. However, the observed ^{140}La is the daughter nuclide from the decay of ^{140}Ba, and not a sign of significant La release during the core meltdown. Further, there is the total absence of the ^{95}Zr line at 757 keV, showing that no significant amount of radioactive Zr was released [92].

1.4.3.4. Iodine and caesium

There were releases of long lived medium or low volatility fission products from the Fukushima Daiichi NPP reactors, but the atmospheric release was dominated by volatile isotopes of iodine and caesium. The chemical composition of the fission product release had the direct consequence on the land contamination. The contamination was dominated by the deposition of ^{131}I, ^{134}Cs and ^{137}Cs during the first days and weeks of the accident, and by ^{134}Cs and ^{137}Cs afterwards, when most of the iodine had decayed (with a half-life of 8 days). As caesium forms water soluble compounds, the land contamination decreases faster than would be expected by its radioactive decay alone. However, it persists in the environment for several years [91, 94, 95]. More information is provided in Technical Volume 4, Section 4.1.

1.4.3.5. Plutonium

Isotopes of plutonium can be major contributors to total radiological risk if they are inhaled or ingested. Most of the low volatility actinides are alpha emitters, which cannot be detected by gamma spectroscopy. Therefore, between 25 and 28 March 2011, several samples of soil, plants, litter and water were collected at different locations around the site to examine for contamination with plutonium. It should be noted that the isotopes of plutonium are still present in the environment due to nuclear weapon tests in the 1950s and 1960s, but their concentration is very low, about 0.15 Bq/kg in Japan [75] and ~1 Bq/kg in the USA [96]. Only a few samples collected after the Fukushima Daiichi accident showed the isotopic signature of reactor plutonium, in excess of the concentration ratios associated with historical nuclear weapon tests [97-99]. The concentration of plutonium isotopes found at the Fukushima Daiichi site (^{239}Pu and ^{240}Pu ~0.1 Bq/kg together [98, 99]) corresponded to the background level, indicating that the releases of plutonium from the Fukushima Daiichi units during the accident were limited. The isotopic ratios and concentrations of plutonium varied between neighbouring sampling areas (which indicates that the plutonium was in particulate form), resulting in a non-uniform deposition. There is possibility of locations with larger deposition, however, the data indicate that plutonium release due to the core melts in the Fukushima Daiichi NPP did not notably increase the environmental distribution of plutonium.

1.4.4. Atmospheric release

Multiple estimations of the atmospheric source term were made in 2011–2013 by different organizations around the world, as presented in Table 1.4–6. Most of them predict the total activity released between 11 and 31 March 2011 in terms of ^{131}I, ^{137}Cs and ^{133}Xe. Figures 1.4–4 and 1.4–5 illustrate some of those estimated release rates of ^{137}Cs and ^{131}I extracted from the studies listed in Table 1.4–4. Some of the studies provide uncertainty ranges for their estimations, which are shown in these figures. Both figures include comparisons to the much higher total releases from the Chernobyl accident. A statistical analysis of the numerical studies for Fukushima Daiichi was performed. The major results of this analysis are the mean values and confidence limits for the major isotopes. Further discussion and results are given in Technical Volume 4, Section 4.1.

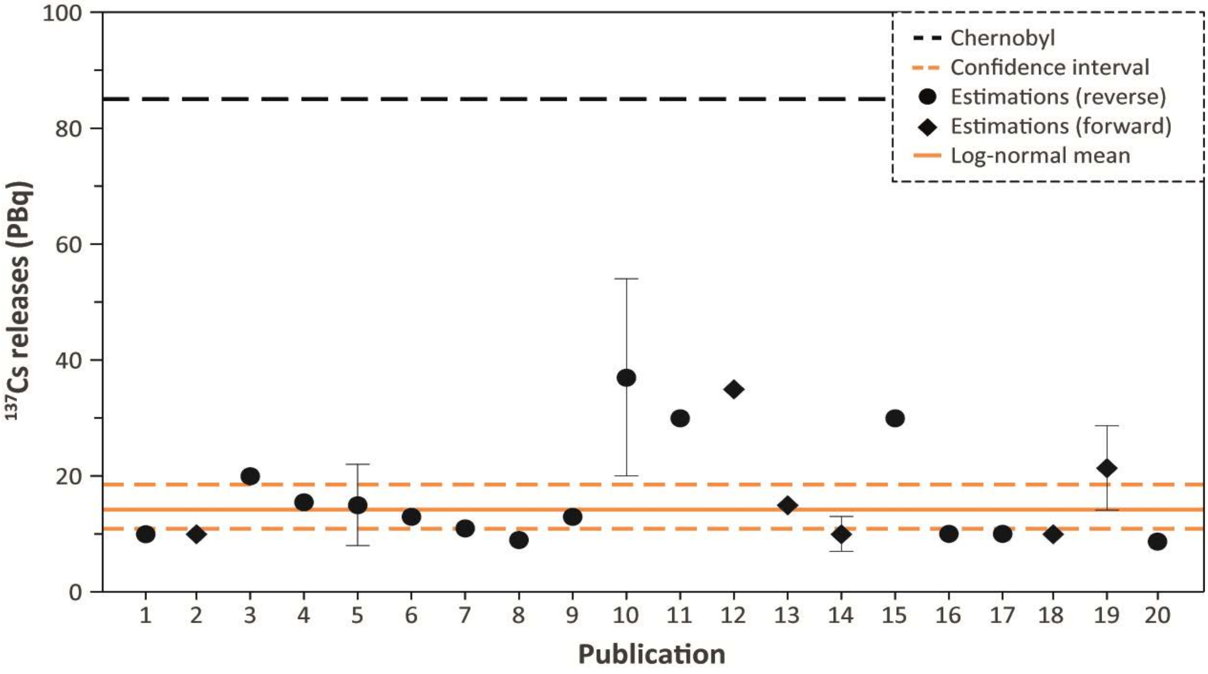


FIG. 1.4–4. Estimated atmospheric releases of ^{137}Cs (see Table 1.4–6).

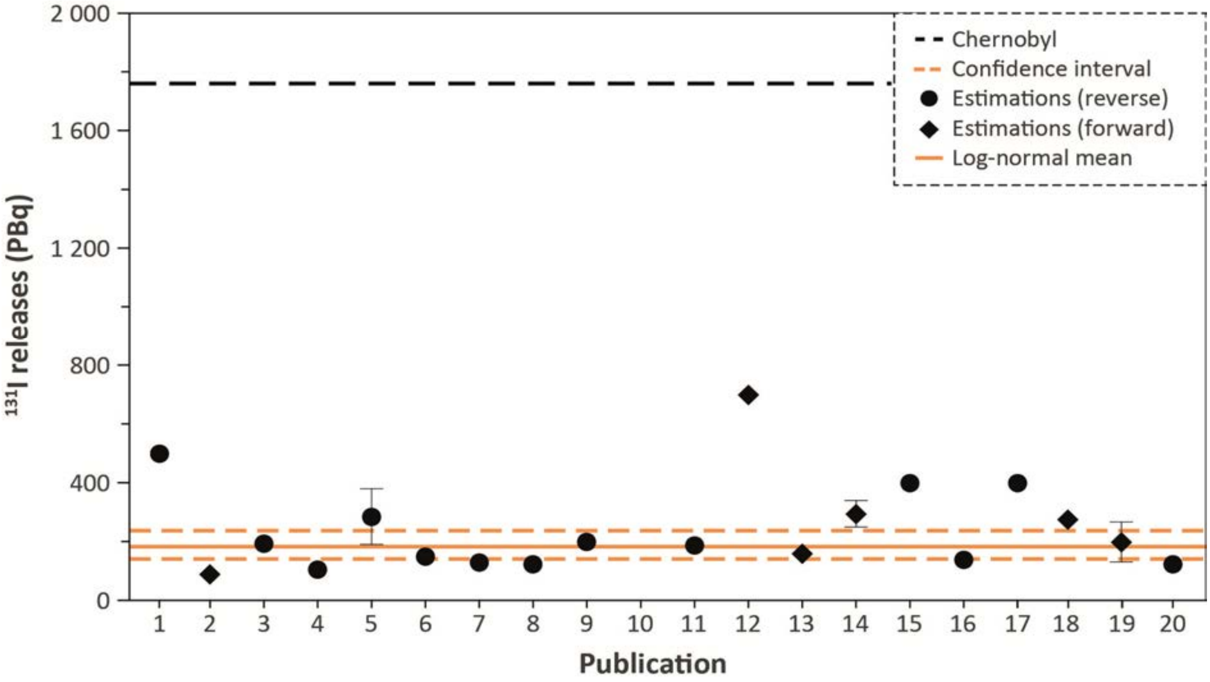


FIG. 1.4–5. Estimated atmospheric releases of ^{131}I (see Table 1.4–6).

TABLE 1.4–6. SUMMARY OF DIFFERENT ESTIMATES FOR THE ATMOSPHERIC SOURCE TERM IN 2011 (^{137}CS, ^{131}I, ^{133}XE), IN PBq

	Author publication	^{137}Cs	^{131}I	^{133}Xe	Release duration	Method used	Models or codes used
1	TEPCO, 2012 [6, 100]	10	500	0.5×10^3	12.03–31.03	Reverse modelling	Weather data (measurements on site and AMEDAS)/ DIANA
2	IRSN-1, 2011 (Emergency Response) [101]	10	90	2×10^3	11.03–22.03	Estimate of reactor state, analysis of information	Available operational data about the accident progression and reactor state
3	IRSN-2, 2012 [101-103]	20–21	190–197	5.9×10^3	11.03–27.03	Forward + reverse modelling	ECMWF + ARPEGE + local observations/ C3X (ldX+pX)/ ASTRID
4	IRSN-3, 2013 [104]	15.5	105.9	12×10^3	11.03–27.03	Reverse modelling	ECMWF/ C3X (ldX)
5	CEREA, 2012 [105, 106]	12–19, uncertainty 15–20%	190–380, uncertainty 5–10%	—	11.03–27.03	Reverse modelling	ECMWF, WRF/ Polair3D (polyphemus platform)
6	JAEA-1, 2011 (Chino et al.) [107]	13	150	—	12.03–05.04	Reverse modelling	SPEEDI (PHYSIC/ PRWDA21); WSPEEDI-II (MM5/GEARN)
7	JAEA-2/NSC, 2012 (Katata et al.) [2, 108, 109]	11	130	—	12.03–05.04	Reverse modelling, refinement of JAEA-1 source term	WSPEEDI-II (MM5/GEARN) + JMA data (WRF)
8	JAEA-3, 2012 (Terrada et al.) [110]	8.8	124	—	12.03–30.04	Reverse modelling, refinement of JAEA-2 source term	WSPEEDI-II (MM5/GEARN) + JMA data (WRF)
9	JAEA-4, 2013 (Kobayashi et al.) [111]	13	200	—	12.03–30.04	Reverse modelling	Same as JAEA-3 + SEA-GEARN
10	NILU, 2012 [112]	37, uncertainty 20–53	—	15×10^3, uncertainty $(12–18) \times \cdot 10^3$	11.03–05.04	Reverse modelling	ECMWF + NCEP GFS/ FLEXPART
11	IBRAE, 2012 [87, 113, 114]	30	188	0.4×10^3	15.03	Forward + reverse modelling (iterations)	SOCRAT/ ARW-WRF/ NOSTRADAMUS
12	SEC NRS, 2011 [115]	35	700	—	11.03–17.03	Estimate of fuel inventory, reactor state, analysis of information	SCALE6 (ORIGEN-ARP)/ WASH-1400/ NUREG-1150
13	NISA, 2011 [2, 116]	15	160	11×10^3	11.03–15.03	Forward modelling	MELCOR

TABLE 1.4–6. SUMMARY OF DIFFERENT ESTIMATES FOR THE ATMOSPHERIC SOURCE TERM IN 2011 (^{137}CS, ^{131}I, ^{133}XE), IN PBq (cont.)

	Author publication	^{137}Cs	^{131}I	^{133}Xe	Release duration	Method used	Models or codes used
14	JNES, 2012 [117]	7.3–13	250–340	9×10^3	11.03–17.03	Forward modelling	MELCOR
15	ZAMG, 2011 [118]	30	400	—	11.03–15.03	Reverse modelling	ECMWF/ FLEXPART
16	NIES, 2011 [119]	9.9 (100%–particulate, 1 μm)	142 (80%–gaseous form)	—	11.03–30.03	Reverse modelling	Models-3 CMAQ/ WRF + JMA data
17	CEA, 2012 [120]	10	400	6.0×10^3	12.03–01.05	Reverse modelling	MM5, WRF, NCEP GFS/ FLEXPART
18	SNL, 2013 [115]	10	276	7.9×10^3	11.03–15.03	Forward modelling	Fractional releases, ORIGEN core inventories
19	ENEA, 2014 [121]	21.4	199	5.56×10^3	11.03–16.03	Forward modelling	RASCAL 4.2
20	UNSCEAR, 2014 [122]	8.8	124 (50%–gaseous form)	7.3×10^3	Same as in JAEA-3	Reverse modelling	Same as in JAEA-3
	Chernobyl source term, IAEA, 2006 [93]	85	1760	6.5×10^3			

Comparing the various estimations of the atmospheric source term, shown in Table 1.4–6, illustrates between one and seven orders of magnitude for particularly relevant isotopes. Normally, it is impossible to draw conclusions from data with such a large scatter. However, the application of Bayesian statistics may help in some cases and can be applied to the analysis of release data from the Fukushima Daiichi accident. Assuming log-normal distribution of the data measured (or estimated) by various groups, the Bayesian analysis in which the quoted uncertainties are treated as the minimal ones, results in the values presented in the Table 1.4–7.

TABLE 1.4–7. UNCERTAINTIES IN ATMOSPHERIC SOURCE TERM ESTIMATES FOR KEY ISOTOPES

Isotope	Accuracy (%)	Normal		Log-normal	
		Mean (PBq)	Standard deviation (PBq)	Median (PBq)	Range (PBq)
^{131}I	25	144	32	183	141–237
	46*	144	36	200	154–259
^{133}Xe	25	469	238	9 425	4 879–18 208
	46	502	359	7 721	4 040–14 757
^{137}Cs	25	12.2	2.2	14.2	10.9–18.5
	46	12.4	2.5	15.7	12.1–20.4

* The largest uncertainty that was estimated by authors of the source term provided in Table 1.4–6.

The following conclusions can be drawn from these results:

- The differences between the estimations obtained within normal and log-normal distributions are not large; the means and medians coincide within the standard deviations.
- The estimated range of medians obtained for log-normal distributions (see last column of Table 1.4–7) includes the values corresponding to the maximum probabilities calculated for normal distribution; therefore, these ranges could be treated as representing our real knowledge of the releases (see also Figs 1.4–4 and 1.4–5).
- The log-normal distribution demonstrates the scatter of results better than the normal distribution, and so is more appropriate for considering possible health effects of the release.
- The data for ^{133}Xe are so dispersed that the normal distribution cannot be applied.

However, even with these uncertainties the different estimates of the releases of ^{131}I and ^{137}Cs are consistent and fall within a relatively narrow range: 90–700 PBq for ^{131}I, 7–50 PBq for ^{137}Cs. If the very first estimates made in March–April 2011 (when very limited information was available) are discarded, the range becomes narrower: 100–400 PBq for ^{131}I and 7–20 PBq for ^{137}Cs. The preliminary estimates of the source term for ^{133}Xe were more uncertain and were between 500 and 15 000 PBq. However, in more recent calculations this uncertainty has also decreased to give a range between 6000–12 000 PBq. For isotopes of elements other than iodine and caesium the range of the estimates is larger, because there were almost no direct measurements of these isotopes around the site.

1.4.4.1. Comparison with the atmospheric release from the Chernobyl accident

The total amount of aerosol based fission product releases from all of the Fukushima Daiichi NPP units was about one order of magnitude smaller than that from the Chernobyl accident [93]. Based even on the most conservative estimates, the releases of iodine and caesium did not exceed 25% and 45% of the Chernobyl release, respectively. The radionuclide release from Fukushima Daiichi NPP contained much less medium volatility isotopes such as ^{90}Sr, ^{103}Ru and ^{140}Ba, and practically no refractory elements like zirconium (^{95}Zr) [92] and plutonium (Pu) [75]. The releases of semi-volatile elements and non-volatile elements are estimated to be ~0.01–0.1% of those resulting from the Chernobyl accident. The release of plutonium isotopes from Fukushima Daiichi was estimated by UNSCEAR to be 10^{-6} GBq [123], which was four orders of magnitude lower than that released at Chernobyl [99]. The isotopic signature of the releases from the Fukushima Daiichi accident is a direct indication that core temperatures during the core degradation phase were lower than those from the Chernobyl accident.

The amount of radioactive noble gases released from the Fukushima Daiichi NPP exceeded the corresponding release from Chernobyl. The release of the noble gas ^{133}Xe is estimated in the later studies to be larger than the corresponding release at Chernobyl by a factor of 1.5–2. The explanation for this is the larger total fuel inventory of ^{133}Xe in the cores of Fukushima Daiichi NPP Units 1–3 compared with the Chernobyl core. However, as the noble gases do not contribute to deposition, their release had only a minor influence on the radiological consequences of the accident.

The smaller total atmospheric release in the Fukushima Daiichi accident compared with Chernobyl stems from the different accident scenarios and mechanisms of radioactive releases. In Chernobyl, the release started with a nuclear criticality accident which triggered an in-core steam explosion, causing an intensive ejection of the overheated core material and extensive burning of graphite and reactor materials over a long period of time. The core degradation could not be limited by the safety systems, and the release was not confined because RMBK reactors did not have a containment structure. The fast power spike or explosion not only overheated and fragmented the fuel, producing aerosols and particles containing all kinds of isotopes (including those that were non-volatile), but it also opened a direct path for radioactive product release to the environment, enhanced by entrainment in the smoke from graphite burning. At the Fukushima Daiichi NPP, there were no explosions within the cores, but progressive heating, oxidation and meltdown of the cores. The energy in the cores was produced over a much longer time, so it did not instantly destroy all fission barriers and safety systems. The radioactive products were thus released from the core much more gradually, and some of the radioactive material was confined by containment structures which partially retained their general function. Also, scrubbing of radioactive products by the water in the suppression pool reduced the atmospheric release at the Fukushima Daiichi NPP. However some medium to non-volatile products were released to the atmosphere during the accident [97, 98]. The lack of measurements of these isotopes around the Fukushima Daiichi NPP site does not allow for a consistent analysis of the corresponding source term. The data available include the ratios of specific isotopes to key radionuclides, e.g. iodine and caesium. Such ratios are consistent for the isotopes of the same element, but may change over distance from the source because the isotopes of different elements may have different properties influencing their deposition.

1.4.5. Groundwater and ocean release

The oceanic release from the Fukushima Daiichi NPP was the largest release of radionuclides from a nuclear accident into an ocean based on the measured radionuclide concentrations. There were several ways by which radioactive material entered the ocean following the Fukushima Daiichi accident:

- Direct release from the flooded trenches and shafts;
- Atmospheric deposition onto the surface of the ocean during March–April 2011;
- Drainage of contaminated groundwater;
- Drainage of contaminated water from rivers;
- Planned release of low level wastewater;
- Runoff of deposited radioactive material following rains, typhoons, tides, etc.

Among these, the largest contributing factors to ocean contamination are thought to be the direct release of radioactive liquid effluents and atmospheric deposition.

During the accident and at a subsequent stage of molten core cool down, water was injected into the RPVs of Units 1–3. Some of it flowed from the RPV into the PCV through the possible openings, such as SRVs, gaps in flanges and/or RPV breaches which occurred during core heat up and melting, and then it drained from the PCV to the bottom compartments of the RB. On its way, the injected water came into contact with melted fuel and leached any soluble material and particulates. The flow rate of injected water was 350–400 m^3 per day.

Multiple estimates of the source term to the ocean were performed in 2011–2013 (Table 1.4–8). There is considerable variation between different analyses. The levels of radionuclides in the ocean were evaluated by sampling water, sediments and biota, together with numerical modelling of the dispersion of radioactive material. Numerical reconstruction of the marine source term was mainly based on measurements of ^{137}Cs and ^{131}I, two isotopes that are representative of dissolved substances. At the time of writing, most of the analyses provided the estimated radioactivity levels of ^{137}Cs, although some also estimated the levels of ^{134}Cs. Only few analyses provide a source term of ^{131}I, because its short half-life makes it difficult to determine from measurements undertaken in May 2011, when extensive measurements began. Activities of other radionuclides detected in sea water are usually referenced to ^{137}Cs or ^{134}Cs activity, with consideration of their decay. The activity ratio of ^{134}Cs to ^{137}Cs was close to 1. The presence of another gamma emitting isotope ^{110m}Ag with ratio ^{134}Cs:^{110m}Ag about 0.8–4.7 was found in zooplankton [124]. Activities of some other isotopes were found to be much lower than ^{137}Cs activity. Thus, for beta-emitting isotopes ^{90}Sr and ^{99}Tc the activity ratios were 0.02–0.24 [125, 126] and about 0.01 [125], respectively. The large uncertainty in the release of ^{90}Sr is explained by the scarcity of measurements in sea water.

As westerly winds were dominant during the initial atmospheric releases, wet and dry deposition of the airborne ^{137}Cs over the Pacific Ocean has to be accounted for in studies of the radionuclide levels in the ocean. As there were no measurements of dose rates above the ocean surface during atmospheric releases in the first weeks of the accident, the estimates of radioactive deposition are uncertain and vary over a wide range, from about 0.18 PBq to 10 PBq (Table 1.4–8). The fraction of the deposition over the ocean to the total level of deposit is also uncertain, with different studies ranging from 40–80% [112, 127].

TABLE 1.4–8. SUMMARY OF DIFFERENT ESTIMATES FOR THE MARINE SOURCE TERM

Study	Source term (PBq)/release duration (in 2011)	
	Direct release	Atmospheric deposition
TEPCO [1, 128]	Near water intake of Unit 2 4.7 (^{131}I+^{134}Cs+^{137}Cs) 0.94 (^{137}Cs) 05:38, 1–6 April	—
	Near water intake of Unit 3 0.02 02:00, 10 May and 19:00, 11 May	—
	Planned low waste release: 1.5 × 10^{-4} 4–10 April	—
IRSN, 2011 [129]	2.3 (^{137}Cs) 1–6 April	10 (^{137}Cs) 12 March–23 March
IRSN (Bailly du Bois et al.), 2012 [101, 125]	22 (uncertainty 10–34, ^{137}Cs) 26 March–8 April 27 (uncertainty 12–41, ^{137}Cs) 26 March–18 July	0.076 (within a radius of 80 km)
JAEA-1, 2011 [130]	0.9496 (^{137}Cs) 1 April	7.5 (^{137}Cs)
Buesseler et al., 2011 [131]	1.9–2.1 (^{137}Cs), total over 150 000 m^2 March–June	
Kawamura et al., 2011 [127]	11 (^{131}I) 4 (^{137}Cs) 21 March–30 April	57 (^{131}I) 5 (^{137}Cs) 12 March–30 April
Nakano and Povinec, 2012 [132]	Same as Kawamura (^{137}Cs) 5 (^{134}Cs) 21 March–30 April	Same as Kawamura (^{137}Cs) 6 (^{134}Cs) 12 March–30 April
Tsumune et al., 2012 [133]	3.5 ± 0.7 (^{137}Cs) 26 March–end of May	—
Estournel et al., 2012 [134]	5.1–5.5 (^{137}Cs) 12 March–30 April	5.7–5.9 (^{137}Cs) 0.23–0.33 (^{137}Cs) within a radius of 80 km
Honda et al., 2012 [135]	3.7 (^{137}Cs) 21 March–6 May	0.18 (^{137}Cs) 12 March–May
IFM-GEOMAR [136]	2.3 (^{137}Cs) 1 April instant	—
Byung-Il Min et al., 2013 [137]	Same as TEPCO (^{137}Cs)	5.8 (^{137}Cs) within (138°–145°E, 34°–40°N) 12 March–6 April
Rossi et al., 2013 [138]	Same as Bailly du Bois (^{137}Cs) 1 month (mid-March–mid-April)	—
Stohl et al., 2012 [112]	—	28

TABLE 1.4–8. SUMMARY OF DIFFERENT ESTIMATES FOR THE MARINE SOURCE TERM (cont.)

Study	Source term (PBq)/release duration (in 2011)	
	Direct release	Atmospheric deposition
JAMSTEC-1, 2012 [139]	14.8 (^{137}Cs) 21 March–6 May	—
JAEA-2 (Kobayashi et al.), 2013 [111]	11 (^{131}I) 3.5 (^{137}Cs) 26 March–30 June	99 (^{131}I) 7.6 (^{137}Cs) 12 March–1 May
WHOI-1, 2013 [140]	11–16 (^{137}Cs) early April 2011	—
WHOI-2, 2013 [141]	9.1–17.8 (^{137}Cs) mean 16.2; 1σ 1.6	0–11 (^{137}Cs) mean 0.5; 1σ 2.7
Sirocco, 2012 [139]	4.2 (^{137}Cs) 20 March–30 June	—
JAMSTEC-2, 2013 [142]	5.5–5.9 (^{137}Cs)	5.5–9.7 (^{137}Cs)
Kanda et al., 2013 [143]	2.27 (^{137}Cs) — from harbour to open ocean by water exchange (3 April 2011–30 September 2012) 2.25 (^{137}Cs) (1 April–31 May 2011)	—
UNSCEAR [122]	9–18 (^{131}I) 3–6 (^{137}Cs)	60–100 (^{131}I) 5–8 (^{137}Cs)

If the direct release from the site to the ocean had ended in May 2011, and assuming that the mixing processes in the ocean did not appreciably change, ^{137}Cs activities would have decreased by a factor of 1000 from May to June 2011 [124]. As per the concentration decrease, the change in slope of ^{137}Cs activity occurred approximately in late April. Some analyses of ocean contamination provide not only the integral value of the source term but its kinetics as well.

Most analyses estimate the source term of direct release based on numerical modelling of ^{137}Cs dispersion in the ocean and using the measurement data as validation basis. In the study presented in Ref. [134], the observations of ^{137}Cs concentrations near the outlets of the power plant were used in the inverse method to calculate the amounts of radionuclides released after the accident. IRSN [129] interpolated the individual measurement made in a period from 11 April to 12 July 2011. TEPCO used photographs, calculations of the flow rate, and measurements of activity concentrations in the leaking water to directly estimate the released activity.

The uncertainty in the direct release source term is generally smaller and most analyses show results in the range from 1 PBq to 5.5 PBq of ^{137}Cs (Table 1.4–8), except for the most conservative integral estimation given by IRSN (27 PBq, with an uncertainty band of 12–41 PBq) [125]. However, in 2013 new studies by the Woods Hole Oceanographic Institution in the USA [140, 144] partly confirmed this large IRSN value, thus making the uncertainty broader. The lower bound of the release range corresponds to estimates by TEPCO based on calculation of leakage flow rate and concentration readings (0.94 PBq in case of the leakage near the water intake of Unit 2, other leakages being much smaller).

The variability in the predictions of total direct ocean discharges of Cs is due to large uncertainties in the different oceanic circulation and radionuclide dispersion models and inversion processes used by each study and the lack of spatially distributed observations in the surrounding region. In much the same way as in atmospheric releases, the uncertainty of results was analysed using Bayesian techniques. The results are presented in Table 1.4–9.

TABLE 1.4–9. UNCERTAINTIES OF MARINE SOURCE TERM ESTIMATES FOR THE MAIN ISOTOPES (ALL VALUES IN PBQ)

Isotope	Accuracy (%)	Normal		Log-normal	
		Mean	Standard deviation	Mean	Range
^{137}Cs, deposition	25	1.24	1.33	6.34	3.81–10.53
	40*	1.77	1.55	6.43	3.94–10.52
^{137}Cs, direct inflow	25	2.70	0.76	3.79	2.73–5.28
	40	1.54	0.72	4.00	2.82–5.69
^{137}Cs, total	25	8.67	1.95	10.5	6.4–17.0
	40	6.79	2.23	10.5	6.4–17.3

* The largest uncertainty that was estimated by authors of the source term provided in Table 1.4–8.

Based on the results presented in Table 1.4–9, the following conclusions can be drawn:

- When normal distribution of the original data is assumed, the maximum likelihood values tend to be smaller than those for log-normal distribution. This follows from the higher weights ascribed to low values of releases and is a direct consequence of the mathematical model.
- The log-normal distribution is preferable in this kind of calculation. It is also less sensitive to the assumptions about the relative accuracy of the original results. For conservatism, the uncertainty range may be taken from the smallest value to the largest one. For example, in the case of direct deposition of ^{137}Cs to the sea, one could accept a mean value of 3.9 PBq within the range 2.7–5.7 PBq.

Before 25–26 March 2011, atmospheric deposition was the major source of radionuclides in the ocean arising from the Fukushima Daiichi accident, as the direct releases were likely to have been much lower in comparison. It has to be noted, however, that no observations of the concentration were available before 21 March 2011 near the southern outlet, or before 23 March near the northern outlet. Therefore, it is difficult to evaluate the direct release in these days. The impact of the importance of a no-observation period in the total release assuming two options was discussed in Ref. [134] as: a nil release and a release rate equal to the first measured value. The difference between two alternative scenarios demonstrated that the amount of ^{137}Cs released to the ocean before 21 March was 8% of the total liquid release. Most studies consider that the major direct release occurred in the period between 23 March and 8 April 2011. For example, the results obtained in Ref. [134] show a strong increase in direct release rate (>0.1 PBq/L) on 25 March. Another study [133] concluded from the analysis of the ^{131}I/^{137}Cs activity ratio that the contribution of direct release to the measured ^{137}Cs concentration became larger than atmospheric deposition after 26 March 2011.

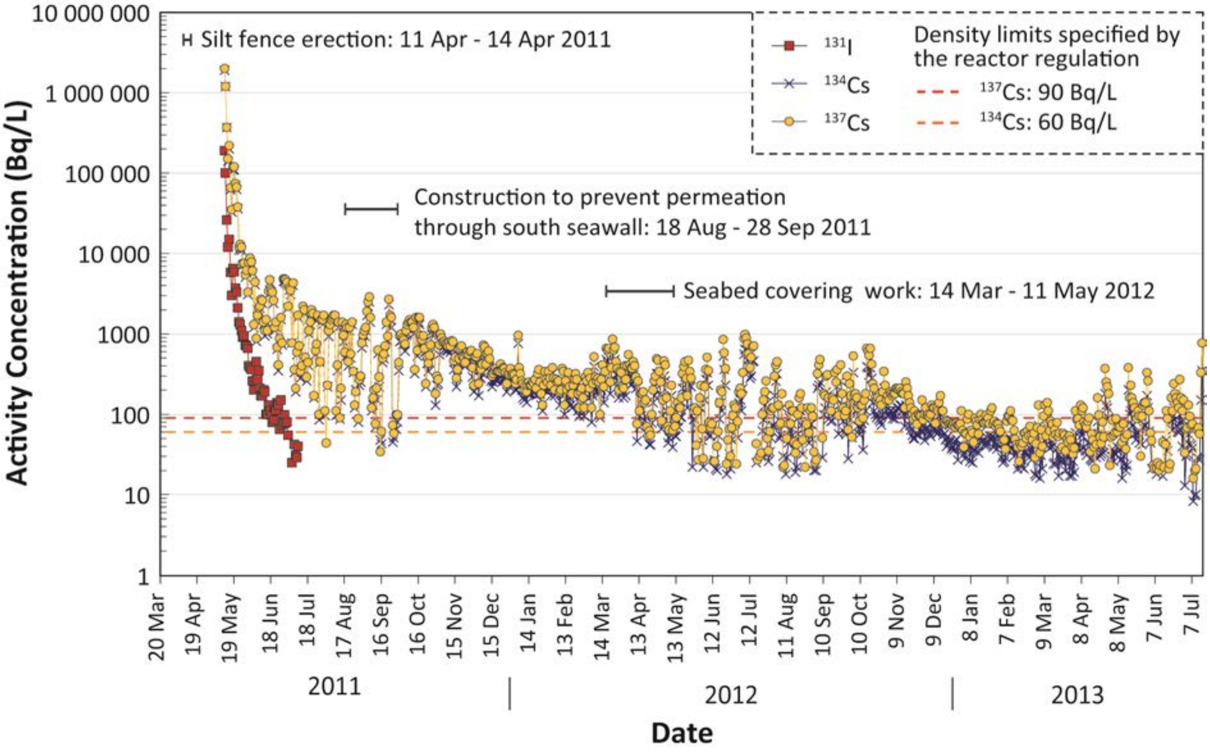
The relative contributions of direct release and deposition from the atmospheric release to ocean contamination over the full time period from 12 March 2011 to May 2011 are judged very differently by different studies. The ratio of the corresponding values of the source term (Bq released directly versus Bq deposited) varies from 0.13 [130] to 300 [125], while some analyses demonstrate equal contributions [127, 134].

Measurements of concentrations in ocean water close to the Fukushima coast show that, while the release rate has decreased over the first two years, radioactive material is still being discharged into the ocean. The possible sources of continued releases are likely to be drainage of groundwater transferring radioactive material from the basements of reactors, trenches or, to a lesser extent, leakage from a storage tank, and runoff of sediments from the ground during rains.

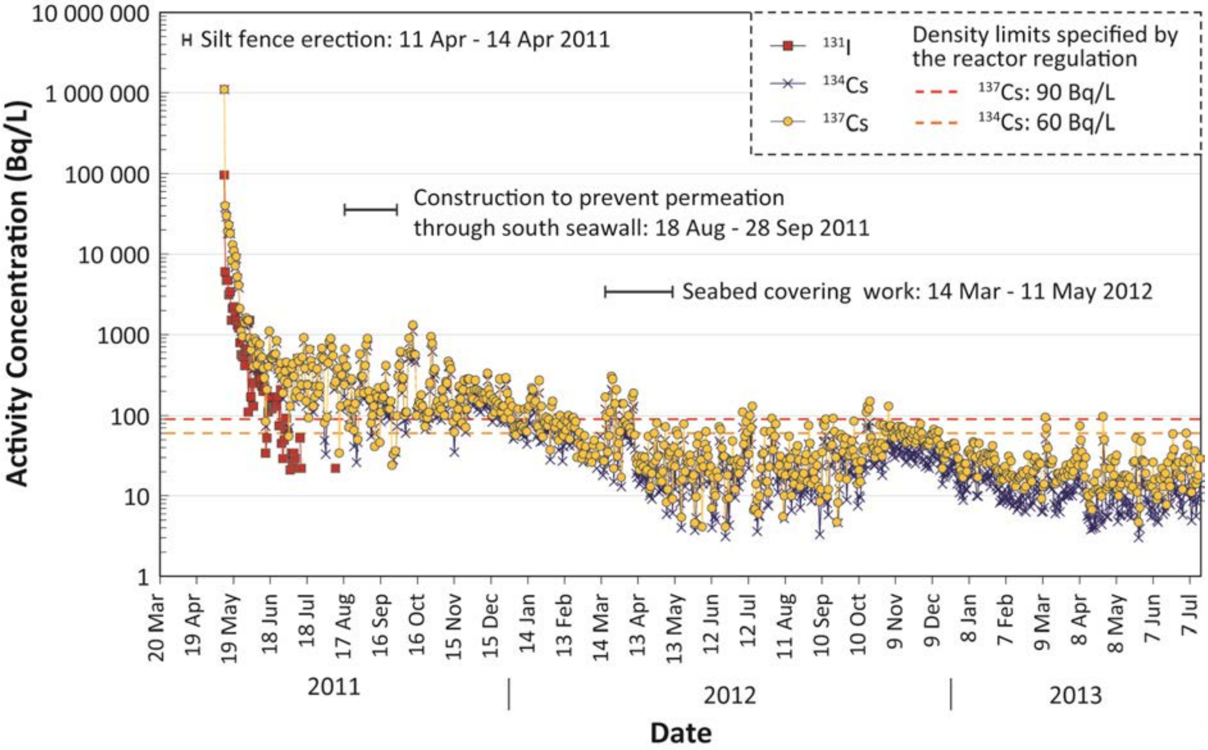
Radioactive materials deposited at the site may also be washed out to the ocean by the discharge of groundwater and river runoff, so an addition of radioactivity to the ocean from the contaminated watersheds also needs to be taken into account in long term analyses. According to Ref. [143], the release of ^{137}Cs from small rivers between April and September 2012 was estimated to be not more than 0.32 TBq/month. The study by IRSN [129] provides almost the same value, but only for the Ukedo River, the largest of the small rivers in the affected region of Japan. The larger Abukuma River has been estimated to release up to 0.87 TBq/month of ^{137}Cs [145]. Releases from other rivers (Naruse, Nanakita, Natori, Kuji and Naka) are of the same order of magnitude. A later study, in 2013 [146], showed that heavy rains during Typhoon Roke on 21–22 September 2011 transferred large amount of particulate ^{134}Cs and ^{137}Cs, deposited on the land, to the watersheds of the Natsui and Same Rivers and coastal marine environments. The rate at which radiocaesium was transported was estimated to be 0.020–0.026 TBq/d in the Natsui River and 0.007–0.009 TBq/d in the Same River, which is 30–50% of the total annual river transport from 11 March to 31 December 2011.

1.4.6. Additional radiological release since the accident

The concentration of radioactivity in the seawater of the port at Fukushima Daiichi has decreased since immediately after the accident. In 2013, the concentrations inside the port (water intakes, open culvert, inner side of the silt fence) fluctuated, but did not exceed the values measured in the summer of 2011 (Fig. 1.4–6). This is believed to be due to continuous leakages of contaminated groundwater, leakages of deposits from the seawall, changes in the tides and precipitation.



(a)



(b)

FIG. 1.4–6. Temporal change of measured radioactivity concentrations in the seawater inside (a) and outside (b) silt fence at Unit 3 intake [147].

The landscape features of the NPP site favour groundwater flow from the west-side hills to the eastern shore (Fig. 1.4–7). According to estimates by TEPCO, the flow rate of groundwater is approximately 1000 m^3/d. Because of the lack of water sealing in the basements, some groundwater enters the RBs and TBs of Units 1–4 and the auxiliary buildings that house the cleaning systems. TEPCO estimates that the daily contribution of groundwater to the flooding of these buildings is about 400 m^3.

This influx of groundwater and the water injected into the RPVs have created large pools of contaminated water in the RB basements with radioactivity concentrations of about 10^7 Bq/L [148]. As of 25 March 2014, the volume of these pools at Units 1, 2 and 3 was 13 700 m^3, 21 100 m^3 and 21 000 m^3, respectively, totalling 55 800 m^3. The basement of Unit 4 RB was flooded with 15 900 m^3 of water. Water also leaked from the RBs to the two TBs basements which are shared between pairs of units (Units 1 and 2, Units 3 and 4). Directly contributing to the release of radioactivity to the environment, large amounts of contaminated water that accumulated inside the RBs and TBs became a major concern.

By September 2013, the underground trenches and shafts were flooded with approximately 11 000 m^3 of water contaminated to ~10^9 Bq/L [148][149]. That water is gradually seeping into the ground through the layer of crushed stones, contaminating the clean groundwater that bypassed the basements of the buildings, and the whole amount is flowing to the ocean.

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[149] Here activity concentrations for ^{137}Cs are given, since it is the main contributing radionuclide.

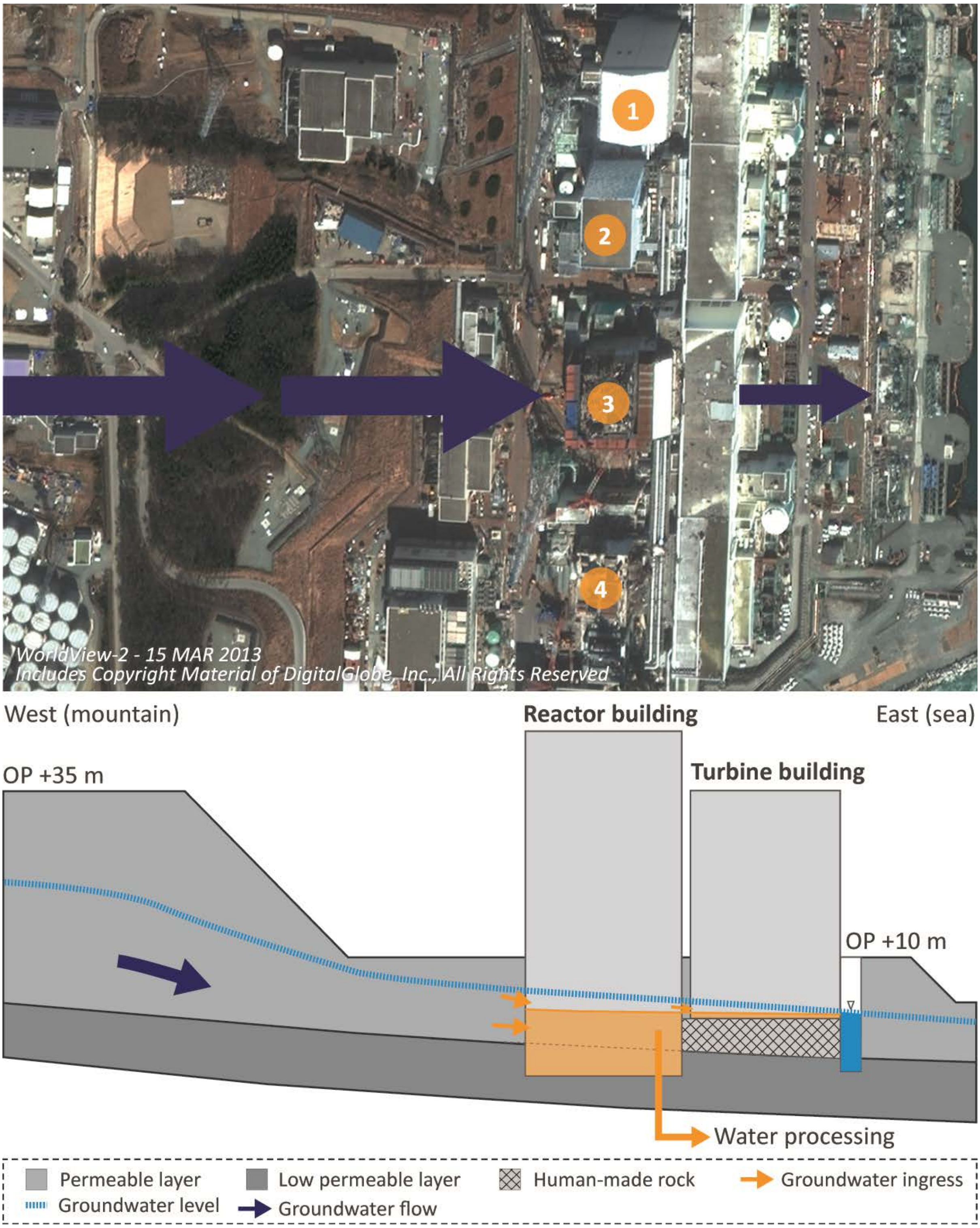


FIG. 1.4–7. Layout of groundwater flow trend at the Fukushima Daiichi site.

In order to reduce the infiltration of radioactivity into the groundwater and ocean, TEPCO installed a treatment and storage system coupled with a water injection system. It allows the radioactively contaminated water stored in the basements of the TB to be treated and reused for injection into the RPV. However, because of additional basement flooding with groundwater, the total amount of water accumulating in the basements (~800 m^3) exceeds the amount needed to cool the corium (~400 m^3), and so each day a surplus of ~400 m^3 is accumulating at the site. That excess of low activity salted water is collected in cylindrical storage tanks and stored at the NPP site. By the end of March 2014, the total volume of these tanks reached about 350 000 m^3.

Since the accident, several major events have occurred in which contaminated water has been released to the ground or ocean:

- On 2 April 2011, TEPCO found that highly contaminated water, with readings over 1000 mSv/h, was leaking directly into the sea from a 20 cm crack in a pit wall storing electric cables near the intake channel of Unit 2. Several measures were taken and the water discharge was stopped on 6 April. Based on ambient dose rates measured on 1–2 April 2011 near the sea surface around the Unit 2 screen, TEPCO estimated that the contaminated water had been flowing out between 1 and 6 April. The outflow rate was calculated to be 4.3 m^3/h. Given the sampling results, the total inventory of radioactive materials released with this water was estimated at 4.7 PBq;
- A planned and approved discharge of low contaminated water to the ocean occurred in April 2011. Then, TEPCO decided to discharge the low level radioactively contaminated water accumulated in the Radioactive Waste Treatment Facilities and subdrains of Units 5 and 6 in order to create space for the highly concentrated radioactive wastewater accumulated in the basement floor of the turbine building of Unit 2, which they feared might escape. About 10 000 m^3 of water was discharged to the ocean from 4 to 10 April, containing a total activity of about 1.5 × 1011 Bq [1].
- Another outflow of contaminated water into the sea occurred from a pit near the Intake Channel of Unit 3 on 11 May 2011. The leakage lasted for 41 hours and the volume of water released was estimated at 250 m^3. The total amount of radioactive material released to the sea was estimated at 0.02 PBq.

TEPCO disclosed on 21 August 2013 [149] that a leakage of approximately 300 m^3 of β and low level caesium contaminated water had occurred on 19 August from a storage tank, which was categorized as an INES 3 event by the Nuclear Regulation Authority (NRA). The causes of the leakage were loose flanges and a drain valve left in the open position. The radioactivity in the leaked water was deemed to have been released into the ground. However, most of the seawater samples taken later near the Fukushima Daiichi NPP remained below the detection limits, and no change was observed before and after the leakage from the cylindrical storage tank.

In order to investigate and mitigate the consequences of the leak, multiple wells were dug around the location and between the tank and the seashore (Fig. 1.4–8). The sampling results as of 22 April 2014 are shown in Tables 1.4–10 and 1.4–11. The maximum values from the sampling in the ground bypass pump wells were observed regularly at No. 7 and No. 12 and did not exceed 1600 Bq/L of ^{3}H. As of 22 April 2014, the maximum value of gross β activity concentration (710 000 Bq/L) around the tank area was found on 10 November 2013, while the highest activity concentration of ^{3}H (790 000 Bq/L) was measured on 17 October 2013.

Besides these events, several other minor leaks of contaminated water from the storage tanks have occurred since April 2011 in different areas. For instance, the discovery of two leaks of contaminated water from cylindrical storage tanks was announced by TEPCO on 21–22 December 2013. The total amount of water that could have escaped into the ground was estimated to be 1.8 t. The level of radioactivity was measured to be 1000 Bq/L for β and 190 Bq/L for ^{90}Sr in the first leak location, and 25 Bq/L for β and 2.7 Bq/L for ^{90}Sr in the second leak location.

Another leak coming from the upper part of a tank containing reverse osmosis concentrated salt water was discovered on 19 February 2014 [150]. The flow of water was stopped on 20 February 2014. Inspection of the area showed that contaminated water had not escaped into the sea, since there were no drainage channels in the surrounding areas. According to TEPCO's estimates, the volume of the leakage was approximately 100 m^3.

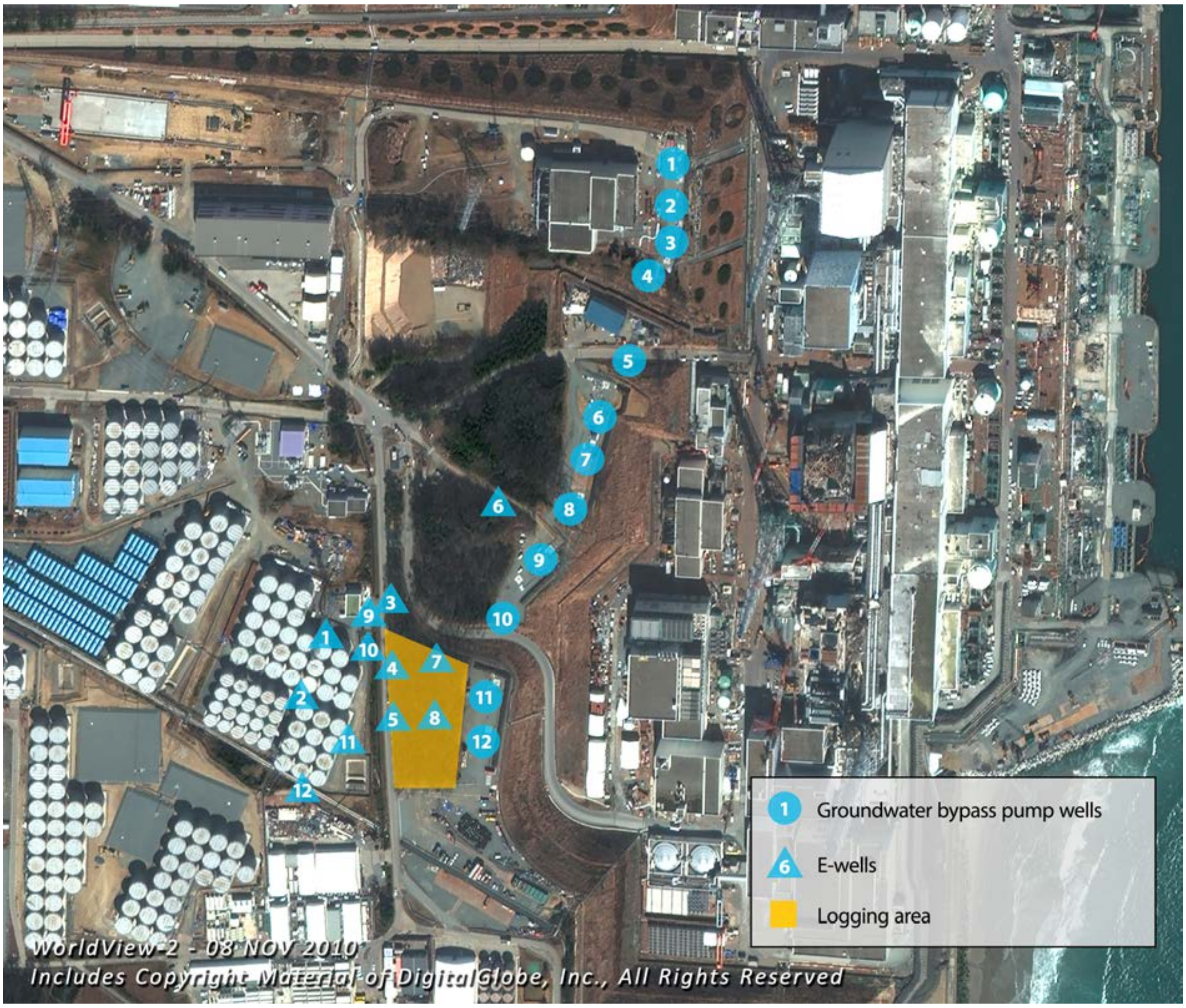


FIG. 1.4–8. Map of wells around the leaking tank location [151].

TABLE 1.4–10. RESULTS OF GROUNDWATER SAMPLING FROM E-WELLS, IN Bq/L (19 APRIL 2014) [151]

Measured parameter	E-Well				
	E-1	E-2	E-3	E-4	E-5
Gross β	29 000	28	18	37	26
^{3}H	23 000	430	5500	1800	1000

TABLE 1.4–11. RESULTS OF GROUNDWATER SAMPLING FROM GROUND BYPASS PUMP WELLS, IN Bq/L (15 APRIL 2014) [152]

Measured parameter	Well											
	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	No. 7	No. 8	No. 9	No. 10	No. 11	No. 12
Gross β	nd(13)	nd(13)	nd(13)	nd(13)	nd(13)	nd(13)	nd(13)	nd(13)	nd(13)	nd(13)	nd(13)	nd(4.4)
^{3}H	nd(5.2)	25	40	63	19	170	330	90	77	190	310	1600

Note: ‘nd’ indicates that the measurement result is below the detection limit, and the detection limit of each nuclide is provided in parentheses.

High concentrations of caesium were found in groundwater samples taken in 2013–2014 in the wells approximately 50 m from the coast. The highest radioactivity level (93 000 Bq/L of ^{137}Cs and 37 000 Bq/L of ^{134}Cs) was measured on 13 February 2014 near Unit 2. This demonstrates that contaminated water may still be seeping from underground trenches connected to the basements of the turbine buildings.

TEPCO considers that up to 10 TBq of strontium and up to 20 TBq of caesium have leaked into the port from the trenches and similar locations. At the same time the concentrations of tritium and all beta radiation inside the port and in the vicinity of the entrances to the port (port entrance, north intake, near the south intake) are below detectable limits (in the range of several tens of Bq/L). According to measurements, the fluctuations in radiation concentrations are limited to inside the Unit 1–4 open culvert and have no impact offshore or inside the port [147].

1.5. ACTIONS BY ORGANIZATIONS OTHER THAN TEPCO

This section describes actions during the accident by organizations other than TEPCO. Such off-site organizations supported the accident management and emergency response and recovery processes, mainly to protect the environment and general public near the accident, in Japan and internationally. Some off-site organizations also participated in directing actions taken by on-site organizations.

Technical Volume 2, Safety Assessment, and Technical Volume 3, Emergency Response, provide further information and analyses of the emergency preparedness and response issues described in this section.

Section 1.5.1 summarizes how the off-site organizations were structured and interacted with each other. It also describes how they were activated as the accident progressed. Sections 1.5.2–1.5.5 present the actions of national off-site organizations in response to the accident in chronological order. Section 1.5.6 presents the actions of international organizations.

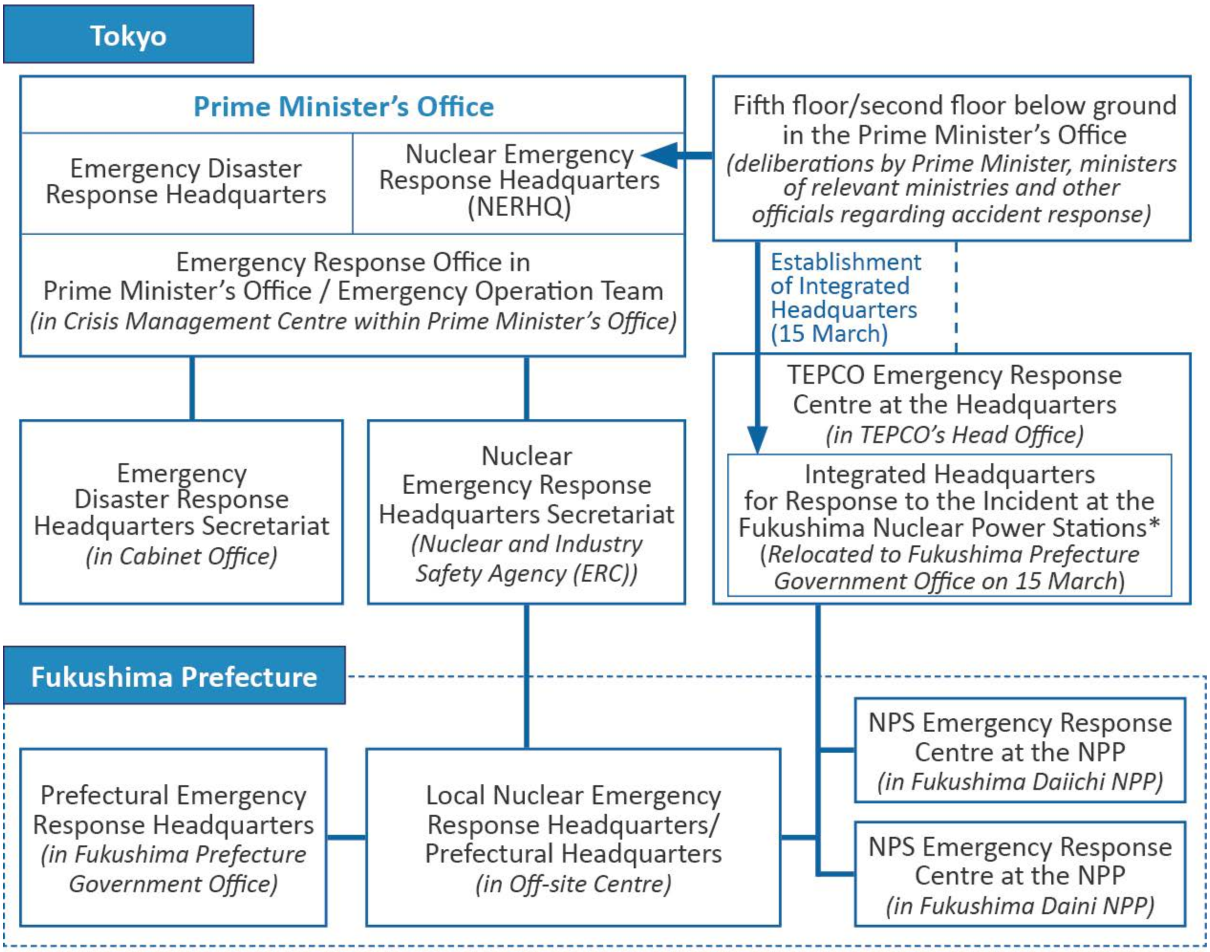
1.5.1. Structure and interactions of on-site and off-site organizations

Immediately following the earthquake, a number of local, regional and national emergency response organizations were activated. Their main point of on-site contact was the on-site ERC that TEPCO had immediately established at the seismically isolated building at the Fukushima Daiichi NPP site. The Site Superintendent was the designated emergency preparedness manager responsible for directing the site response and for coordinating with on-site and off-site organizations.

Within 20 minutes of the earthquake, at 15:06, an off-site ERC was also established at TEPCO Headquarters in Tokyo. It was responsible for managing both the response to earthquake damage at all of TEPCO’s facilities and the recovery from electric outages in its service area. The off-site ERC was headed by TEPCO’s Vice President, on behalf of TEPCO’s President, and staffed by internal duty personnel. One of TEPCO’s directors was designated as the off-site ERC’s Manager for oversight and response management. TEPCO’s on-site ERC was responsible for communicating with off-site emergency organizations, principally TEPCO’s off-site ERC. As the accident progressed into a nuclear emergency, the Fukushima Daiichi and Daini sites became the main focus of TEPCO’s off-site ERC, which was linked to both sites’ on-site ERCs by real-time videoconferencing. The communication system between TEPCO’s on-site and off-site ERCs was not connected with other off-site organizations, which inhibited real-time information sharing among all relevant parties.

As off-site non-TEPCO organizations, such as the national Government and local governments, activated their emergency response and recovery processes, TEPCO’s off-site ERC served as the interface between TEPCO’s on-site ERC and the national Government in Tokyo. TEPCO’s on-site

ERC meanwhile, communicated directly with local emergency response organizations, including the national Government's local emergency organization (Fig. 1.5–1).



*Although its purpose is disaster response, this ad hoc body is not classified as a legal entity under legislation

FIG. 1.5–1. Organizational structure and interfaces for initial accident response at the Fukushima Daiichi and Daini nuclear power plants [1].

The Basic Act for Emergency Preparedness governs the structure of governmental organizations during a national disaster. It includes the Prime Minister's Office and other government entities in Tokyo, as well as regional and local entities near the disaster location. As summarized in Fig. 1.5–2 and described below, the roles of these organizations varied from monitoring and advising to commanding and controlling countermeasures.

In response to the earthquake, national and local governments initially established emergency response organizations for a 'general earthquake disaster emergency' (not a nuclear emergency), including the following:

— The Emergency Response Headquarters of the Ministry of Economy, Trade and Industry (METI) was established in the ERC of METI, in Tokyo at 14:46. As a general earthquake response organization under the ministry which is responsible for nuclear infrastructure, it started collecting information on the state of the reactors at all nuclear power stations in the affected areas. Its response initially was not specific to a nuclear emergency at a specific nuclear power plant.

- The Emergency Response Office Headquarters for the earthquake at the Prime Minister's Office was established in Tokyo at 14:50, headed by the Deputy Chief Cabinet Secretary for Crisis Management. The Emergency Operations Team (EOT) members were called in to the Crisis Management Centre (CMC), located inside the Prime Minister's Office as the Emergency Response Office in the Prime Minister's Office. The EOT's responsibility was for the general emergency due to the earthquake, not the nuclear emergency.
- In accordance with the Disaster Countermeasures Basic Act, the Emergency Disaster Response Headquarters Secretariat in the Cabinet Office was established in Tokyo at 15:14 to coordinate the response to the earthquake at the Cabinet level.

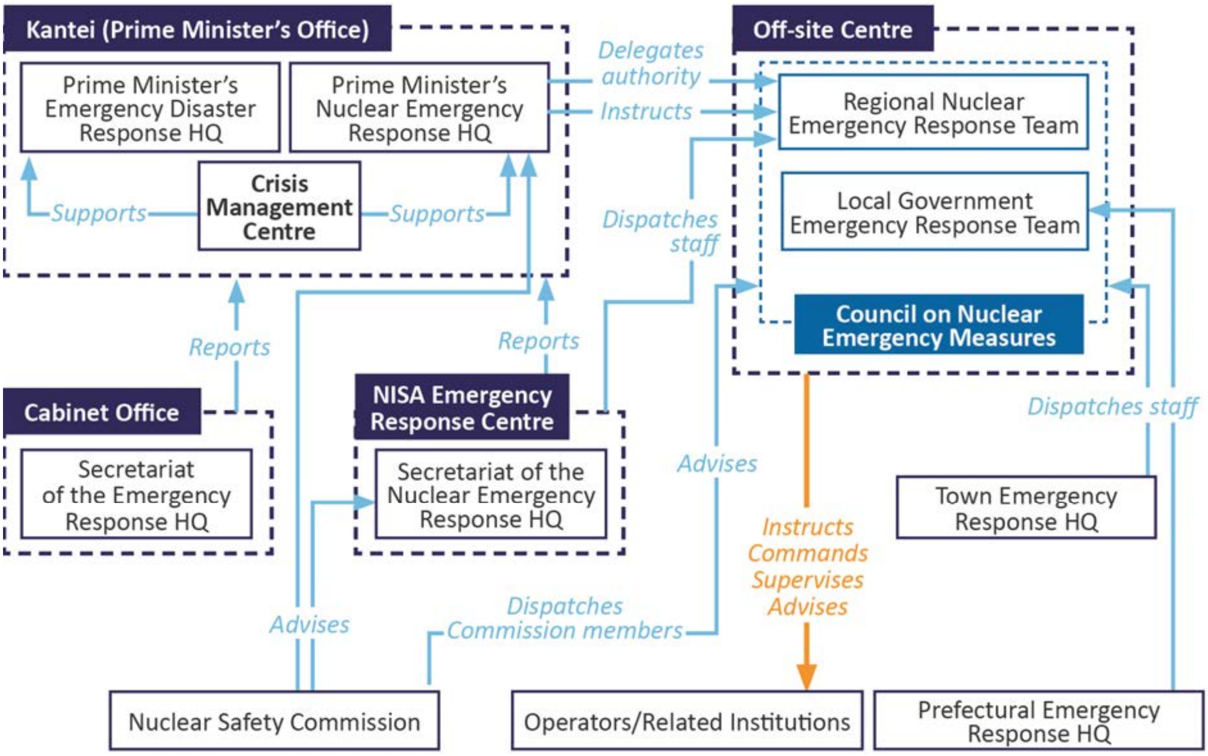


FIG. 1.5–2. Japanese governmental emergency organizations and interfaces [5].

At 15:42, about one hour after the earthquake and seven minutes after the tsunami (the first wave hit at 15:27 and the second wave at 15:35), TEPCO's Fukushima Daiichi NPP Site Superintendent declared emergency in accordance with Article 10. Through TEPCO Headquarters, he notified the Government at 16:00, through the Nuclear and Industrial Safety Agency (NISA) of METI, that the tsunami had rendered the facility's on-site AC power supply inoperable, resulting in the loss of all AC power (an SBO) for Units 1–5. Pursuant to Article 10, Paragraph 1 of the Nuclear Emergency Act [19], this served as the notification to the Government by the nuclear operator of a nuclear emergency. This notification was provided via fax and telephone to the relevant government institutions. Further requirements of the Act included the issuance of relevant information on the plant's status to the public.

Upon this notification, pursuant to Article 10, the national and local government organizations immediately established off-site response centres for 'the nuclear event'. These included:

- A Nuclear Emergency Preparedness Headquarters in the Emergency Response Centre (ERC) of the Ministry of Economy, Trade and Industry (METI), in Tokyo at around 16:00.

- A Local Nuclear Emergency Preparedness Headquarters at the designated Off-site Centre (OFC), by METI, in Okuma Town in the Fukushima Prefecture at around 16:00 (the building initially designated for the OFC was inoperable due to insufficient provisions for an emergency situation caused by the earthquake, and the OFC was subsequently relocated due to the worsening radiological conditions).
- An Emergency Technical Advisory Body established by the Nuclear Safety Commission in Tokyo at 15:59 upon being notified by NISA about the Article 10 notification from TEPCO.

As the accident progressed, TEPCO determined, at 16:36, the situation as a ‘nuclear emergency’ under Article 15 of the Act [19], because the reactor water level in Fukushima Daiichi Unit 1 could no longer be determined and there was evidence that core cooling had been lost.

Nine minutes after making this determination, at 16:45, TEPCO communicated an ‘Article 15 notification’ to the Government. At about the same time, TEPCO’s on-site ERC cancelled the Article 15 declaration in Unit 1 upon recovering the ability to determine the reactor water level. However, once this ability was again lost, Article 15 was re-declared, at 17:07, and the Government was notified at 17:12.

Upon receiving the Article 15 notification, the Government, through the Prime Minister’s Office, declared a nuclear emergency, and the national and local government organizations’ off-site response centres for a nuclear emergency were established, all at about 19:03. These included:

- An NERHQ at the Prime Minister’s Office in Tokyo, with the Prime Minister as Director General.
- The expansion of the Crisis Management Centre (CMC) team, which supported the Prime Minister’s Office Emergency Response Headquarters, to cover the nuclear emergency and coordinate tasks required for disaster response.
- The Local Nuclear Emergency Response Headquarters (Local NERHQ) at the OFC, with the Senior Vice Minister of METI serving as chief at the OFC. The building originally designated for the OFC was inoperable, as noted above was relocated to the Fukushima Prefecture Government office on March 15).
- The NERHQ Secretariat in METI’s ERC in Tokyo.

1.5.2. Actions by the Prime Minister’s Office and METI

This section summarizes the actions of the Prime Minister’s Office (Kantei) and METI in chronological order. All times are JST.

Important interactions with other organizations are indicated in brackets.

11 March 2011

At 14:50, the Kantei Emergency Response Headquarters (for the earthquake), headed by the Deputy Chief Cabinet Secretary for Crisis Management, was established. The Emergency Operations Team (EOT) members were called to staff the CMC for the earthquake emergency. The task of the EOT was to support the Kantei Emergency Response Headquarters by gathering information on the situations in the disaster stricken areas, reviewing potential evacuation measures, procuring supplies and equipment, identifying additional ways to help victims, and issuing instructions and requests to other government departments.

At 15:14, the Secretariat of the Emergency Disaster Response Headquarters was established and began reporting to the Kantei Emergency Response Headquarters.

At 16:00, the Kantei was notified by NISA, pursuant to Article 10, that the TEPCO's Fukushima Daiichi NPP's on-site AC power supply was inoperable due to the tsunami and that Units 1–5 had lost all AC power. As mentioned earlier, the Nuclear Emergency Preparedness Headquarters in the ERC of METI was established by METI, in Tokyo, in addition to the Local Nuclear Emergency Preparedness Headquarters at the designated Off-site Centre (OFC) in Okuma Town in the Fukushima Prefecture.

At 16:36, TEPCO notified the Government, in accordance with Article 15 of the Nuclear Emergency Act, that it could no longer determine the reactor water level in Units 1 and 2.

At 16:36, a Nuclear Emergency Preparedness Office was established in the Kantei and the Emergency Operations Team was expanded to respond to the nuclear emergency.

At 16:45, TEPCO reported to NISA that it might have already become impossible to inject water into Units 1 and 2 using the emergency core cooling systems.

At 16:45, the Article 15 notification, sent by TEPCO at 16:36, was received by the Government. [At about the same time, TEPCO's on-site ERC cancelled the Article 15 declaration upon recovering the ability to determine Unit 1's reactor water level.]

Shortly before 17:00, the Prime Minister summoned the NISA Director General to his office to find out about the conditions at the Fukushima Daiichi NPP. At that time, the NISA Director General had been provided general information about the situation. Details of the plant's condition were not available.

At around 17:00, the Prime Minister also summoned TEPCO staff to explain the conditions at the plant. TEPCO sent four staff to the Prime Minister's Office, but they also had only preliminary information and could offer only general explanations of possible consequences.

At about this time, the NISA Deputy Director General notified METI's Minister of the situation at the Fukushima Daiichi NPP.

At 17:12, the Government was notified about the re-declaration of Article 15 by TEPCO at 17.07.

At 17:35, after NISA had conducted its own technical verifications, the NISA Deputy Director General obtained the approval of METI's Minister's for the declaration of a nuclear emergency.

At 17:42, METI's Minister and NISA officials went to the Prime Minister's Office to notify the Prime Minister of the nuclear emergency and obtain his approval for formally declaring a nuclear emergency. The NISA officials had only preliminary information on the accident, especially on its predicted progress and the potential for hydrogen explosions and core melting.

The Prime Minister also requested information on the provisions of the Nuclear Emergency Preparedness Act as well as related laws and regulations. These were subsequently provided by METI and NISA officials.

By 18:30, the Prime Minister gave his approval for declaring a nuclear emergency.

At 19:03:

- A nuclear emergency was declared by the Japanese Government.
- The Prime Minister's Office established the NERHQ and the Local NERHQ.

- The Deputy Chief Cabinet Secretary for Crisis Management expanded the CMC's scope from the earthquake emergency to include the nuclear emergency, and officials at the Director General level from relevant ministries and agencies began assembling at the CMC; the Emergency Operations Team was formed in the CMC and included the nuclear disaster response staff.
- The first meetings of the NERHQ and the Cabinet Office Emergency Response Headquarters were held. Following these meetings, the Prime Minister discussed possible responses to the accident with METI's Minister, the Deputy Chief Cabinet Secretary and his Special Advisors.

Later, at a press conference around 19:45, the Chief Cabinet Secretary announced that a nuclear emergency had been declared.

At around 20:30, the Prime Minister went to the CMC in order to personally assume the duties of crisis manager and direct the Government's response to the earthquake/tsunami/nuclear emergency. Until then, the Deputy Chief Cabinet Secretary for Crisis Management had been managing the response with the government officials from relevant ministries.

The Prime Minister later left the CMC and continued to direct the response from his office in the same building, together with the Minister of METI, Chief Cabinet Secretary, Deputy Chief Cabinet Secretary and the Prime Minister's Special Advisors. The Chair of the Nuclear Safety Commission, the NISA Deputy Director General, a TEPCO consultant and others were also assembled in the Prime Minister's office, at a more remote location than the CMC. Topics discussed in the Prime Minister's Office included evacuation and sheltering areas, measures to be taken at the plant (e.g. pressure venting and water injection to the reactors) and logistical support such as the procurement of supplies and equipment. The discussions were based on the information made available from the CMC and the information gathered from the TEPCO staff over mobile phones. Although TEPCO sent staff to the Prime Minister's Office only to provide briefings on conditions at the plant, the staff stayed to serve as liaison staff to the Prime Minister's Office. Thus, the arrangement for communicating information about conditions at the plant between the Prime Minister's Office and the site initially depended on TEPCO's liaison staff using their mobile phones to talk to people at the site.

Between 20:00 and 21:00, the Cabinet Members of relevant ministries met with the NSC Chair, the NISA Deputy Director General, and TEPCO staff and decided to establish an evacuation area with a radius of 3 km from the Fukushima Daiichi NPP, and an in-house sheltering area between 3 km and 10 km from the NPP.

At 21:23, the Prime Minister issued the evacuation order for the 3 km zone and the instruction to stay indoors between 3 km and 10 km from the plant.

12 March 2011

At 01:30, the Prime Minister, together with the Minister of METI, and the Deputy Director General of NISA were informed about TEPCO's plans to vent the containments at Units 1 and 2.

[TEPCO's off-site ERC then told its on-site ERC that the venting should proceed after 03:00, when the Minister of METI announced the venting.]

At around 02:00, the Prime Minister became concerned that the Local NERHQ was not functioning as it should, and hence, the Prime Minister's Office had to make decisions without complete and timely information on conditions at the plant. The Prime Minister therefore planned to travel to the site to talk directly with the Site Superintendent and to see the extent of the damage.

At 05:44, the Government ordered the evacuation of residents living within 10 km of the Fukushima Daiichi NPP.

At 06:15, the Prime Minister left his office with his Special Advisor and the NSC Chair to travel to the accident site.

At 06:50, METI issued the order for containment venting.

At 07:11, the Prime Minister arrived at the Fukushima Daiichi site.

At the site, the Prime Minister and his team met with the Site Superintendent inside the seismically isolated building. Also at the meeting were the Senior Vice Minister of METI, who headed the local NERHQ, a TEPCO Vice-President who was from the TEPCO off-site ERC, and the NCS Chair.

At 8:04, the Prime Minister left the Fukushima Daiichi site.

[At 9:04, containment venting began.]

At 15:36, the Prime Minister's Office first learned about the hydrogen explosion at Unit 1's reactor building (RB) from a television report but was unable to obtain further information about the explosion directly from TEPCO.

At 18:25, the Government ordered the evacuation of residents within 10 km of the Fukushima Daini nuclear power plant and within 20 km of the Fukushima Daiichi NPP.

[When TEPCO staff returned from the NERHQ to TEPCO Headquarters on the night of 12 March, they pointed out the need to improve communication between TEPCO Headquarters and the Prime Minister's Office.]

13 March 2011

On the morning of 13 March, TEPCO Headquarters sent three staff as liaison to the Prime Minister's Office, together with fax machines and personal computers. This improved communication between TEPCO's headquarters and the Prime Minister's Office.

Throughout the day, management and engineering staff participated in meetings at the Prime Minister's Office, including the NSC Deputy Chair, the NISA Deputy Director General in charge of nuclear power plant safety and fuel cycles, engineers representing relevant plant vendors and staff from JNES.

There were frequent telephone calls between the CMC, TEPCO Headquarters, the Prime Minister, the Chief Cabinet Secretary and the Fukushima Daiichi Site Superintendent. Personnel at the Prime Minister's Office advised TEPCO Headquarters and the Fukushima Daiichi Site Superintendent by telephone on whether sea water should be injected into the reactor and on which unit should be given priority for water injection.

Members of the Emergency Operations Team at the CMC in the Kantei began communicating directly with TEPCO Headquarters through the several TEPCO personnel who had been dispatched to the CMC.

14 March 2011

On the morning of 14 March, NISA and TEPCO executives moved to a different room where TEPCO's telephones and fax machines were installed. From then on, this room functioned as a liaison information point between TEPCO and the Prime Minister's Office.

15 March 2011

The Prime Minister proposed that the Government and TEPCO should establish an integrated ERC inside TEPCO Headquarters to ensure rapid information sharing and promote comprehensive measures to deal with the Fukushima Daiichi accident. The order for the sheltering of residents living within a radius of 20–30 km area around the Fukushima Daiichi NPP was given on 15 March and remained in force until 25 March.

16 March 2011

On 16 March, the Prime Minister appointed a special advisor to the Cabinet. The Special Advisor joined with a member of the House of Representatives and others to form a private initiative Advisory Team at offices in the Secretariat of the Atomic Energy Commission (AEC). This Advisory Team served as technical consultants. It obtained documentation (primarily nuclear power plant information and monitoring data) mainly from the NERHQ via the AEC and used it to examine responses to the accident both inside and outside the plant.

17 March 2011

The Prime Minister met with the Director General of the IAEA, who visited Tokyo for this purpose. The Prime Minister committed himself to transparent information sharing with the IAEA and making every effort to provide accurate and objective information to the international community.

20 March 2011

[Senior TEPCO executives joined the core staff of the Emergency Operations Team.]

21 March 2011

The Prime Minister, as the Director General of the NERHQ, directed the Governors of Fukushima, Ibaraki, Tochigi and Gunma Prefectures to impose restrictions on the distribution of spinach and kakina harvested in these prefectures, and fresh raw milk produced in the Fukushima Prefecture. Further food restrictions in these and other prefectures were announced in subsequent days and months.

23 March 2011

[Concentrations of ^{131}I exceeded established limits in raw milk samples in the Fukushima Prefecture and in spinach samples in the Ibaraki Prefecture].

In response, the Prime Minister, as the Director General of the NERHQ, instructed the Governor of Fukushima Prefecture to restrict the distribution (and restrict the consumption) of certain leafy vegetables (spinach, komatsuna, cabbages, etc.) and flower-head brassicas (broccoli, cauliflower, etc.) produced in the Fukushima Prefecture until further notice. He also instructed the Governor of the Ibaraki Prefecture to restrict the distribution of fresh raw milk and parsley produced in the Ibaraki Prefecture until further notice.

25 March 2011

On 25 March 2011, a recommendation for voluntary evacuation was issued by the national government to residents within the 20–30 km zone.

29 March 2011

The Government of Japan founded ‘The Support Team for Residents Affected by Nuclear Incidents’ headed by NERHQ.

4 April 2011

The Government of Japan gave TEPCO permission to discharge 10 000 t of low level contaminated water into the sea.

11 April 2011

The Government of Japan announced the establishment of ‘Deliberate Evacuation Areas’ and ‘Evacuation Prepared Areas’ located further than 20 km from the Fukushima Daiichi NPP.

The Support Team for Residents Affected by Nuclear Incidents established a Headquarters for Measures against the Economic Impact Caused by the Nuclear Power Station Incident.

21 April 2011

The Government established restricted areas (Technical Volume 3 details the restricted areas further).

22 April 2011

The Chief Cabinet Secretary announced instructions from the Prime Minister about protective actions to be taken by the Government of Fukushima Prefecture and the governments of affected municipalities in connection with the ‘Planned Evacuation Areas’ and ‘Evacuation Prepared Areas’. These instructions included:

- Designating ‘planned evacuation zones’ more than 20 km from the Fukushima Daiichi NPP in Iitate Village, parts of Katsurao Village, parts of Namie Town and Kawamata Town, and part of Minamisoma City, where planned evacuations were expected to be implemented within approximately one month.
- Designating as an ‘emergency evacuation prepared area’ the area between 20 and 30 km from the plant, excluding those areas designated as ‘deliberate evacuation zones’, i.e. Hirono Town, part of Kawauchi Village, part of Naraha Town, and parts of Tamura City, Minamisoma City and Iitate Village. In the emergency evacuation prepared area, preparations were to be made so that residents could take shelter indoors or evacuate by their own means in the event of a further emergency. The instructions simultaneously lifted the advisory for sheltering indoors that had been in effect in the areas between 20 and 30 km from the plant.

1.5.3. Actions by NISA and the NSC

The chronology in this section highlights the immediate efforts made pertinent to NISA and the Nuclear Safety Commission (NSC) relevant to the accident. Although these entities are part of (or connected to) the Government of Japan, their actions are reiterated in this section due to their specific roles and responsibilities.

11 March 2011

Following the earthquake, NISA summoned the essential personnel from the ERC of NISA and formed six teams, each with a specific function for general affairs, radiation, plant, medical, resident safety, and public relations. It also made preparations to gather information and respond as necessary.

At 15:42, the TEPCO's Fukushima Daiichi NPP Site Superintendent notified NISA via TEPCO Headquarters that the facility's on-site AC power supply had been rendered inoperable by the tsunami resulting in the loss of all AC power for Units 1–5. NISA then notified the Prime Minister's Office and other relevant organizations on the declaration pursuant Article 10 of the Nuclear Emergency Act at the Fukushima Daiichi NPP.

At 15:59, NISA notified the Nuclear Safety Commission (NSC) on the declaration pursuant Article 10 of the Nuclear Emergency Act at the TEPCO's Fukushima Daiichi NPP.

At 16:00, the NSC held an extraordinary meeting, formed the Emergency Technical Advisory Body, sent emails to the members of the Emergency Technical Advisory Body asking them to remain on standby, and dispatched one member of the NSC Secretariat to the ERC to serve as a liaison staff member. The Emergency Technical Advisory Body formed by NSC met on a regular basis, thereafter.

At around 17:00, NISA's Director General joined the CMC in the Prime Minister's Office as a member of the Emergency Operations Team. The NISA officials, who were accompanying METI's Minister, had preliminary information on the details of the accident sequence, especially on predicted progress of the accident conditions at that time, including the potential core melt and hydrogen explosion.

At around 18:00, the NSC Chair and the Secretary General of the NSC headed to the Prime Minister's Office to attend the first NERHQ meeting. After the meeting, upon return to the NSC Secretariat, they were called back to the Prime Minister's Office.

Also at around 19:03, NISA dispatched the Director General and a number of liaison personnel to the CMC at the Prime Minister's Office. Later, the Deputy Director General and other executives joined the CMC's Emergency Operations Team, alternating periodically with each other.

At 19:03, the Government issued the emergency declaration and established the NERHQ and the Local NERHQ (OFC). At the same time, NISA also established the Secretariat of the NERHQ in the NISA-ERC. Members of the NISA-ERC received information about the Fukushima Daiichi NPP through several TEPCO personnel who were dispatched earlier, soon after the accident, from TEPCO Headquarters.

At TEPCO Headquarters, updated information on the Fukushima Daiichi NPP was received via an in-house videoconferencing system, beginning immediately after the accident. However, the NISA-ERC did not utilize TEPCO's videoconferencing devices for their information gathering purposes. NISA did not send staff to TEPCO Headquarters or arrange for the same system to be expanded to the ERC. Arrangements were made, before dawn on 12 March, for the system to be used by NISA personnel dispatched to the OFC.

Between 20:00 and 21:00, the NSC Chair, the NISA Deputy Director General and TEPCO management met with the cabinet members of relevant ministries and decided to establish an evacuation area with a radius of 3 km around the Fukushima Daiichi NPP, and an sheltering area in the zone from 3 km to 10 km from the NPP. Later, some of these people met to discuss changes to the evacuation areas, measures to be taken at the Fukushima Daiichi NPP such as water injections into the reactors and pressure venting, and logistical support for the procurement of supplies and equipment.

12 March 2011

At 06:15, the NSC Chair accompanied the Prime Minister visiting the Fukushima Daiichi NPP site.

13 March 2011

Throughout the day, the Deputy Chair of the NSC, the NISA Deputy Director General in charge of NPP safety, engineers representing the plant manufacturers, and personnel from the Japan Nuclear Energy Safety (JNES) organization joined the deliberations in the Prime Minister's Office from time to time.

14 March 2011

NISA reported to the IAEA that about 185 000 residents have been evacuated from the towns near Fukushima Daiichi NPP.

12 April 2011

NISA issued a new provisional rating for the accident at the TEPCO's Fukushima Daiichi NPP, rating it as a 'Major Accident', or Level 7 on the INES scale.

14 April 2011

NISA reported that among the approximately 300 workers at the Fukushima Daiichi site, 28 had received accumulated doses in excess of 100 mSv in the period related to this emergency.

16 April 2011

NISA directed TEPCO to increase the number of sea sampling points (from 10 to 16).

1.5.4. Actions by the local governments

11 March 2011

The Fukushima Prefecture Government building became unusable due to the earthquake. Essential equipment and supplies were moved to the third floor of the adjacent Fukushima Prefecture Local Government Hall, where the Fukushima Prefectural Emergency Response Headquarters (HQ) was established with the Fukushima Prefecture Governor as the director.

The Prefectural Emergency Response HQ began efforts to verify the safety of personnel, while gathering information on the Fukushima Daiichi and Daini NPPs.

At around 15:50, staff from TEPCO's Fukushima City office went to the Local Government Hall, and reported to emergency response staff that the TEPCO's Fukushima Daiichi NPP had issued a notification that an emergency situation existed due to loss of all AC power. This information was conveyed to the Governor of Fukushima Prefecture and other prefecture officials. The Government of Fukushima Prefecture initiated preparations for a nuclear emergency response by retrieving documents, such as nuclear emergency response manuals and supplies and equipment from the damaged prefecture government building.

The Prefectural Emergency Response Headquarters continued to obtain information regarding the Fukushima Daiichi and Daini NPPs, mainly from the TEPCO Fukushima City office. Contact between these two locations was maintained primarily through the use of satellite phones and by TEPCO staff carrying documentation and information, in person, to the Local Government Hall.

At around 16:48, the Prefectural Emergency Response Headquarters received a report from the Fukushima Daiichi NPP, stating that a nuclear emergency had been declared because the capability to determine the reactor water level and the status of cooling water injection into the core had been lost at 16:36.

After the press conference at 19.45 announcing the declaration by the national Government (at 19:03) of a nuclear emergency, Fukushima Prefecture Government officials began examining the need to issue an evacuation directive to residents near the Fukushima Daiichi NPP.

At 20:50, the Governor of Fukushima Prefecture issued an evacuation order for the residents of Okuma Town and Futaba Town to evacuate the area within a 2 km radius of the Fukushima Daiichi NPP. This order was announced to the public by a press conference, which was the first press conference by the Fukushima Prefecture Government after the accident.

Following the issuance of the evacuation order, the Deputy Governor of Fukushima Prefecture joined the Local Nuclear Emergency Preparedness Headquarters at the designated OFC, in Okuma Town in the Fukushima Prefecture. Thereafter, he participated in coordination of the national and local efforts at the OFC in accordance with provisions in the Fukushima Prefecture Local Disaster Response Plan.

1.5.5. Actions by international entities

In response to the accident at the Fukushima Daiichi NPP, the IAEA and the international community immediately offered both technical and humanitarian assistance to the Government of Japan and TEPCO. The Japanese Government and TEPCO also actively requested foreign countries and international organizations, including the IAEA, to provide their knowledge, experience and technologies to be utilized in response to the accident.[150] Over 25 countries and international organizations immediately offered and supplied equipment and materials for stabilizing the power plant, as well as supporting the evacuation efforts. This section summarizes the activities provided by the international entities. Further information on international actions are provided in Technical Volume 3.

1.5.5.1. Actions by the IAEA

The responsibility for responding to a nuclear or radiological emergency and for the protection of workers, the public and the environment, rests with the operating organization at the level of the facility concerned, and with the affected State at the local, regional and national levels.

The IAEA has a central role in the international framework for emergency preparedness and response.[151] This role includes: (1) notification and official information exchange through officially designated contact points; (2) provision of timely, clear and understandable information; (3) provision

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[150] Government of Japan did not request assistance under the Convention on Assistance in the Case of a Nuclear Accident and Radiological Emergency [72].

[151] The international emergency preparedness and response framework at the time of the accident consisted of: (a) international legal instruments and agreements, in particular the Convention on Early Notification of a Nuclear Accident (Early Notification Convention) and the Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency (Assistance Convention); (b) IAEA safety standards and technical guidance in the area of emergency preparedness and response; and (c) international operational arrangements and tools, in particular the Emergency Notification and Assistance Technical Operations Manual (ENATOM), the IAEA Response and Assistance Network (RANET) and the Joint Radiation Emergency Management Plan of the International Organizations (JPLAN).

and facilitation of international assistance upon request; and (4) coordination of the inter-agency response.[152]

The IAEA discharges this role through its Incident and Emergency System (IES). This system includes a 24-hour contact point and an operational focal point, the Incident and Emergency Centre (IEC).

As the initial response to the emergency, the IAEA's IES was activated, at 15:42 JST on 11 March 2011, following notification from the IAEA's International Seismic Safety Centre (ISSC) of the earthquake and of the potential for damage at four nuclear power plants on the north-east coast of Japan as well as the potential for a tsunami. At 16:21 JST, the IEC established initial communication with the official contact point designated by Japan, METI and NISA, and the IEC was activated to Full Response Mode [153]. The information about the accident was communicated to the Member States via the Early Notification and Assistance Conventions (ENAC) web site and periodic press briefings as well as updates on the IAEA web site (www.iaea.org) provided accident information to general public.[153]

An offer of assistance by the IAEA (referred to formally as 'the Agency's good offices') was sent to METI–NISA and the Permanent Mission of Japan in Vienna at 16:48 JST. On 12 March 2011 the Agency again sent an offer of good offices to Japan. Three days after the accident, on 14 March, the Government of Japan requested the IAEA to provide expertise. On 15 March, the Japanese Government requested assistance from the IAEA in the areas of environmental monitoring and assessing the effects of radiation on human health, in the form of an IAEA team of experts in Japan to assist local experts.

Within the IAEA, the Director General established the Fukushima Accident Coordination Team (FACT) to ensure effective interdepartmental coordination. Through FACT, the IAEA provided information on radioactive releases to the Preparatory Commission for the Comprehensive Nuclear-Test-Ban Treaty Organization and the World Meteorological Organization's Regional Specialized Meteorological Centre.

On 16 March, Japan asked the IAEA to provide an inventory of items that might be potentially needed to help deal with the emergency, such as remote controlled monitoring robots, aerial survey systems, unmanned trucks and unmanned helicopters. In response to this request, the IAEA collected information from Member States about available materials and equipment, some of which were later provided to Japan.

From 17 to 19 March, the IAEA Director General visited Japan and held high level consultations with Japanese organizations, including the Japanese Prime Minister and the Ministers of the Ministry of Foreign Affairs (MOFA) and METI. He also met with senior TEPCO and NISA officials. At the time of this visit, IAEA initiated support to Japan, comprising the following:

- A senior IAEA official was deployed to Japan to coordinate the IAEA's assistance and activities, and the offers of assistance from Member States to the Japanese authorities;

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[152] The primary coordinating body for nuclear and radiological emergencies is the Inter-Agency Committee on Radiological and Nuclear Emergencies (IACRNE). This body was established following the Chernobyl accident in 1986 and currently includes 18 international organizations. One of the primary roles of IACRNE is the development and maintenance of the Joint Radiation Emergency Management Plan of the International Organizations (JPLAN 2010 at the time of the accident).

[153] The first message for Member States and international organizations was published on the ENAC web site at 17:06 JST and the first press statement was published on the IAEA web site at 17:30 UTC on 11 March 2011.

- IAEA liaison officers were deployed to Tokyo to facilitate and improve communication between IAEA and NISA;
- The IAEA's radiation monitoring team was deployed, which began transmitting measurements to Vienna from various locations in Japan, including locations near to the Fukushima site.

Starting from 18 March, the IAEA sent several expert teams to Japan, including experts in radiation measurement, marine, food monitoring and BWRs:

- Between 18 March and 18 April 2011, the IAEA sent four teams to Japan for radiological monitoring. The teams assisted in validation of the radiological measurements being made by the Japanese authorities. The four teams also took measurements at a number of locations inside and outside the 20 km evacuation zone around the Fukushima Daiichi NPP site. Another team was deployed in the general vicinity of Tokyo for radiological measurement assistance.
- A Joint FAO/IAEA Food Safety Assessment Team (FSAT) visited Japan from 26 to 31 March 2011. The team provided technical advice and assistance to the Japanese organizations, including local governments, on issues related to food safety and agricultural countermeasures. The issues supported by the team included sampling and analytical strategies and validation and assessment of monitoring data to ensure that reliable information could be provided to the public and the international community on the extent of food contamination in the affected areas.
- At the Government of Japan's request, the IAEA sent an expert team from the IAEA Marine Environment Laboratories in Monaco, from 31 March to 7 April 2011 to assist marine monitoring programmes. From 2–4 April, the team joined Japanese experts on a research vessel to observe and to provide technical advice on the collection of seawater samples in the ocean monitoring activities. The team also reviewed and provided advice on the marine monitoring process that was coordinated by MEXT.
- A BWR expert team was sent to Japan by the IAEA from 3 to 12 April, 2011. The team mission held meetings with TEPCO and NISA staff to discuss technical issues in detail, focusing on the reactors and spent fuel pools. The team visited the Fukushima Daiichi and Daini NPP sites in order to communicate directly with those working on the ground to mitigate the conditions and, hence, to gain a first-hand understanding of the accident. The team exchanged views with officials of the Japanese Government and TEPCO technical teams.
- From 27 to 30 April, the FAO/IAEA FSAT visited the areas neighbouring the Fukushima Daiichi site to exchange views with relevant local authorities and to provide technical advice on food monitoring.

On 12 April 2011, industry guidelines for the transportation of people who may have been contaminated (internally or externally) with radioactive material and for aircraft decontamination were adopted. These guidelines were developed by the IAEA, the International Air Transport Association (IATA) and the International Civil Aviation Organization (ICAO). They were subsequently incorporated into the technical instructions[154] and put into force internationally for air transport. Additionally, the IAEA and the IMO reviewed maritime safety issues and prepared guidance and distributed internationally.

The IAEA Director General presented a report [153] to the IAEA Board of Governors on the IAEA's activities in response to the Fukushima Daiichi accident which provided details of all activities, including the ones listed above.

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[154] As an addendum to the 2011–2012 edition of ICAO Technical Instructions for the Safe Transport of Dangerous Goods by Air.

1.5.5.2. IAEA Ministerial Conference on Nuclear Safety

In June 2011, a Ministerial Conference on Nuclear Safety was convened by the Director General at IAEA Headquarters with the objective of strengthening nuclear safety by drawing on the lessons from the accident. The conference provided an opportunity to undertake, at the ministerial and senior technical levels, a preliminary assessment of the accident. The conference also considered actions for safety improvements, issues regarding emergency preparedness and response, and implications for the global nuclear safety framework.

The outcome was a Ministerial Declaration on Nuclear Safety [154], which outlined a number of measures to further improve nuclear safety, emergency preparedness and radiation protection of people and the environment worldwide. It also expressed the firm commitment of IAEA Member States to ensure that these measures were taken. The key measures were to: strengthen the IAEA safety standards; systematically review the safety of all NPPs, including by expanding the IAEA's programme of expert peer reviews; enhance the effectiveness of national nuclear regulatory bodies and ensure their independence; strengthen the global emergency preparedness and response system; and expand the IAEA's role in receiving and disseminating information. The Ministerial Declaration also requested the Director General to prepare a draft IAEA Action Plan on Nuclear Safety in consultation with Member States.[155]

1.5.5.3. Actions by other international organizations

International organizations such as the World Health Organization (WHO), the International Civil Aviation Organization (ICAO), the International Air Transport Association (IATA) and the International Maritime Organization (IMO), as well as the International Commission on Radiological Protection (ICRP), evaluated radiological impacts on human health and transportation infrastructure. They provided technical information to the global community which, for example, showed that radiation levels at and around airports and seaports in Japan did not pose health or transportation risks, and provided appropriate advice for travellers to Japan. The World Meteorological Organization (WMO) also provided essential information on meteorological situations and weather patterns.

1.5.5.4. Actions by Member States and other organizations

The Japanese Government received assistance offers from foreign countries through MOFA. The delivery and distribution of material and expert assistance was coordinated by NISA. Initially, there were difficulties in the receiving procedure because such procedure had not been defined in the basic emergency preparedness plan or other documents. It was difficult to ascertain the needs and to obtain such information as names, specifications, numbers and delivery timing of necessary equipment and materials. It took some time to secure storage places and to mobilize the necessary number of officials to handle the process. However, the situation improved in April and the work went more smoothly from then onwards.

The equipment and materials provided included, among others:

— **USA:** Fire engines, large capacity water pump set, feedwater pumps, water carrying barges, boron, remote control robots, equipment for aircraft monitoring, gamma cameras, germanium

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[155] The Action Plan, unanimously endorsed by the 55th IAEA General Conference in 2011, defined a programme of work to strengthen the global nuclear safety framework. It consists of 12 main actions related to: safety assessments; IAEA peer reviews; emergency preparedness and response; national regulatory bodies; operating organizations; IAEA safety standards; the international legal framework; Member States planning to embark on a nuclear power programme; capacity building; protection of people and the environment from ionizing radiation; communication and information dissemination; and research and development. For a detailed discussion of the Action Plan, see the Report by the Director General.

radiation detectors, personal protective equipment and materials, personal dosimeters, and survey meters.
- **France:** Environment monitoring cars, pumper trucks, generators, compressors, survey meters, personal protective equipment and materials, and personal dosimeters.
- **United Kingdom:** Personal protective equipment and materials, survey meters, and personal dosimeters.
- **Canada:** Survey meters and personal dosimeters.
- **China:** Concrete pumping vehicle.
- **Republic of Korea:** Survey meters and boron.
- **Germany:** Robots for site restoration and debris removal.
- **Russian Federation:** Personal dosimeters, personal protective equipment and materials.
- **Finland:** Survey meters.
- **Ukraine:** Survey meters, personal protective equipment and materials.

The pumps, fire engines and mobile concrete pumps were used by TEPCO for cooling the nuclear reactors and other facilities. The barges were used for transferring fresh water to be injected into the nuclear reactors and spent fuel pools in the early stages of the accident. The remote controlled robots were used for inspection inside the plant where worker access was difficult due to high levels of radiation. The survey meters, personal dosimeters and personal protective materials such as protective clothing, masks, and gloves were used for the inspection/restoration work at the plants as well as the evacuation of local inhabitants. Supplies of protective clothing, rubber gloves and boots became short after the middle of March and several countries supplied those materials at the request of Japan.

Some offers for material and equipment were specifically declined by the Government of Japan on the basis that either they would require specific training in their use or the equipment/material was abundant in Japan. For example, an offer to supply stable iodine was declined since Japan already had large stocks (and/or the storage and transportation of the stable iodine, in liquid form, was expensive). The supply of unmanned robots or monitoring vehicles was also rejected, since operation of those would have required training for operators in non-feasible conditions, e.g. training to be performed in the donor country or requiring a long period of time.

In addition to material and equipment, many states provided expert support. After the accident occurred, many experts visited Japan from China, France, the Republic of Korea, the Russian Federation, the United Kingdom and the USA to discuss the relevant issues and potential assistance with Japanese Government agencies and TEPCO. Japan received much advice, especially on the stabilization of the reactors and spent fuel pools, prevention of dispersion of radioactive materials and measures to cope with accumulations of radioactively contaminated water.

Organizations with expertise and capabilities in nuclear energy mobilized quickly and offered critical help. The United States Nuclear Regulatory Commission (NRC) interfaced early on with its Japanese regulatory counterparts and sent two experts to Tokyo to support immediate Japanese efforts. By 14 March, it had dispatched a total of 11 NRC staff to provide technical support in Tokyo. The US military stationed in or around Japan was also mobilized to help deliver food, water, blankets, clothing, and medical supplies to the people affected by the earthquake and tsunami.

In addition to governmental assistance, the nuclear industry and research organizations immediately offered assistance by sending supplies, technology and industry support teams, comprised of nuclear engineers and other experts, to lend technical expertise. Among others, these included:

- Radiation specialists from the US Argonne National Laboratory Radiological Assistance Program (RAP) who supported the collection of radiation readings and soil samples in the region around the Fukushima Daiichi site.

— The Korea Atomic Energy Research Institute (KAERI) and the Korea Institute of Nuclear Safety (KINS), in the Republic of Korea, both of which provided technical support.
— Experts from the member countries of the OECD/NEA visited and advised Japan.

Teams put together by multinational, private nuclear industry organizations, composed of representatives from vendors and electric utilities also provided technical assistance for assessment and issue resolution at the accident site. These included the World Association of Nuclear Operators (WANO), the Institute of Nuclear Power Operations (INPO), the Electric Power Research Institute (EPRI), as well as a number of individual companies, e.g. Exelon Corporation, AREVA, Bechtel Corporation, GE-Hitachi Nuclear Energy, The Shaw Group, Westinghouse Energy Company, and STP Nuclear Operating Company.

1.6. ACTIONS TAKEN IN THE AFTERMATH OF THE ACCIDENT

This section describes actions taken between May 2011 and December 2014.[156] It also provides an update on the status of the Fukushima Daiichi reactors and the Japanese nuclear industry as a whole. The actions taken have included short term countermeasures to deal with the day to day situation at the Fukushima Daiichi site, as well as mid-term and long term measures by TEPCO and the Japanese Government aimed at decommissioning of the NPP and remediation of the off-site contaminated areas.

The following sections provide the details of those actions and the results observed from those actions and will be discussed further in Technical Volume 5 and, as relevant, in Technical Volumes 2, 3 and 4.

1.6.1. Actions taken towards stabilization and restoration of the Fukushima Daiichi units

On 17 April 2011, TEPCO issued the Roadmap towards Restoration from the Accident at Fukushima Daiichi Nuclear Power Station [23] in order to bring the reactors and spent fuel pools to a stable cooling condition and mitigate the release of radioactive material. The immediate actions for achieving stability were focused on the areas of cooling, mitigation, monitoring and decontamination. The Government of Japan and TEPCO agreed to work together to implement the roadmap in order to steadily reduce radiation levels and to undertake to control and to minimize releases of radioactive material, when necessary [155].

1.6.1.1. Establishment of recirculation cooling of fuel debris

Following the initial seawater injection during the accident and subsequent transition to freshwater coolant by fire engines, starting in May 2011 cooling of the reactors in Fukushima Daiichi Units 1–3 was temporarily provided by fresh water injected through the feed water system piping utilizing temporary electric pumps. On 30 April, TEPCO started building a water treatment and reprocessing system, which became operable on 17 June. Recirculation cooling for all three reactors was established on 27 June 2011, using the new system (Fig. 1.6–1). TEPCO also started operation of the second caesium adsorption system on 19 August 2011 to improve the recirculation cooling loop while controlling radioactivity (water reprocessing is discussed further below).

After recirculation cooling was established, the RPV and PCV temperature monitors showed continuous cooling of the reactors.

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[156] In some cases, additional information is available up until March 2015 and this information is provided where possible.

Until early September 2011, cooling was controlled by adjusting the amount of circulation water injected via the feedwater line through the downcomer and lower plenum into the core region. In September 2011, an additional injection path through the core spray system was established which allowed water to be sprayed over the core region from the top.

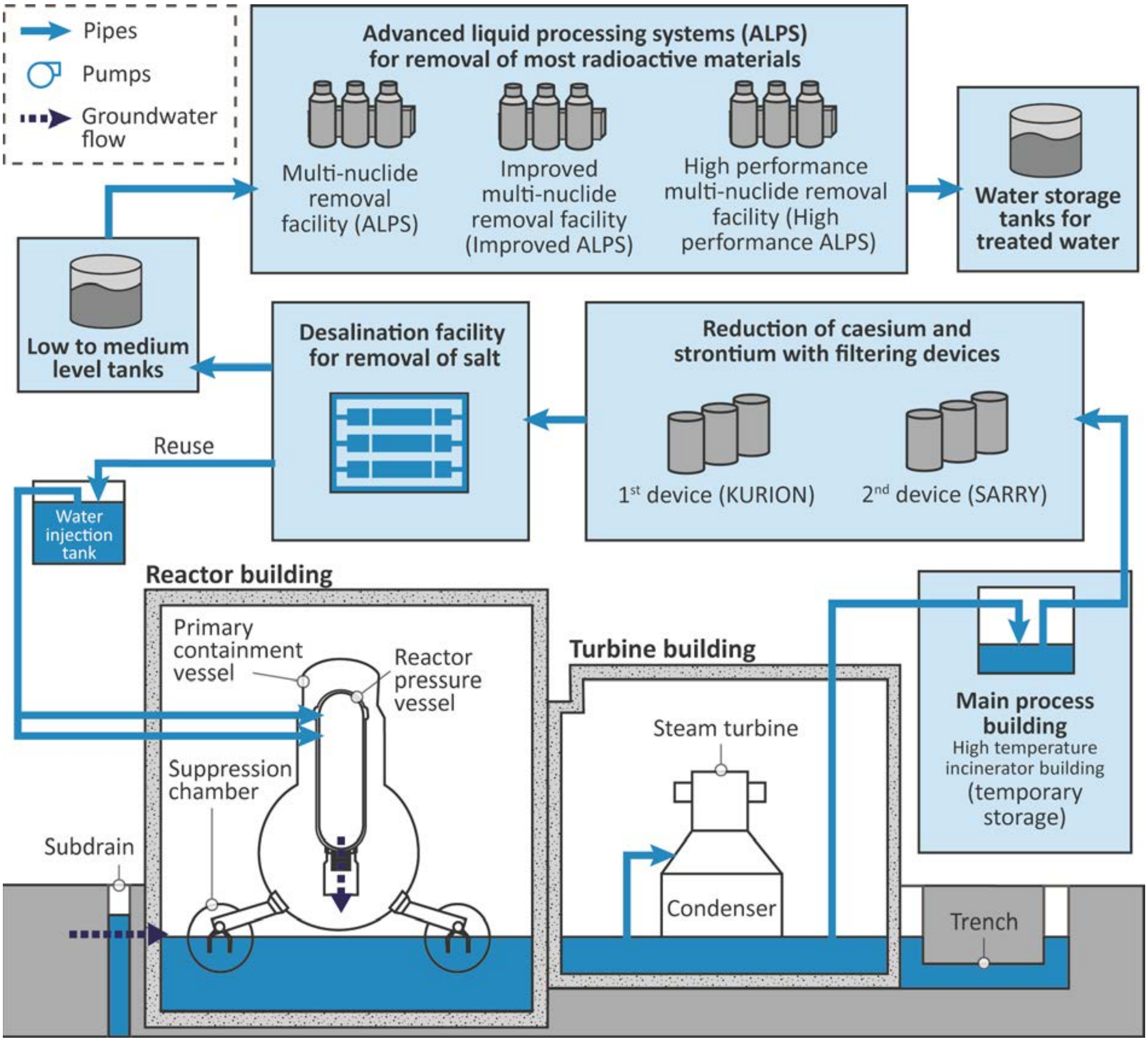

FIG. 1.6–1. Diagram of the circulating water cooling system for Units 1–3 [156].

1.6.1.2. Construction of water cleanup facilities

As the priority action following the accident was to establish circulating water cooling of fuel debris in Units 1–3, and the water became contaminated after flowing through the fuel debris, the installation of a water cleanup system became a key issue. On 30 April 2011, TEPCO started building the water treatment facilities incorporating oil separation, caesium adsorption, decontamination and water desalination with a reverse osmosis membrane. The facilities started operation on 17 June 2011 [157]. Further, TEPCO started installation of the second caesium adsorption system, SARRY (Simplified Active Water Retrieve and Recovery System), on 26 July, and it started operation on 19 August 2011. TEPCO implemented the distillation apparatus for desalination in series with the RO membrane apparatus and started operating the KURION-AREVA and SARRY systems in parallel. The levels of accumulated water in the basements of turbine buildings started to decrease following start of operation of the SARRY water processing facility on 19 August 2011, as shown in Fig. 1.6–2.

After mid-September 2011, TEPCO focused its efforts on controlling the water level to prevent the outflow of contaminated water and minimizing penetration of groundwater from outside into the turbine buildings, as will be discussed in Section 1.6.2.

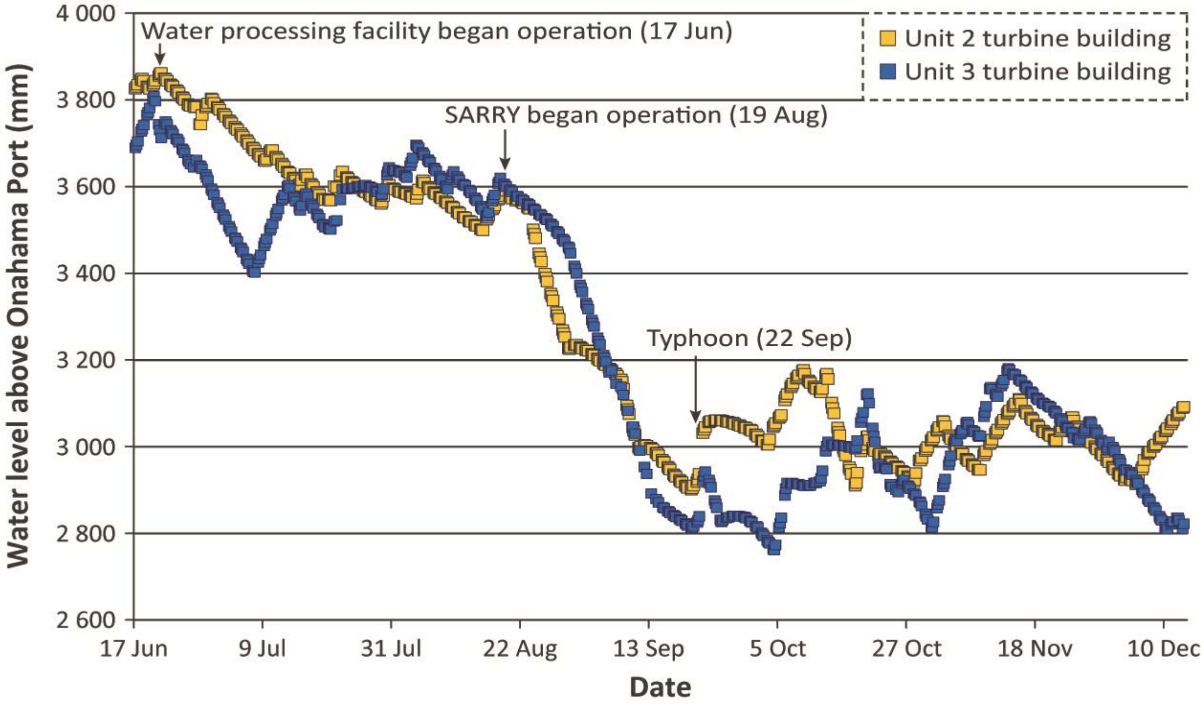

FIG. 1.6–2. Water levels in the turbine buildings in Units 2 and 3 [157].

1.6.1.3. Cooling of spent fuel in the spent fuel pools

In order to remove heat from the spent fuel stored in the SFPs of Fukushima Units 1–4, alternative circulating cooling systems were installed and started operation first in Unit 2 (31 May 2011), and later in Unit 3 (30 June), Unit 4 (31 July) and Unit 1 (10 August). A quasi-stable condition with temperatures of 30–40°C in SFPs was achieved by 27 August, 5 June, 7 July and 3 August 2011 at Units 1, 2, 3 and 4, respectively.

In Units 5 and 6, stable cooling has been maintained since the operating mode was changed to the shutdown cooling mode on 25 June and 6 May 2011 at Units 5 and 6, respectively.

In the common SFP, the water temperature had increased continuously until 24 March 2011 before the temporary cooling system started operation. Since then, stable cooling has been maintained.

During the accident, seawater was injected into the SFPs of Units 1–4. In order to mitigate the adverse effects of salt such as corrosion of structural components, TEPCO started desalination of Unit 2 SFP water with the reverse osmosis membrane method on 19 January 2012, and finished on 19 July 2012 by confirming that the salt concentration decreased from about 1350 ppm to 11 ppm. Similarly, desalination started on 11 April 2012 and finished on 18 March 2013 at Unit 3, and started on 29 November 2011 and finished on 12 October 2012 at Unit 4.

In order to prevent corrosion of structural components, hydrazine injection was started in Unit 1 SFP in August 2012, and later in the Unit 2–4 SFPs.

1.6.1.4. Assessment and stabilization of the Unit 4 SFP

After the inspections of the facility on 7 May 2011, TEPCO decided that due to the potential structural impact of the accident, the Unit 4 SFP needed reinforcements to enhance seismic safety margin. On 30 July 2011, TEPCO completed installation of the necessary reinforcements, although the preliminary assessments had shown sufficient seismic margin still remain. A detailed analytical assessment of Unit 4 SFP integrity and stability was performed by TEPCO in May 2012, which showed that the structural integrity is adequate.

1.6.1.5. Measures to reduce releases of radioactive materials to the atmosphere

After the initial releases of radioactive material in the early stages of the accident, TEPCO undertook a number of actions to contain the material that had already been released and to limit further releases to the atmosphere. The result of these measures was a dramatic reduction in atmospheric releases between July and August 2011, followed by a more gradual reduction between August 2011 and February 2012, when the release was essentially zero (see Fig. 1.6–3).

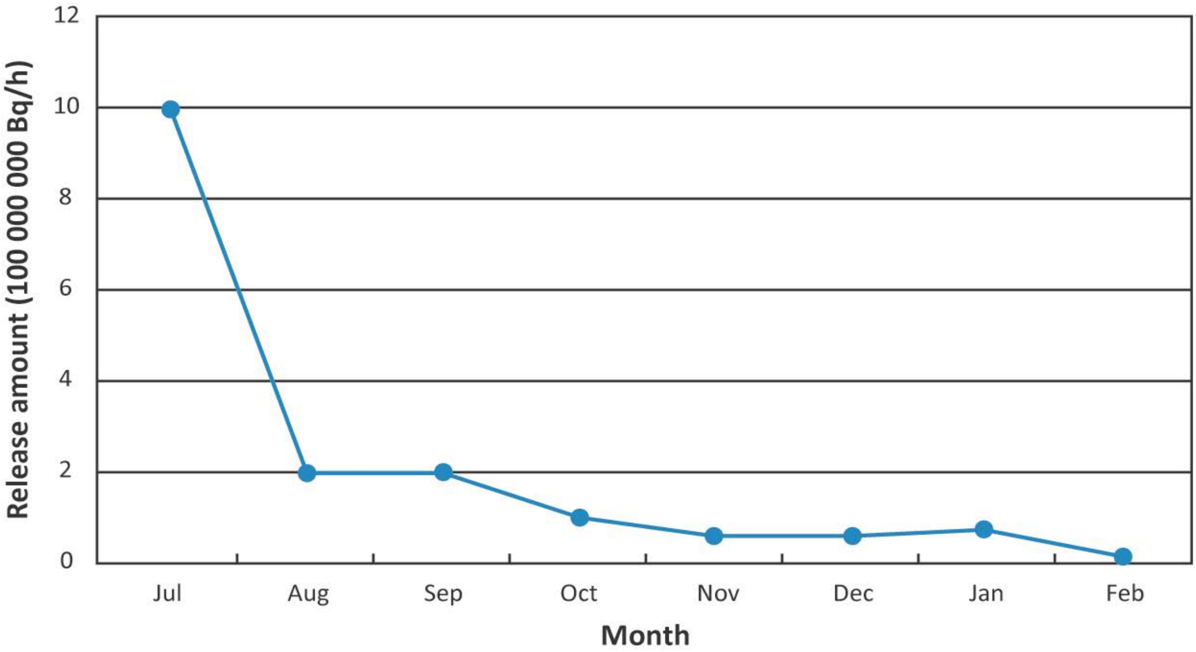

FIG. 1.6–3. Atmospheric release from the Fukushima Daiichi units between July 2011 and February 2012 [158].

The following actions were taken by TEPCO to reduce the release of radioactive material to the atmosphere:

- Following the accident, TEPCO sprayed dust inhibitor on the buildings and site ground to prevent the dispersal of dust in order to reduce radioactive material emissions to the atmosphere. In the early stages, the dust inhibitor was sprayed manually and then by a mobile pump was used for spraying. After May 2011, a concrete pumper and a bendable spray tower vehicle were used. By the end of June 2011, the work had been completed covering the target area of approximately 560 000 m^2 [158].

- On 28 October 2011, TEPCO completed the construction of a structure covering the RB of Unit 1 to suppress the dispersal of radioactive materials [158]. The cover consisted of a steel frame structure with roof and wall panels made of polyester fibre fabric. It is equipped with an exhaust system with filters which remove 99% of the radioactive materials before they can reach the outside atmosphere.
- TEPCO also installed gas control systems to reduce the radioactive releases from the primary containment vessels of Units 1–3, with a target filtering efficiency of 99%. The systems started operation first in Unit 2 in October 2011, and then Unit 1 in December 2011 and in Unit 3 in February 2012. As well as reducing the radioactive releases to less than 1%, the systems also analyse the radioactive nuclide content of the release and measures its hydrogen concentration, as discussed in Section 1.6–5.

1.6.1.6. Measures to reduce releases of radioactive material to the ocean

According to TEPCO [158], it was found that highly contaminated water had been leaking to the site harbour near the Unit 2 intake on 2 April 2011.[157] The leakage was stopped on 6 April [159]. Later, on 11 May 2011, a similar leakage took place near the Unit 3 intake [78]. TEPCO assumed that the highly contaminated water that had accumulated in the basement of the turbine building had leaked through the trench located between the turbine building and the intake. The trench had been damaged by the earthquake and/or tsunami.

TEPCO injected coagulator into the soil around the points where leaks had been found and also applied cement grout to the cracks. According to TEPCO, all the possible leakage paths were plugged by June 2011.

In April 2011, TEPCO closed off the entrances to the intake of Units 1–4 with silt fences and closed off the water intake of Units 1–4 with concrete block walls in June 2011.

From July to September 2011, in order to prevent radioactive materials from flowing into the ocean, TEPCO placed piles of steel pipe sheets at the permeation prevention structure located near the open conduit of southern water intake at Units 1–4. In addition, on 26 October 2011, TEPCO started construction of a water shielding wall in front of the existing seawall of Units 1–4.

TEPCO had also covered the seabed of the site harbour with a mixture of cement and clay in order to prevent radioactive materials deposited in the seabed from being stirred by bad weather conditions or turbulence caused by marine traffic.

In April 2013, the Council for the Decommissioning of TEPCO's Fukushima Daiichi Nuclear Power Plant, chaired by the minister of METI, established a Committee on Measures related to Contaminated Water Treatment to cope with this issue. On 30 May 2013, the committee issued a report [160] and proposed to implement a 'frozen soil wall' enclosing Units 1–4.

At a press conference on 19 June 2013, TEPCO said it identified high concentrations of tritium and strontium in the groundwater samples from the No. 1 observation well located at the sea side of the turbine building of Units 1 and 2. On 22 July, TEPCO acknowledged that the groundwater containing radioactive materials was leaking to the site harbour. By then, TEPCO had started cleanup of the contaminated water in the trenches. The R&D activities associated with using 'ice plugging' technology, in order to stop the leaks between the TB and the trenches, was also started by TEPCO.

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[157] Start time of the leak is unknown.

On 8 July 2013, TEPCO started injecting coagulator (water glass) into the soil of the surrounding area. This was called ‘ground improvement’. TEPCO also started pumping up groundwater by using the ‘well point’ method.

On 3 September 2013, the NERHQ issued Basic Policy for the Contaminated Water Issue at the TEPCO’s Fukushima Daiichi Nuclear Power Station [161] stating that the Government of Japan would take a more proactive role in the contaminated water issue, and establishing the roles, responsibilities and interfaces of government branches and TEPCO. The policy also described the activities to control contaminated water issues.

1.6.1.7. Hydrogen control

As mentioned above, TEPCO installed gas control systems to reduce radioactive releases from the primary containment vessels between October 2011 and February 2012. These systems have also been utilized to monitor hydrogen concentrations. Control measures to maintain hydrogen levels below flammable concentrations have been provided by nitrogen injection and purge of hydrogen, when necessary. Nitrogen gas injection to control hydrogen concentration below flammable limits started on April 2011 at Unit 1 PCV in order to purge the hydrogen gas produced by radiolysis [1, 2]. Nitrogen gas injection started at Units 2 and 3 as well on 28 June and 14 July 2011, respectively.

1.6.1.8. Recriticality control

After the initial boron injection as boric acid mixed with sea or fresh water to prevent recriticality during the accident, TEPCO installed a Boric Acid Injection Facility connected to the recirculation water system in June 2011 to guard against possible return to criticality in Units 1–3 and to reduce the potential for criticality in the SFPs of Units 1–4.

The potential return to criticality has been monitored by looking for increases in the ^{135}Xe concentration and/or abnormal temperature/pressure increases in the containment and reactor vessels. On 1 November 2011, TEPCO detected the possible presence of ^{133}Xe and ^{135}Xe gases in samples from inside the PCV of Fukushima Daiichi Unit 2. It responded to this development by injecting 10 t of boric acid solution (water containing 480 kg of boric acid) into Unit 2 on 2 November 2011 [162]. Again, on 7 February 2012, a temperature increase in the Unit 2 RPV bottom also triggered boric acid injection. To prevent criticality in the SFPs, TEPCO also injected boric acid solution into the SFP of Unit 3 on 27 June 2011.

1.6.1.9. Post-accident radiation monitoring

Radiation levels have been monitored continuously by TEPCO at the site boundaries of Fukushima Daiichi NPP site. There was a significant amount of debris and rubble on the site, some of which had high radiation dose rates. These were removed using heavy machinery. TEPCO compiled an on-site dose survey map and used it to help reduce the exposures of on-site workers. In addition, monitoring has been carried out at the north and south water discharge channels to the sea.

Marine monitoring has been conducted since March 2011 and a systematic plan was established in October 2011. The Monitoring Coordination Meeting, which was established under the NERHQ and chaired by the Minister of the Environment, developed a Comprehensive Radiation Monitoring Plan [163] on 1 April 2013. Also, a revised version of the 2013 Implementation Guides on Sea Area Monitoring was enclosed in the plan.

1.6.2. Actions towards a mid-term and long term roadmap for decommissioning

On 6 May 2011, the Integrated Countermeasure Headquarters for the Fukushima Nuclear Power Plant Accident, which was established on 15 March 2011 by the Prime Minister's Office, was reorganized into the Government–TEPCO Integrated Response Office under the NERHQ of the Japanese Government.

On 19 July 2011, the Government–TEPCO Integrated Response Office released its first announcement, stating that the first condition of 'cold shutdown state' defined in the Roadmap towards Restoration as "[r]adiation dose is in steady decline", had been achieved. This achievement was based on the data taken at the on-site and off-site monitoring posts, which showed that the release of radioactive materials had steadily decreased [156, 164].

On 16 December 2011, the Government–TEPCO Integrated Response Office announced that the second condition of 'cold shutdown state' had been achieved in Units 1–3 by stating that: (1) the temperatures measured at the RPV bottom and those of the gaseous phase inside the PCV were maintained below approximately 100°C; and (2) as a result, the radiation doses at the site boundary due to the additional release of radioactive materials from the PCVs was evaluated to be 0.1 mSv/a, well below the target of 1 mSv/a.

Upon declaration of the achievement of 'cold shutdown state' on 16 December 2011, the Government–TEPCO Integrated Response Office was abolished and a new organization, the Government–TEPCO Mid-to-Long Term Response Council[158], was created in TEPCO Headquarters. On 21 December 2011, the Council issued the Mid-and-Long-Term Roadmap towards the Decommissioning of Fukushima Daiichi Nuclear Power Station Units 1–4, TEPCO (hereafter the Roadmap) [165]. Its basic concept is shown in Fig. 1.6–4.

On 27 June 2013, the Council revised the roadmap. In the revised version, for example, multiple plans are provided for fuel debris removal and the target for commencement is accelerated [166]. The Japanese Government and TEPCO have conducted various activities according to the roadmap under the management of the Council. Those activities are described in the following sections.

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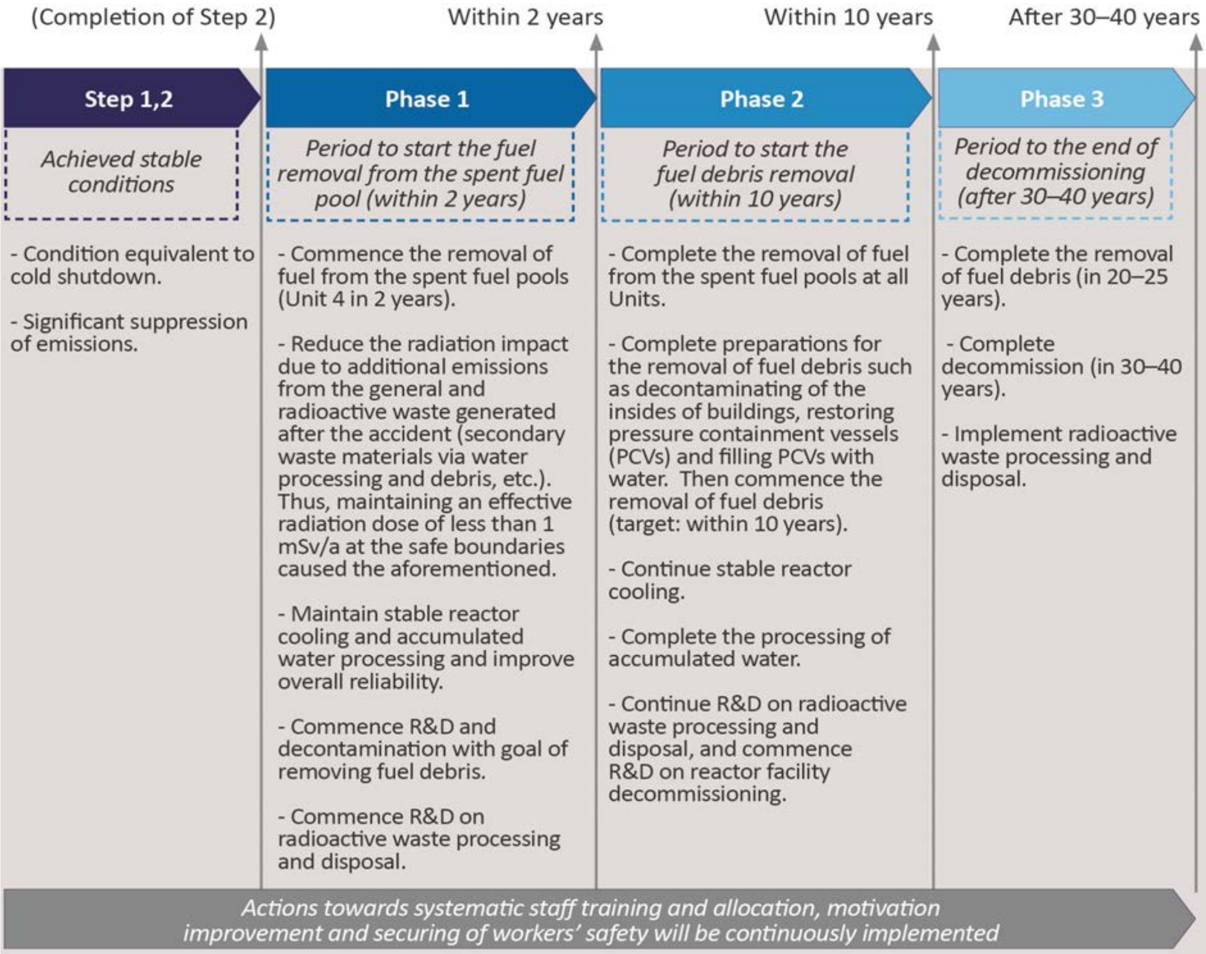
[158] Later, on 8 February 2013, the name of the Council was changed to the Council for the Decommissioning of TEPCO's Fukushima Daiichi Nuclear Power Plant by adding members from research organizations.



Achieved stable conditions

- Condition equivalent to cold shutdown.
- Significant suppression of emissions.

Period to start the fuel removal from the spent fuel pool (within 2 years)

- Commence the removal of fuel from the spent fuel pools (Unit 4 in 2 years).
- Reduce the radiation impact due to additional emissions from the general and radioactive waste generated after the accident (secondary waste materials via water processing and debris, etc.). Thus, maintaining an effective radiation dose of less than 1 mSv/a at the safe boundaries caused the aforementioned.
- Maintain stable reactor cooling and accumulated water processing and improve overall reliability.
- Commence R&D and decontamination with goal of removing fuel debris.
- Commence R&D on radioactive waste processing and disposal.

Period to start the fuel debris removal (within 10 years)

- Complete the removal of fuel from the spent fuel pools at all Units.
- Complete preparations for the removal of fuel debris such as decontaminating of the insides of buildings, restoring pressure containment vessels (PCVs) and filling PCVs with water. Then commence the removal of fuel debris (target: within 10 years).
- Continue stable reactor cooling.
- Complete the processing of accumulated water.
- Continue R&D on radioactive waste processing and disposal, and commence R&D on reactor facility decommissioning.

Period to the end of decommissioning (after 30–40 years)

- Complete the removal of fuel debris (in 20–25 years).
- Complete decommission (in 30–40 years).
- Implement radioactive waste processing and disposal.

Actions towards systematic staff training and allocation, motivation improvement and securing of workers' safety will be continuously implemented

FIG. 1.6–4. *Basic concept of the Mid-and-Long-Term Roadmap towards the Decommissioning of Fukushima* Daiichi *Nuclear Power Station Units 1–4, TEPCO [165].*

1.6.2.1. Construction of a multi-nuclide removal facility

The decontamination facilities which were constructed just after the accident mainly remove caesium. A multi-nuclide removal facility, namely the Advanced Liquid Processing System (ALPS), was constructed to further reduce the radioactivity of the processed water by removing a larger number of radioactive nuclides (excluding tritium) down to levels less than the detection limit. TEPCO started its construction in June 2011 and completed it in October 2012 [167]. The test operation of ALPS started in November 2013. The operation of expanded ALPS started in September 2014. The operation of High-performance ALPS (HERO) started in October 2014.

1.6.2.2. Groundwater bypass

TEPCO has estimated that approximately 400 m^3/d of groundwater is penetrating into the reactor buildings and turbine buildings of Units 1–4 from the hill side. Approximately the same amount of water is circulating for debris cooling in the reactor vessels. Since the penetrating groundwater is mixed with the circulating water, a total of approximately 800 m^3/d of water is being processed [168]. Nearly 400 m^3/d of this processed water is injected back to the reactor vessels for debris cooling and the remaining 400 m^3/d has to be stored in the contaminated water storage tanks.

TEPCO is conducting 'groundwater bypass' to reduce the amount of groundwater penetrating into the buildings by pumping up groundwater from upstream of the buildings. Figure 1.6–5 shows its concept. For this purpose, TEPCO constructed a total of 12 pump wells and water transfer systems by February 2012. Since 21 May 2014, pumped-up groundwater has been transferred to the temporary water storage tanks and, after the water contamination has been measured, discharged to the sea.

1.6.2.3. Removal of fuel from the Unit 4 SFP

In March 2012, in accordance with the Roadmap towards Decommissioning, TEPCO started preparatory activities for this fuel removal operation and in April 2012, started the construction of the cover structure for this purpose. The cover structure was completed in September 2013 and it was reviewed and approved by the regulatory body in November 2013 for use in fuel movement.

The fuel removal operation started on 18 November 2013 and the removal of all spent fuel was completed on 22 December 2014. The fuel assemblies stored in the fuel rack inside the Unit 4 SFP were taken out and transferred to the common pool for centralized storage located within the station site. The fuel assemblies already in the common pool were transferred to the temporary cask custody area in order to make space for the fuel assemblies from Unit 4.[159]

1.6.2.4. Measures taken against external hazards

Taking into account the damage to the reactor buildings of Units 1, 3 and 4 as a result of hydrogen explosions, TEPCO conducted seismic structural assessments of the reactor buildings to ensure structural integrity against further earthquakes with the design basis earthquake ground motion. TEPCO also conducted analyses demonstrating that the impact of the design basis earthquake is "fairly lower than the evaluation criterion" [169].

As discussed earlier, on 30 July 2011, TEPCO completed installation of the necessary supporting structures at the Unit 4 SFP. On 22 January 2012, TEPCO also conducted a survey and inspection of the fifth floor of the reactor building and confirmed that the water surface of the reactor well was parallel with the floor level. This indicated that the building had not tilted. On 9 February 2012, a visual inspection of SFP using an underwater camera was conducted to confirm that the fuel rods stored in the racks had not been dislodged. This was done by comparing with an earlier visual inspection conducted on 7 May 2011 [171]. On 20 March 2012, similar measurements were repeated, confirming that the structure had not been changed since 9 February 2012.

In June 2011, TEPCO analysed potential measures that could be taken with the existing configuration of the facility against a postulated tsunami with a maximum height of 7 m to 8 m [170]. As a result of this study, all the pumps for water injection into the RPVs of Units 1–3 were moved to higher locations by July 2011. The mobile emergency power sources, fire engines and other equipment were also moved to higher locations. TEPCO also constructed a temporary seawall using sandbags of height varying from 2.4 m to 4.2 m at the 10 m level to protect the major buildings.

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[159] The fresh fuel assemblies were transferred to the Unit 6 SFP.

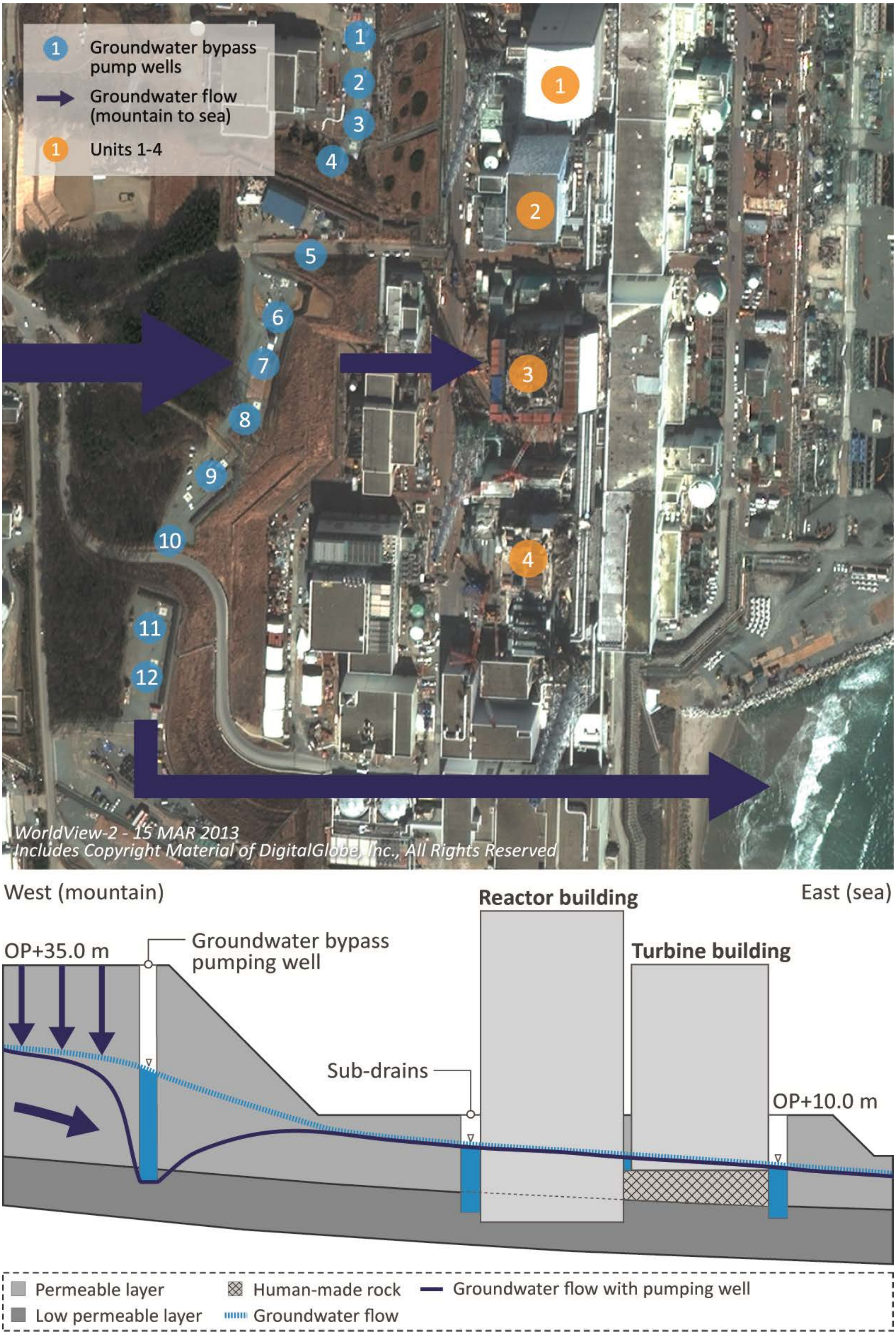

FIG. 1.6–5. Concept of groundwater bypass [170].

1.6.2.5. Enhancement of reliability

TEPCO established an organization for reliability enhancement, referred to as the Immediate Response Headquarters for Reliability Improvements, in April 2013 following frequent failures of equipment and associated events. Since the organization has been put in place, it has performed reviews of plant documents to identify vulnerabilities and common cause failures. Its teams have also conducted targeted facility walkdowns to confirm the assurance of reliability and to identify any potential issue that would affect essential functions of the equipment, to keep safe and stable conditions. TEPCO has reported that the primary functions targeted for this effort were: controlling radioactive material release, cooling the reactors and spent fuel pools, preventing hydrogen explosions, and preventing criticality [172].

In order to enhance reliability of water injection to the RPVs, redundancy and diversity of water and power sources were implemented with multiple pumps, tanks, and redundant off-site and on-site power sources. In addition, water can be retrieved from a nearby hydro dam. Seawater injection by fire engines is available as a final option.

Water injection for SFP cooling was also enhanced with redundant equipment. TEPCO installed two redundant trains of fuel pool cooling systems, each of which has a heat exchanger with a secondary system with an air-fin cooler. It also installed an emergency water injection system. Water from the filtrated water tanks and raw water underground tanks can be injected by the electric pumps, fire engines, or alternatively by concrete pumper. Two lines of the off-site power supply are available and, in case of loss of off-site power, on-site emergency power supply and mobile power sources are available.

1.6.3. Government/regulatory actions

1.6.3.1. Reorganization of the regulatory body

On 19 September 2012, the Nuclear Regulation Authority (NRA) was established [173]. Taking into account the lessons learned from the Fukushima Daiichi accident, the NRA was set up as an independent commission body affiliated to the Ministry of the Environment (MOE) and its chairman and commissioners were appointed by the Prime Minister, as approved by the National Diet of Japan. In addition, the roles and responsibilities that had been assigned to different governmental organizations were integrated into the NRA.

Regarding the technical support organizations, the NRA holds jurisdiction over part of the affairs of the National Institute of Radiological Sciences (NIRS) and the Japan Atomic Energy Agency (JAEA) and Japan Nuclear Energy Safety Organization (JNES), which was merged with NRA on 1 March 2014 [174]. New structure of the regulatory body is further discussed in Technical Volume 2.

1.6.3.2. Amendments to the Atomic Energy Basic Act and the Reactor Regulation Act

The amendments of the Basic Act and the Reactor Regulation Act, which were promulgated in June 2012, came into force on 19 September 2012. The amended Reactor Regulation Act also clarified the objectives of safety regulation and established new requirements, as further discussed in Technical Volumes 2 and 5, including [174]:

- Mandatory severe accident measures;
- Mandatory backfitting;
- Forty year lifetime limit for NPPs (with the possibility of up to a 20 year extension).

Based on this new legal framework, the NRA developed the new regulatory requirements which came into force on 8 July 2013. Immediately after this, four utilities applied for a review of 12 units at six sites.

1.6.3.3. New regulatory framework for the Fukushima Daiichi NPP facility

To cope with the Fukushima Daiichi accident, the former regulatory bodies NISA and NRA had taken 'emergency measures' stipulated in Article 64 of the Reactor Regulation Act.

When the Reactor Regulation Act was amended in September, 2012, a new regulatory framework was introduced for the regulation of 'Disaster-Experienced Facilities', such as the Fukushima Daiichi NPP. In this framework, the NRA designates such facilities as 'Specified Nuclear Facilities' by detailing the 'items for which the measures shall be taken for operational safety', based on Article 64–2, Paragraph (1) of the amended Act. In such a case, the licensee is required to submit a plan, referred as the 'Implementation Plan'. Then, the NRA reviews and approves it, and then conducts the regulatory oversight and control according to the Plan.

On 7 November 2012, the NRA designated Fukushima Daiichi NPP as specified nuclear facilities and required TEPCO to submit the Implementation Plan, while detailing the items for which the measures should be taken and the applicable time limit. The major points of the items are as follows: (1) with the goal of completing fuel removal as promptly as possible and reducing risks of the specified nuclear facilities as a whole, thereby ensuring safety on-site and offsite, measures shall be taken promptly and efficiently; (2) regarding Units 1–4, decommissioning measures, including removal and storage of fuel debris from molten cores, shall be completed as early as possible, while ensuring safety in the process; (3) regarding Units 5 and 6, stable cold shutdown conditions shall be maintained; and (4) Workers' exposure doses shall be ascertained and managed.

On 7 December 2012, TEPCO submitted the Implementation Plan to the NRA for review and approval [175]. The plan consisted of seven specific sections corresponding to the measures to be taken, as specified by the NRA, on: the overall process towards decommissioning and risk assessment of the 'specified nuclear facilities'; design and operation of structures, systems and components (SSCs) of the specified nuclear facilities; safety management of the specified nuclear facilities; protective measures for specified nuclear fuel materials; removal of fuel debris and decommissioning; promotion of public understanding of the Implementation Plan; and regulatory inspections based on the Implementation Plan. Upon receipt of the Implementation Plan, the NRA established the Commission on Supervision and Evaluation of the Specified Nuclear Facilities, for oversight of the plan implementation as well as site inspection.

1.6.3.4. New framework for emergency preparedness and response

In conjunction with the establishment of the NRA in September 2012, the Basic Act, the Nuclear Emergency Act and other related laws and regulations were amended. As a result of the revisions of laws and regulations, a new governmental framework for nuclear emergency preparedness was developed on the basis of the experience and lessons learned from the accident at the Fukushima Daiichi NPP [174]. The new framework included:

- Nuclear emergency preparedness has to be addressed and promoted by the entire Government in a consistent manner. In this context, the Nuclear Emergency Preparedness Council, chaired by the Prime Minister, was established within the Cabinet as a standing organization to promote the implementation and coordination of the emergency preparedness actions during normal times [176]. The chairperson of the NRA serves as one of the vice chairpersons of the Council, and the secretariat of the Council is headed by the Minister of Environment.

- The allotment of roles within the NERHQ was clearly defined [174]. The NRA takes responsibility for technical and professional matters concerning the safety of the affected nuclear facility. Arrangements for equipment and materials necessary for coping with the situations at the site and off-site response activities are carried out by other relevant ministries and agencies under the supervision of the head of the NERHQ.
- In line with the enhancement of nuclear emergency response systems, the nuclear emergency preparedness part of the Basic Plan for Emergency Preparedness was revised, incorporating the changed division of responsibilities which resulted from the establishment of the NRA, the crisis management system involving the NRA at the Prime Minister's Office, and clarification of on-site and off-site response activities [174].
- The Nuclear Emergency Preparedness Council approved the Nuclear Emergency Response Manual, which specifies such items as staff deployment and response procedures of the relevant ministries and agencies, including the NRA during an emergency.
- In conjunction with the enforcement of the amended Nuclear Emergency Act, the Cabinet Office revised related ministerial ordinance for the off-site centres and issued complementary guidelines specifying the technical standards for the off-site centres.
- In accordance with the provisions of the amended Nuclear Emergency Act and the newly established Guide for Nuclear Emergency Preparedness and Response, the relevant municipalities revised their regional emergency preparedness plans, which include evacuation plans in case of a nuclear accident.
- Recognizing the need for more realistic emergency response actions as soon as possible in the areas surrounding NPPs, a subcommittee of the former Nuclear Safety Commission started to study the revision of the Guide for Nuclear Emergency Preparedness and Response with the aim of incorporating the lessons learned from the Fukushima Daiichi accident into the Guide. A draft document showing the basic principles of the revision was issued on 1 November 2011 [177]. In the Guide, principles regarding the areas in which emergency preparedness should be concentrated were defined, and new zones, the Precautionary Action Zone and Urgent Protective Action Planning Zone, were proposed to replace the previous Emergency Planning Zone. These arrangements were implemented in the completely revised Guide by the NRA on 31 October 2012. The Guide entered into force on 27 February 2013 [178].

1.6.3.5. Plan for remediation of off-site areas

The Special Act for Decontamination[160] entered into force in August 2011, except for some parts [179].

Decontamination has been conducted according to the basic policy [180] developed from the Special Act for Decontamination, with the goal of reducing, in a phased manner, the areas where the additional annual exposure dose (in addition to natural and medical exposure dose) is higher than 20 mSv. For the Special Decontamination Areas, the Japanese Government prepared the decontamination plan and proceeded with the work according to the Decontamination Roadmap [181].

1.6.3.6. Actions on the health management of residents living nearby

Following the accident, surveys on the health conditions of residents in response to the accident were conducted by Fukushima Prefecture and other relevant organizations. Their respective roles in implementing health management surveys are specified in the Act on Special Measures for

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[160] Titled 'The Act on Special Measures concerning the Handling of Environment Contamination by Radioactive Materials Discharged by the NPS Accident Associated with the Tohoku District off the Pacific Ocean Earthquake that Occurred on March 11, 2011', 30 August 2011.

Fukushima Reconstruction and Revitalization and other related laws and regulations. A team was put together and, after study and deliberations compiled a summary on 19 February 2013. Based on the results of the study by an advisory team, the NRA issued, on 6 March 2013, a set of recommendations on the health management of the residents living nearby.

1.6.3.7. Return of residents

The Government of Japan issued a policy statement on 26 December 2011 to review and rearrange the evacuated areas by the end of March 2012. The policy statement defined basic principles for determining to which zones in the evacuated areas residents would be allowed to return.

Rearrangement of areas to which evacuation was ordered pursuant to the policies mentioned above was completed in August 2013 for Kawauchi Village, Tamura City, Minamisoma City, Iitate Village, Naraha Town, Okuma Town, Katsurao Village, Tomioka Town, Namie Town, Futaba Town and Kawamata Town [182]. The evacuation order was lifted for the Miyakoji district of Tamura City on 1 April 2014 for the first time after the accident. On 1 October 2014, the Government also partially lifted the evacuation in Kawauchi Village which enabled the residents to return.

1.6.3.8. Guidance for the management of decontamination and disposal of waste

The Ministry of the Environment issued guidelines for handling, decontamination, and disposal of contaminated material on 14 December 2011. The guidelines provided a structure for the processing of decontamination wastes [183].

1.6.3.9. Interim storage facilities for decontamination wastes

The interim storage facilities were proposed to be built in the Fukushima Prefecture by the Japanese Government.[161] Borehole drilling investigation has started in some of the candidate areas. The interim storage facilities were planned to include a volume reduction facility, atmospheric and groundwater radiation monitoring facility, information service centre, and an R&D facility for the development and evaluation of effective volume reduction technology [184].

1.6.3.10. Revision of energy policy (Basic Energy Plan) in Japan and the status of NPPs

The Fukushima Daiichi accident resulted in changes in energy policy in Japan as a consequence of widespread and serious concerns over the safety of nuclear power. This necessitated a reconsideration of the feasibility of the large scale nuclear expansion, included in the 2010 Basic Energy Plan [185]. Therefore, the Japanese Government embarked on a comprehensive review of the Basic Energy Plan. Special government advisory committees were established to discuss the revision of the Plan. Then the Energy and Environment Council, a central body in charge of energy policy review in the Government, decided to adopt the Innovative Energy and Environment Strategy, on 14 September 2012, in which it was stated that Japan should seek to end its reliance on nuclear power as soon as possible [186]. However, following the formation of a new Japanese Government and further discussion, the Strategic Policy Committee released a draft recommendation in late 2013 on the Basic Energy Plan, positioning nuclear power as a key energy source while giving top priority to safety based on the lessons learned from the Fukushima Daiichi accident. The Government of Japan published a draft version of the Basic Energy Plan (based on the recommendations of the Committee) on 25 February 2014, which was subsequently submitted for Cabinet Decision [187].

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[161] Consultations with local people in the candidate areas and negotiation with relevant municipalities are currently continuing to obtain acceptance.

In May 2012, the last remaining nuclear plant stopped operation for maintenance, and Japan experienced a ‘zero nuclear’ situation for the first time since nuclear power was introduced in 1966. Although two units of the Ohi NPP, operated by the Kansai Electric Power Company, restarted operation in July 2012, the plants were shut down for regular maintenance in September 2013. The NRA is responsible for conducting safety reviews for permitting the restart of the shutdown NPPs requesting permission. These reviews are based on the new regulatory requirements which include a wide range of safety measures for large scale earthquakes, tsunamis and severe accidents. As of August 2014, power companies had submitted applications to restart 19 nuclear power plants at 12 sites.

1.6.3.11. Investigation and analysis of the accident by the regulatory body

The NRA conducts technical reviews, taking into account the results from both medium and long term investigations of the inside of the damaged units. TEPCO investigated the inside of the Unit 1 containment in October 2012 and investigated the high dose areas within the Unit 3 reactor building by using a robotic camera in November 2012. Investigations by NRA mainly focus on:

- Technical issues identified by the National Diet commission and government committee that need further verification;
- Consequences of the accident and subsequent actions taken for the systems and components, including the reactors;
- Technical issues that need clarification in order to incorporate the lessons into future safety regulations.

TEPCO also continues to conduct further investigations into the inside of the containments and reactor buildings and informs the NRA of the results of these investigations in support of NRA’s efforts.

1.6.4. Other events at the Fukushima Daiichi site following the accident

Following the initial stage of the accident, the situation at the site remained very complex and required the implementation of special controls and monitoring activities in order to maintain stability. The complexity and specialty of the situation at site were underlined by emerging issues and events. Pursuant to Paragraph 1 of Article 25 of the Act on Special Measures for Nuclear Emergency Preparedness, TEPCO is required to report the events at Fukushima Daiichi NPP site that adversely affect the stability of the facilities, such as those which led to the leakage of water containing radioactive materials, to the NRA.

As discussed earlier, the Reactor Regulation Act was amended in September 2012 and a new regulatory framework was introduced for the Fukushima Daiichi NPP site. Based on this new framework, the NRA approved TEPCO’s Implementation Plan on 14 August 2013 [173]. Since then, TEPCO has reported events to the NRA pursuant to the amended Reactor Regulation Act. The following sections outline significant ones of those reported events.

1.6.4.1. Leakage of water containing radioactive material in the Unit 3 turbine building on 14 August 2012

Water containing radioactive material leaked from the line used to transfer water from the turbine building in Unit 4 to the water cleanup systems [188]. A second water leakage occurred in the same transfer line in the Unit 3 turbine building on 15 October, prior to implementation of corrective actions from the 14 August incident.

TEPCO started replacing the original pressure hoses by polyethylene pipes, which were more reliable, and completed all the replacements by June 2013 [189].

1.6.4.2. Fall of a steel beam into the SFP in Unit 3 on 22 September 2012

During debris removal from the upper part of the Unit 3 reactor building, a steel beam (approximately 300 mm × 200 mm × 7 m, and weighing 470 kg) fell into the SFP as workers were trying to clear the debris using a crane [190].

1.6.4.3. Water leakage from the vent line of the SARRY on 20 November 2012

Water leaked from the Simplified Active Water Retrieve and Recovery System (SARRY) vent line running from the high temperature incinerator building to the outside [191]. TEPCO shut down the operation and confirmed that the leakage had stopped. TEPCO evaluated the amount of leaked water from the size of the puddle on the ground (16 m × 11 m × 1 mm) to be approximately 176 L. Chemical analysis of the water showed the following radioactive nuclide concentrations: ^{134}Cs: 3.7×10^2 Bq/cm^3, ^{137}Cs: 6.5×10^2 Bq/cm^3, ^{60}Co: 3.5 Bq/cm^3.

1.6.4.4. Suspension of facility operation due to blackout on 18 March 2013

On 18 March 2013, a blackout occurred in part of the power supply system. As a result, the alternative cooling system for the SFP, the cooling system for the common SFP, part of the gas control system for the Unit 3 containment vessel, the caesium adsorption equipment, and part of the nitrogen gas transfer unit stopped operation.

Investigation discovered charred parts in the makeshift switchboard and the body of a small animal was found on the floor nearby. TEPCO concluded that the animal may have touched the conduction system, causing a short circuit and subsequent blackout.

1.6.4.5. Leakage of contaminated water from the storage tank on 19 August 2013

On 19 August 2013, it was found that water that had accumulated inside the dyke around the contaminated water storage tanks (so-called ‘flange type’ tanks in the H4 tank area) and had leaked outside the dyke through the drain valve [192]. High radiation doses were detected in the leaked puddle of water outside the dyke.

On 28 August 2013, the NRA categorized the leakage of contaminated water as a ‘serious incident’, i.e. Level 3 on the International Nuclear and Radiological Event Scale.

On 6 December 2013, TEPCO submitted a preliminary report to the NRA [193]. According to the report, TEPCO estimated the total amount of the leak to be approximately 300 m^3 since the water level of the tank was about 3 m lower than the presumed initial level (there was no water level measurement device in this tank). The concentrations of radioactive nuclides in the water were ^{134}Cs: 44 Bq/cm^3, ^{137}Cs: 92 Bq/cm^3, ^{125}Sb: 53 Bq/cm^3, total β: 2.0×10^5 Bq/cm^3. Since the amount of collected water from the tank area surrounded by the dyke was approximately 4 m^3 and that of the puddle outside the area was approximately 8 m^3, TEPCO presumed that most of the leaked water had escaped outside and permeated the soil.

Water sampling continued to be carried out not only at the existing ground water bypass and observation wells, but also at ones drilled specifically for the purpose of understanding how the leaked water affected the groundwater and sea water [193].

1.6.4.6. Water leakage from the contaminated water storage tank on 2 October 2013

On 2 October 2013, TEPCO was pumping up the water accumulated inside the dyke at B South Tank area to prepare for the rainfall expected from an approaching typhoon [194, 195]. The pumping was conducted by setting the limit for the maximum water level without quantitatively considering the ground slope.

After completing the pumping operation, the water level of B-A1 tank was 98.6%, but it decreased finally to 98.1% after the leak stopped. The reverse osmosis treated water (desalinated water) inside the tank had leaked from the flange part between the top plate and side plate, which was not leaktight. The estimated amount of the leak was approximately 17 m^3 inside the dyke and approximately 430 L outside the dyke.

1.6.4.7. Leakage of contaminated water from the desalination system on 9 October 2013

On 9 October 2013, water leaked from a pipe joint of the desalination system inside the temporary warehouse [196, 197]. TEPCO confirmed that the water was retained inside the dyke installed in the warehouse, but six out of the eleven workers involved received some internal exposure. The amount of the leak was approximately 11 m^3.

1.6.4.8. Inappropriate transfer of contaminated water on 13 April 2014

On 11 April 2014, TEPCO found that the level of contaminated water in the central waste building had decreased although the contaminated water was not transferred to other places. On 13 April, it was found by TEPCO that some contaminated water in the central waste building was transferred to the incineration building, which had been prepared as an emergency storage facility for contaminated water. TEPCO stopped the transfer of contaminated water [198]. The total amount of inappropriately transferred water was estimated by TEPCO to be approximately 203 m^3.

1.6.4.9. Leakage of contaminated water from the storage tanks on 9 June 2014

On 9 June 2014, the NRA's resident inspectors identified a small leakage of contaminated water near the bolt on the side of each of the two 'notch-tanks' [199]. On the same day, TEPCO transferred the water to the other tanks and then the leakages were stopped. Based on the fact that no anomaly was identified during the last surveillance in February 2014, TEPCO estimated that the total amount of the contaminated water leaked to the outside of the area surrounded by the weir was approximately 3.4 m^3 and its radioactivity was approximately 2.5×10^8 Bq (sum of all β nuclides). Since TEPCO treated the tanks in that area in a similar manner to those for storing the rain water temporarily, the drain valve from the area surrounded by the weir was left open. Actually, however, the radioactivity level of the water was high due to the influence of past leakages.

1.6.5. International actions

Numerous actions were undertaken in response to the Fukushima Daiichi accident by the nuclear international community with the aim of supporting the efforts of TEPCO and the Japanese authorities in the recovery efforts and learning the lessons from the accident to strengthen the safety of nuclear power plants worldwide.

The most relevant of these actions to this report are listed in the following sections.

1.6.5.1. Meetings of the Contracting Parties to the Convention on Nuclear Safety

At the Fifth Review Meeting of the Contracting Parties to the Convention on Nuclear Safety, held from 4 to 14 April 2011, the Parties adopted a statement in which they, inter alia, reaffirmed their commitment to the objectives of the Convention. The Contracting Parties agreed to hold an extraordinary meeting to review and discuss initial analyses of the accident and the effectiveness of the Convention.

Extraordinary Meeting of the Contracting Parties to the Convention on Nuclear Safety

The Extraordinary Meeting was convened at IAEA Headquarters in Vienna from 27 to 31 August 2012. The Contracting Parties discussed: external events; design issues; severe accident management and recovery (on-site); national organizations; emergency preparedness and response; post-accident management (off-site); and international cooperation.

The Contracting Parties also agreed by consensus on a number of concrete actions to enhance the effectiveness of the peer review process. The three underlying guidance documents of the Convention were amended in order to enhance the transparency of the review process, encourage Contracting Parties to refer to the IAEA safety standards in their National Reports; and reinforce efforts for continuous improvement by performing periodic reassessments of safety through periodic safety reviews or alternative methods.[162]

A Working Group on Effectiveness and Transparency was established to report to the Sixth Review Meeting of the Contracting Parties on further actions to strengthen the Convention on Nuclear Safety and on proposals to amend it, where necessary. The Contracting Parties also considered a list of action-oriented objectives for strengthening nuclear safety, which was attached to the Summary Report of the Extraordinary Meeting [203].

Sixth Review Meeting of the Contracting Parties to the Convention on Nuclear Safety

The Sixth Review Meeting of the Contracting Parties to the Convention on Nuclear Safety was held from 24 March to 4 April 2014. During a special session of the meeting, Contracting Parties reported on the actions carried out in light of the Fukushima Daiichi accident. It was noted that, while nuclear safety and arrangements for emergency preparedness and response had improved, more remained to be done. National safety frameworks were being further enhanced, with steps taken to establish the effective independence of regulatory bodies and to update regulations. International cooperation had also increased, with greater participation in peer reviews and exchange of information [204].

The Contracting Parties to the Convention on Nuclear Safety reported the implementation of safety upgrades, including: the introduction of additional means to withstand prolonged loss of power and cooling; enhancement of power systems to improve reliability; re-evaluation of site-specific external natural hazards and multi-unit events; improvements of on-site and off-site emergency control centres to ensure protection from extreme external events and radiation hazards; the strengthening of measures to preserve containment integrity; and improvement of severe accident management provisions and guidelines.

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[162] The Rules of Procedure and Financial Rules [200], the Guidelines regarding the Review Process [201] and the Guidelines regarding the National Reports [202].

The Contracting Parties also adopted proposals to further amend the underlying guidance documents of the Convention and made recommendations for action by the IAEA Secretariat, the Contracting Parties and other organizations.

Finally, the Contracting Parties decided by vote to convene a Diplomatic Conference within one year to consider a proposal by Switzerland to amend Article 18 of the Convention, on the design and construction of both new and existing NPPs.

Diplomatic Conference and the Vienna Declaration on Nuclear Safety

The Diplomatic Conference was convened by the Director General at IAEA Headquarters on 9 February 2015 and attended by 71 Contracting Parties. The Parties unanimously adopted the Vienna Declaration on Nuclear Safety. This Declaration included the following principles for the implementation of the third objective of the Convention, which is to prevent accidents with radiological consequences and to mitigate such consequences should they occur:

> “1. New nuclear power plants are to be designed, sited, and constructed, consistent with the objective of preventing accidents in the commissioning and operation and, should an accident occur, mitigating possible releases of radionuclides causing long-term off site contamination and avoiding early radioactive releases or radioactive releases large enough to require long-term protective measures and actions.
>
> 2. Comprehensive and systematic safety assessments are to be carried out periodically and regularly for existing installations throughout their lifetime in order to identify safety improvements that are oriented to meet the above objective. Reasonably practicable or achievable safety improvements are to be implemented in a timely manner.
>
> 3. National requirements and regulations for addressing this objective throughout the lifetime of nuclear power plants are to take into account the relevant IAEA safety standards and, as appropriate, other good practices as identified *inter alia* in the Review Meetings of the [Convention on Nuclear Safety]” [205].

The Vienna Declaration took into account the significant number of efforts and initiatives at the international, national and regional levels that had taken place since the accident at the Fukushima Daiichi NPP to enhance nuclear safety worldwide.

1.6.5.2. The IAEA Action Plan on Nuclear Safety

The IAEA Ministerial Conference on Nuclear Safety, convened in June 2011 to direct the process of learning and to act upon the lessons learned following the accident at the Fukushima Daiichi NPP, requested the IAEA Director General to prepare a draft Action Plan covering all the relevant aspects relating to nuclear safety, emergency preparedness and response, and radiation protection of people and the environment, as well as the relevant international legal framework. The draft IAEA Action Plan on Nuclear Safety was approved by the Board of Governors in September 2011. The Action Plan was then presented at the regular session of the 2011 IAEA General Conference, where it was unanimously endorsed by Member States [206]. The General Conference subsequently called upon the IAEA Secretariat and Member States to implement the actions as an overarching priority in a comprehensive and coordinated manner [207].

Activities under the Action Plan started immediately after its adoption. The full and effective implementation of the activities in this plan required joint efforts and full commitment by the IAEA Secretariat, Member States and other stakeholders.

Since the adoption of the Action Plan, significant progress has been made in several key areas, such as: assessments of the safety vulnerabilities of NPPs; strengthening of the IAEA's peer review services; review and revision, as necessary, of the relevant IAEA safety standards; improvements in emergency preparedness and response capabilities; capacity building; and enhancing communication and information sharing with Member States, international organizations and the public. Regular progress reports were presented to the IAEA Board of Governors and the IAEA General Conference [208-210].

In the resolution adopting the Action Plan, the IAEA's role in responding to a nuclear emergency was expanded to include providing Member States, international organizations and the general public with timely, clear, factually correct, objective and easily understandable information on its potential consequences. This is to include an analysis of available information and a prognosis of possible scenarios based on the evidence, scientific knowledge and the capabilities of Member States.

A number of international experts meetings (IEMs) were organized in different areas of safety to analyse the technical aspects and to learn the lessons from the Fukushima Daiichi accident. Reports on these key safety areas, including the results of the IEMs, were published by the IAEA (see Table 1.6–1).

Additional reports were prepared in 2013 on the following subjects:

- Preparedness and Response for a Nuclear or Radiological Emergency in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant, based on a series of technical meetings held in 2012–2013 [211].
- Strengthening Regulatory Effectiveness in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant, based on the results of the International Conference on Effective Nuclear Regulatory Systems, Ottawa, Canada, 2013 [212].

TABLE 1.6–1. INTERNATIONAL EXPERTS MEETINGS (IEMS)

Date	Title	Focus
19–22 Mar. 2012	IEM I: Reactor and Spent Fuel Safety in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant [213]	Analyse technical aspects; understand root causes; share lessons from the accident.
18–20 Jun. 2012	IEM II: Enhancing Transparency and Communication Effectiveness in the Event of a Nuclear or Radiological Emergency [214]	Identify and analyse lessons from the accident and discuss best practices for improving the dissemination of information.
4–7 Sep. 2012	IEM III: Protection against Extreme Earthquakes and Tsunamis in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant [215]	Share lessons; exchange information and identify issues to be further investigated on: seismic and tsunami hazard assessment; special flooding issues; uncertainties associated with hazard assessments; approaches to establishing design values; addressing beyond design basis events; safety against earthquakes and tsunamis.
28 Jan. – 1 Feb. 2013	IEM IV: Decommissioning and Remediation after a Nuclear Accident [216]	Examine short term and long term issues for decommissioning of accident damaged facilities; management of radioactive waste arising from a nuclear accident; and remediation of the off-site environment.
21–24 May 2013	IEM V: Human and Organizational Factors in Nuclear Safety in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant [217]	Explore ways to improve nuclear safety culture across a range of key institutions, including operating organizations and regulatory bodies.
17–21 Feb. 2014	IEM VI: Radiation Protection after the Fukushima Daiichi Accident: Promoting Confidence and Understanding [218]	Focus on radiation protection issues highlighted by the Fukushima Daiichi accident and how these could be addressed at both the national and international levels.

TABLE 1.6–1. INTERNATIONAL EXPERTS MEETINGS (IEMS) (cont.)

Date	Title	Focus
17–20 Mar. 2014	IEM VII: Severe Accident Management in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant	Gather and share knowledge and experience gained in the light of the Fukushima Daiichi accident concerning severe accident management (SAM); identify lessons and best practices.
16–20 Feb. 2015	IEM VIII: Strengthening the Effectiveness of Research and Development in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant.	Facilitate the exchange of information arising from new R&D activities undertaken by IAEA Member States, as well as by the OECD Nuclear Energy Agency (OECD/NEA) and other international organizations dealing with severe accidents at NPPs, including those affecting spent fuel pools; further strengthen international collaboration among Member States and international organizations.
20–24 Apr. 2015	IEM IX: Assessment and Prognosis in Response to a Nuclear or Radiological Emergency	Facilitate the exchange of timely, clear, factually correct information during a nuclear or radiological emergency and its potential consequences, including analysis of available information and prognosis of possible scenarios based on the evidence, scientific knowledge and the capabilities of Member States.

1.6.5.3. IAEA peer review and assistance missions

Fact finding expert mission

Based upon an agreement with the Government of Japan, an International Fact Finding Expert Mission was undertaken by experts from the IAEA and Member States from 24 May to 2 June 2011. The mission gathered information for a preliminary assessment of the accident at the Fukushima Daiichi NPP and on events at other sites (Fukushima Daini and Tokai Daini). In addition, generic safety issues associated with natural events were identified that needed further exploration or assessment on the basis of the IAEA safety standards. It aimed to identify initial lessons to be learned from the accident at Fukushima Daiichi and share this information with the worldwide nuclear community. The Mission visited three affected NPPs — Tokai Daini, Fukushima Daini and Fukushima Daiichi to gain an appreciation of the status of the plants and the scale of the damage. The preliminary conclusions and lessons were shared and discussed with Japanese experts and officials and fell into three main areas: external hazards, severe accident management and emergency preparedness [62]. The specific scope of the mission included: external events of natural origin; plant safety assessment and the application of defence in depth; plant response after an earthquake and tsunami; management of a severe accident; management of spent fuel in a severely degraded facility; emergency preparedness and response; and radiological consequences. The mission findings [62] included 15 conclusions and 16 lessons, which were reported to the IAEA Ministerial Conference on Nuclear Safety in June 2011 [62].

Mission on remediation of large contaminated areas off-site the Fukushima Daiichi NPP

An IAEA mission to assist the Japanese Government in remediation of the large contaminated areas around the Fukushima Daiichi NPP took place in Japan with FAO and other international experts on 7–15 October 2011. Its main focus was on the remediation of the affected areas outside the 20 km restricted area [219]. The mission objectives were to: provide assistance to Japan in the plans to manage the remediation of large contaminated areas resulting from the accident at the Fukushima Daiichi NPP; and review remediation related strategies, plans and works, including contamination mapping, undertaken by Japan.

Mission to review NISA's approach to comprehensive assessments for safety of existing power reactor facilities

The IAEA organized a mission from 23 to 31 January, 2012 to review NISA's approach to the comprehensive assessment of the safety of existing power reactor facilities [220]. The scope of the IAEA mission covered NISA's comprehensive safety assessment process in order to identify how it is addresses external hazards, evaluation of safety margins, plant vulnerabilities, and severe accident management. The mission consisted of meetings at NISA's offices in Tokyo and a visit to the Ohi NPP to observe an example of how the comprehensive safety assessment was being implemented by the licensee.

Mission to Onagawa NPP to examine the performance of SSCs following the Great East Japan Earthquake and tsunami

The IAEA conducted a mission between 30 July and 11 August 2012 to the Onagawa NPP to examine the performance of the structures, systems and components (SSCs) of the Onagawa units which were subject to high level of ground motion during and following the earthquake and tsunami [221]. The information gathered was intended to be used to populate a database designed to capture the experience and performance of SSCs during strong earthquakes worldwide.

Peer review mission on the Mid-Term and Long-Term Roadmap

An IAEA Peer Review Mission on the Mid-Term and Long-Term Roadmap towards the Decommissioning Fukushima Daiichi NPP was conducted in Tokyo and in the Fukushima Prefecture from 15 to 22 April 2013 as part one of two consecutive missions on the Roadmap [222]. The objective of the first mission was to undertake an initial review of the Roadmap, including assessments of decommissioning strategy, planning and timing of decommissioning phases, and a review of several specific short term issues and recent challenges. The incidents recently experienced at the site, relating to failures of the power supply and leakages of water from the underground reservoirs, were also included in the review of the specific short term issues.

Mission (follow-up) on remediation of large contaminated areas off-site the Fukushima Daiichi NPP

A follow-up to the October 2011 IAEA mission on Remediation of Large Contaminated Areas Off-Site the Fukushima Daiichi NPP took place again in Tokyo and in the Fukushima Prefecture between 14 and 21 October 2013 at the request of the Government of Japan [223]. The follow-up mission was to evaluate the progress of the ongoing remediation works achieved since the previous mission, as well as to review remediation strategies, plans and works, in view of the advice given in the first mission. Its scope also included the provision of assistance to Japan in assessing the progress made with the remediation of the Special Decontamination Area, which was not included in the first mission in 2011, and the Intensive Contamination Survey Areas. The Mission Team, which included FAO and other international experts, visited the affected areas, including several sites where remediation activities were being conducted.

Expert visits for seawater sampling and analysis

An expert visit was held between 6–12 November 2013. The objectives of the visit were to observe seawater sampling and data analysis in Fukushima (7 and 8 November 2013) and to meet the relevant Japanese authorities in Tokyo to collect information on marine monitoring conducted by Japan under its Sea Area Monitoring Plan.

Expert missions on marine monitoring confidence building and data quality assurance were held between 10–16 September 2014 and 4–14 November 2014. The missions focused on availability of marine monitoring results.

Peer review mission (follow-up) on the Mid-Term and Long-Term Roadmap

A second IAEA mission on the Mid-Term and Long-Term Roadmap towards the Decommissioning of TEPCO's Fukushima Daiichi NPP Units 1–4 took place in Tokyo and at the Fukushima NPP from 25 November to 4 December 2013 [224]. The focus of this second IAEA mission was to provide a more detailed and holistic review of the revised Roadmap and mid-term challenges, including a review of specific topics agreed and defined in the first IAEA mission, such as removal of spent fuel from storage pools, removal of fuel debris from the reactors, management of contaminated water, monitoring of marine water, management of radioactive waste, maintenance and enhancement of stability and reliability of structures, systems and components, and R&D relevant to pre-decommissioning and decommissioning activities. The IAEA team also met with the NRA to discuss issues concerning marine monitoring.

Following the recommendation of the second decommissioning mission, projects were started to enhance transparency and to provide independent assessments of monitoring of the marine environment by Japan. Proficiency tests were conducted at the IAEA Environment Laboratories in Monaco to monitor the performance and analytical capabilities of participating laboratories. The results of the marine monitoring programme are regularly updated on the IAEA web site.

Fukushima Ministerial Conference on Nuclear Safety

In December 2012, the Government of Japan organized a Ministerial Conference in the Fukushima Prefecture, co-sponsored by the IAEA, with the principal objective of contributing to strengthening nuclear safety worldwide [225]. The conference provided an opportunity to share with the international community further knowledge and lessons learned from the accident and to discuss the progress of international efforts aimed at strengthening nuclear safety, including progress in the implementation of the Action Plan.

Discussions included: levels of radiation at Fukushima Daiichi; post-accident challenges for decommissioning and remediation; and the status of damage and recovery in the areas around the plant. The conference highlighted the importance of taking actions on the basis of scientific and factual information in the event of a nuclear or radiological emergency, and of enhancing international cooperation.

Memorandum of cooperation with Fukushima Prefecture

A memorandum of cooperation between the IAEA and Fukushima Prefecture was signed in December 2012 [226]. On the basis of this memorandum, practical arrangements on cooperation in the areas of radiation monitoring and remediation [227], human health [228], and emergency preparedness and response [229] were signed, with Fukushima Prefecture, the Fukushima Medical University and the Ministry of Foreign Affairs of Japan, respectively.

An IAEA Response and Assistance Network (RANET) Capacity Building Centre was designated in the city of Fukushima in May 2013. The Centre is used for a range of IAEA activities aimed at enhancing capacity for emergency preparedness and response, both in Japan and worldwide. A number of training workshops were held at the Centre dealing with monitoring during a nuclear and radiological emergency, notification, reporting and requesting assistance, and emergency preparedness and response.

1.6.5.4. Assistance from other international organizations

The OECD/NEA organized a mission to Tokyo from 16 to 18 November 2011 to discuss the complementary safety analyses to be performed for the Japanese NPPs. The OECD/NEA team of international experts met with NISA and JNES to foster a better understanding of post-Fukushima national safety reviews (or ‘stress tests’) conducted by other OECD/NEA member countries [230].

The Institute of Nuclear Power Operations (INPO) and the World Association of Nuclear Operators (WANO) jointly conducted an independent review of the accident in April 2012, at the request of TEPCO, to identify and share operational and organizational lessons with other nuclear operating organizations/companies. The review also included an investigation and analysis of the response to the earthquake and tsunami at the Fukushima Daini NPP as a source for learning additional lessons. INPO published a Special Report on the Nuclear Accident at the Fukushima Daiichi Nuclear Power Plant in 2011 and a document called Lessons Learned from the Nuclear Accident at the Fukushima Daiichi Nuclear Power Station in 2012 [231, 232]. WANO also conducted a shutdown safety review for the Fukushima Daiichi NPP and a corporate peer review for TEPCO in October 2013.

Following the Fukushima Daiichi accident, the OECD/NEA initiated a benchmark study to investigate and reconstruct the accident sequence in order to identify improvements for severe accident management. The Benchmark Study of the Accident at the Fukushima Daiichi Nuclear Power Plant (BSAF), led by the Japan Atomic Energy Agency (JAEA), has two main objectives: to analyse and evaluate the accident progression and current status within the RPV and PCV of Fukushima Daiichi Units 1–3 to assist with future investigation and ultimately with fuel removal at those units; and to improve the methods and models of computer codes to reduce uncertainties in severe accidents analysis and to validate them using actual data from Fukushima Daiichi NPP Units 1–3 [230]. The participants include several organizations from France, Germany, Japan, the Republic of Korea, the Russian Federation, Spain, Switzerland and the USA.

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CONTENTS OF CD-ROM

The following annexes to Technical Volume 1 are included on the attached CD-ROM:

Annex I: Unit 1 sequence of events

Annex II: Unit 2 sequence of events

Annex III: Unit 3 sequence of events

ABBREVIATIONS

ABWR	advanced boiling water reactor
ADS	automatic depressurization system
AEC	Atomic Energy Commission
AESJ	Atomic Energy Society of Japan
ALPS	Advanced Liquid Processing System
AM	accident management
AMG	accident management guideline
AMTA	Ageing Management Technical Assessment
ANRE	Agency for Natural Resources and Energy
AO	auxiliary operator
AOP	abnormal operating procedure
AOV	air operated valve
APD	alarm pocket dosimeter
APWR	advanced pressurized water reactor
ATWS	anticipated transient without scram
BDBA	beyond design basis accident
Bq	becquerel
BSAF	Benchmark Study of the Accident at the Fukushima Daiichi Nuclear Power Plant
BTC	BWR Operator’s Training Centre Corporation
BWR	boiling water reactor
BWROG	BWR Owners’ Group
CAMS	containment atmospheric monitoring system
CCS	containment cooling system
CMC	Crisis Management Centre
CR	control rod
CRD	control rod drive
CRIEPI	Central Research Institute of the Electric Power Industry
CS	core spray
CSC	Convention on Supplementary Compensation for Nuclear Damage
CST	condensate storage tank
DBA	design basis accident
DC	direct current
DDFP	diesel driven fire pump
DG	diesel generator
DGSW	diesel generator seawater
DSS	Deputy Shift Supervisor
DW	dry well
ECCS	emergency core cooling system
EDG	emergency diesel generator
EECW	emergency equipment cooling water
ENAC	Early Notification and Assistance Conventions
ENATOM	Emergency Notification and Assistance Technical Operations Manual
EOP	emergency operating procedure
EOT	Emergency Operations Team
EP	Establishment Permit
EPRI	Electric Power Research Institute
ERC	Emergency Response Centre
ETS	education and training system
FACT	Fukushima Accident Coordination Team
FAO	Food and Agriculture Organization of the United Nations
FBR	fast breeder reactor
FCS	flammability control system

FEPC	Federation of Electric Power Companies
FNEP	Framework for Nuclear Energy Policy
FP	fire protection
FPC	fuel pool cooling
FSAR	Final Safety Analysis Report
FSAT	Food Safety Assessment Team
FW	fresh water
GCR	gas cooled reactor
GE	General Electric
HERO	High-performance ALPS
HO	hydraulic operated
HPCI	high pressure coolant injection
HPCS	high pressure core spray
HQ	headquarters
HVAC	heating, ventilating and air-conditioning
IACRNE	Inter-Agency Committee on Radiological and Nuclear Emergencies
IATA	International Air Transport Association
IC	isolation condenser
ICAO	International Civil Aviation Organization
ICRP	International Commission on Radiological Protection
IEM	International Experts Meeting
IES	Incident and Emergency System
IMO	International Maritime Organization
INES	International Nuclear and Radiological Event Scale
INPO	Institute of Nuclear Power Operations
INSAG	International Nuclear Safety Group
IRRS	Integrated Regulatory Review Service
IRS	International Reporting System
ISO	International Organization for Standardization
ISSC	International Seismic Safety Centre
JAEA	Japan Atomic Energy Agency
JAERI	Japan Atomic Energy Research Institute
JAIF	Japan Atomic Industrial Forum
JANSI	Japan Nuclear Safety Institute
JANTI	Japan Nuclear Technology Institute
JAPC	Japan Atomic Power Company
JBOG	Japanese BWR Owners’ Group
JCO	Japan Nuclear Fuels Conversion Company
JEA	Japan Electric Association
JMA	Japan Meteorological Agency
JNES	Japan Nuclear Energy Safety Organization
JPLAN	Joint Radiation Emergency Management Plan of the International Organizations
JSCE	Japan Society of Civil Engineers
JSME	Japan Society of Mechanical Engineers
JST	Japan Standard Time
KAERI	Korea Atomic Energy Research Institute
KINS	Korea Institute of Nuclear Safety
LBLOCA	large break loss of coolant accident
LOCA	loss of coolant accident
LOOP	loss of off-site power
LPCI	low pressure coolant injection
LPCS	low pressure core spray
LTMP	long term maintenance programme
LUHS	loss of ultimate heat sink
LWR	light water reactor

M/C	metal clad switch gear
MCC	motor control centre
MCR	main control room
METI	Ministry of Economy, Trade and Industry
MEXT	Ministry of Education, Culture, Sports, Science and Technology
MITI	Ministry of International Trade and Industry
MO	motor operated
MOE	Ministry of the Environment
MOFA	Ministry of Foreign Affairs
MOV	motor operated valve
MOX	mixed oxide
MP	measuring point
MP	monitoring post
MSIV	main steam isolation valve
MUWC	make-up water condensate
NERHQ	Nuclear Emergency Response Headquarters
NIRS	National Institute of Radiological Sciences
NISA	Nuclear and Industrial Safety Agency
NPP	nuclear power plant
NPS	nuclear power station
NRA	Nuclear Regulation Authority
NRC	United States Nuclear Regulatory Commission
NSC	Nuclear Safety Commission
NS-net	Nuclear Safety Network
NTC	Nuclear Power Training Centre Ltd
OECD	Organisation for Economic Co-operation and Development
OECD/NEA	OECD Nuclear Energy Agency
OFC	Off-site Centre
OLCs	operational limits and conditions
OP	Onahama Port
OSART	Operational Safety Review Team
P/C	power centre
PA	public address
PARV	power-actuated relief valve
PBq	peta becquerel
PCIS	primary containment isolation signal
PCV	primary containment vessel
PSA	probabilistic safety assessment
PSR	periodic safety review
PWR	pressurized water reactor
QMS	quality management system
R&D	research and development
RANET	Response and Assistance Network
RAP	Radiological Assistance Program
RB	reactor building
RCIC	reactor core isolation cooling
RCS	reactor coolant system
RHR	residual heat removal
RHRC	residual heat removal and cooling system
RHRS	residual heat removal and cooling seawater
RO	reactor operator
RPS	reactor protection system
RPV	reactor pressure vessel
S/S	site simulator
SAM	severe accident management

SAR	safety analysis report
SARRY	Simplified Active Water Retrieve and Recovery System
SB	service building
SBO	station blackout
SC	suppression chamber
SDF	Self-Defense Force
SFP	spent fuel pool
SGTS	standby gas treatment system
SHC	shutdown cooling
SLC	standby liquid control
SO	senior operator
SOP	Severe Accident Operating Procedure
SRO	senior reactor operator
SRV	safety relief valve
SS	shift superintendent
SS	shift supervisor
SSCs	structures, systems and components
SSO	system senior operator
STA	Science and Technology Agency
SV	safety valve
SW	sea water
TAF	top of active fuel
TB	turbine building
TENPES	Thermal and Nuclear Power Engineering Society
TEPCO	Tokyo Electric Power Company
TSC	technical support centre
UHS	ultimate heat sink
WANO	World Association of Nuclear Operators
WHO	World Health Organization
WMO	World Meteorological Organization
WR	wide range
ZPGA	zero period ground acceleration

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Working Group (WG) meetings

18 March 2013
Initial meeting of the WG Co-Chairs, Vienna

21–22 March 2013
1st meeting of all WGs, Vienna

12–14 June 2013
2nd meeting of all WGs, Vienna

12–13 September 2013
3rd meeting of WGs 1 and 2, Vienna

9–13 December 2013
4th meeting of all WGs, Vienna

10–14 February 2014
5th meeting of all WGs, Vienna

14–17 April 2014
6th meeting of WGs 1, 2 and 3, Vienna

International Technical Advisory Group (ITAG) meetings

21–22 March 2013
1st ITAG meeting, Vienna

10 June 2013
1st Joint ITAG/Co-Chairs meeting, Vienna

11 June 2013
2nd ITAG meeting, Vienna

6 December 2013
2nd Joint ITAG/Co-Chairs meeting, Vienna

7 May 2014
3rd Joint ITAG/Co-Chairs meeting, Vienna

23–24 October 2014
4th Joint ITAG/Co-Chairs meeting, Vienna

23–24 February 2015
5th Joint ITAG/Co-Chairs meeting, Vienna

Consultants services (CS) meetings

6–7 August 2013
CS on Source Term, Vienna

Bilateral meetings in Japan

20–24 January 2014
CS to Discuss Issues Related to Regulatory Activities, Operating Experience and Waste Management Topics in Connection with the Preparation of the IAEA Report

23 January 2014
Meetings with Reconstruction Agency and Team in Charge of Assisting the Lives of Disaster Victims — Cabinet Office

24 January 2014
Meetings with the Institute of Energy Economics of Japan

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