The Fukushima Daiichi Accident

Report by the Director General
This Report presents an assessment of the causes and consequences of the accident at the Fukushima Daiichi nuclear power plant in Japan that began on 11 March 2011. Caused by a huge tsunami that followed a massive earthquake, it was the worst accident at a nuclear plant since the Chernobyl disaster in 1986.

The Report considers human, organizational and technical factors and aims to provide an understanding of what happened, and why, so that the necessary lessons learned can be acted upon by governments, regulators and nuclear power plant operators throughout the world. Measures taken in response to the accident, both in Japan and internationally, are also examined.

The immense human impact of the Fukushima Daiichi accident should not be forgotten. More than one hundred thousand people were evacuated because of the release of radionuclides to the environment. At the time of writing, in 2015, many of them were still unable to return to their homes.

I visited the Fukushima Daiichi plant a few months after the accident and saw for myself the powerful and destructive impact of the tsunami. It was a shocking and sobering experience.

But I was deeply impressed by the courage and dedication of those workers and managers who remained at their posts after the tsunami struck and who struggled, in appalling conditions, to bring the stricken reactors under control. They had to improvise a response in circumstances for which they had not been trained, often lacking appropriate equipment. They deserve our respect and admiration.

A major factor that contributed to the accident was the widespread assumption in Japan that its nuclear power plants were so safe that an accident of this magnitude was simply unthinkable. This assumption was accepted by nuclear plant operators and was not challenged by regulators or by the government. As a result, Japan was not sufficiently prepared for a severe nuclear accident in March 2011.

The Fukushima Daiichi accident exposed certain weaknesses in Japan’s regulatory framework. Responsibilities were divided among a number of bodies and it was not always clear where authority lay.

There were also certain weaknesses in plant design, in emergency preparedness and response arrangements and in planning for the management of a severe accident. There was an assumption that there would never be a loss of all electrical power at a nuclear power plant for more than a short period. The possibility of several reactors at the same facility suffering a crisis at the same time was not considered. And insufficient provision was made for the possibility of a nuclear accident occurring at the same time as a major natural disaster.

Since the accident, Japan has reformed its regulatory system to better meet international standards. It gave regulators clearer responsibilities and greater authority. The new regulatory framework will be reviewed by international experts through an IAEA Integrated Regulatory
Review Service mission. Emergency preparedness and response arrangements have also been strengthened.

Other countries responded to the accident with measures that included carrying out “stress tests” to reassess the design of nuclear power plants against site specific extreme natural hazards, installing additional backup sources of electrical power and supplies of water, and strengthening the protection of plants against extreme external events.

Although nuclear safety remains the responsibility of each individual country, nuclear accidents can transcend national borders. The Fukushima Daiichi accident underlined the vital importance of effective international cooperation. The IAEA is where most of that cooperation takes place. Our Member States adopted the IAEA Action Plan on Nuclear Safety a few months after the accident and have been implementing its far-reaching provisions to improve global nuclear safety.

The IAEA, which provided technical support and expertise to Japan after the accident and shared information about the unfolding crisis with the world, has reviewed and improved its own arrangements for responding to a nuclear emergency. Our role during a nuclear emergency has been expanded to include providing analysis of its potential consequences and presenting possible scenarios on how a crisis could develop.

IAEA safety standards embody an international consensus on what constitutes a high level of safety. They were reviewed after the accident by the Commission on Safety Standards. A few amendments were proposed and adopted. I encourage all countries to fully implement IAEA safety standards.

IAEA peer reviews have a key role to play in global nuclear safety, enabling countries to benefit from the independent insights of leading international experts, based on the common reference frame of the IAEA safety standards. They address issues such as operational safety at nuclear power plants, the effectiveness of nuclear regulators and the design of nuclear power plant sites against specific hazards. We have strengthened our peer review programme since the accident and will continue to do so.

I am confident that the legacy of the Fukushima Daiichi accident will be a sharper focus on nuclear safety everywhere. I have seen improvements in safety measures and procedures in every nuclear power plant that I have visited. There is a widespread recognition that everything humanly possible must be done to ensure that no such accident ever happens again. This is all the more essential as global use of nuclear power is likely to continue to grow in the coming decades.

There can be no grounds for complacency about nuclear safety in any country. Some of the factors that contributed to the Fukushima Daiichi accident were not unique to Japan. Continuous questioning and openness to learning from experience are key to safety culture and are essential for everyone involved in nuclear power. Safety must always come first.

I express my gratitude to the experts from many countries and international organizations who contributed to this Report, and to my colleagues at the IAEA who drafted and reviewed it. I hope that the Report, and the accompanying Technical Volumes, will prove valuable to all countries that use, or plan to use, nuclear power in their continuous efforts to improve safety.
The Fukushima Daiichi Accident
Report by the Director General

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THE FUKUSHIMA DAIICHI ACCIDENT

EXECUTIVE SUMMARY

The Great East Japan Earthquake occurred on 11 March 2011. It was caused by a sudden release of energy at the interface where the Pacific tectonic plate forces its way under the North American tectonic plate. A section of the Earth's crust, estimated to be about 500 km in length and 200 km wide, was ruptured, causing a massive earthquake with a magnitude of 9.0 and a tsunami which struck a wide area of coastal Japan, including the north-eastern coast, where several waves reached heights of more than ten metres. The earthquake and tsunami caused great loss of life and widespread devastation in Japan. More than 15 000 people were killed, over 6000 were injured and, at the time of writing of this report, around 2500 people were still reported to be missing. Considerable damage was caused to buildings and infrastructure, particularly along Japan's north-eastern coast.

At the Fukushima Daiichi nuclear power plant, operated by the Tokyo Electric Power Company (TEPCO), the earthquake caused damage to the electric power supply lines to the site and the tsunami caused substantial destruction of the operational and safety infrastructure on the site. The combined effect led to the loss of off-site and on-site electrical power. This resulted in the loss of the cooling function at the three operating reactor units as well as at the spent fuel pools. The four other nuclear power plants along the coast were also affected to different degrees by the earthquake and tsunami. However, all operating reactor units at these plants were safely shut down.

Despite the efforts of the operators at the Fukushima Daiichi nuclear power plant to maintain control, the reactor cores in Units 1–3 overheated, the nuclear fuel melted, and the three containment vessels were breached. Hydrogen was released from the reactor pressure vessels, leading to explosions inside the reactor buildings in Units 1, 3 and 4 that damaged structures and equipment and injured personnel. Radionuclides were released from the plant to the atmosphere and were deposited on land and on the ocean. There were also direct releases into the sea.

People within a radius of 20 km from the site and in other designated areas were evacuated, and those within a radius of 20–30 km were instructed to shelter before later being advised to voluntarily evacuate. Restrictions were placed on the distribution and consumption of food and the consumption of drinking water. At the time of writing, many people are still living outside the areas from which they were evacuated.

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1 March 2015.
2 Of the six units of the Fukushima Daiichi nuclear power plant, Units 1, 2 and 3 were operating at the time of the accident; Units 4, 5 and 6 were in planned shutdown.
3 Higashidori, Onagawa, Fukushima Daini and Tokai Daini nuclear power plants.
Following stabilization of the conditions of the reactors at the Fukushima Daiichi nuclear power plant, work to prepare for their eventual decommissioning began. Efforts toward the recovery of the areas affected by the accident, including remediation and the revitalization of communities and infrastructure, began in 2011.

In the immediate aftermath of the accident, the IAEA discharged its emergency response role. It activated its Incident and Emergency System, coordinated the inter-agency response, and initiated a series of briefings with Member States and the media.

The Director General visited Japan immediately and the IAEA dispatched several missions to Japan, including an international fact finding mission and peer review missions on decommissioning and remediation.

The IAEA organized an International Ministerial Conference on Nuclear Safety in June 2011 which resulted in a Ministerial Declaration on Nuclear Safety. This declaration 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 Ministerial Declaration also requested the Director General to prepare a draft IAEA Action Plan on Nuclear Safety (the Action Plan), in consultation with Member States. The Action Plan, which defined a programme of work to strengthen the global nuclear safety framework, was unanimously endorsed by the 55th IAEA General Conference in 2011.

The IAEA also undertook cooperative activities in Fukushima through a memorandum of cooperation between the IAEA and the Fukushima Prefecture. This provided the basis for cooperation on radiation monitoring and remediation, human health, and emergency preparedness and response.

The IAEA also facilitated and organized a number of international conferences and meetings of its Member States and the Contracting Parties to the Convention on Nuclear Safety. Many of these activities took place under the Action Plan.

Since the accident at the Fukushima Daiichi nuclear power plant, there have been many analyses of its causes and consequences, as well as detailed considerations of its implications for nuclear safety, by IAEA Member States and international organizations and by States party to international nuclear safety instruments, in particular the Convention on Nuclear Safety. An extraordinary meeting of the Contracting Parties to the Convention on Nuclear Safety was held in August 2012 to review and discuss the initial analyses of the accident and the effectiveness of the Convention.

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4 On 16 December 2011, the Government-TEPCO Integrated Response Office announced that the conditions for a 'cold shutdown state' had been achieved in Units 1–3. The term 'cold shutdown state' was defined by the Government of Japan at the time specifically for the Fukushima Daiichi nuclear power plant. Its definition differs from the terminology used by the IAEA and others.

5 The Action Plan defined a programme of work to strengthen the global nuclear safety framework. The Action Plan 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 detail, see Section 6.1.
The Contracting Parties to the Convention on Nuclear Safety at the 6th Review Meeting in March-April 2014 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.

In February 2015, the Contracting Parties to the Convention on Nuclear Safety, at a Diplomatic Conference convened by the IAEA Director General, adopted the Vienna Declaration on Nuclear Safety which included 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.

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 would be “an authoritative, factual and balanced assessment, addressing the causes and consequences of the accident, as well as lessons learned”.

The report on the Fukushima Daiichi accident 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 of the report. Additional internal and external review mechanisms were also instituted.

This 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 Report provides a description of the accident and its causes, evolution and consequences, based on the evaluation of data and information from a large number of sources available up to March 2015, including the results of the work carried out in implementing the Action Plan, and it highlights the main observations and lessons. Significant amounts of data were provided by the Government of Japan and other organizations in Japan.

NUCLEAR SAFETY CONSIDERATIONS

Vulnerability of the plant to external events

The earthquake on 11 March 2011 caused vibratory ground motions that shook the plant structures, systems and components. It was followed by a series of tsunami waves, one of which inundated the site. Both the recorded ground motions and the heights of the tsunami
waves significantly exceeded the assumptions of hazards that had been made when the plant was originally designed. The earthquake and the associated tsunami impacted on multiple units at the Fukushima Daiichi nuclear power plant.

The seismic hazard and tsunami waves considered in the original design were evaluated mainly on the basis of historical seismic records and evidence of recent tsunamis in Japan. This original evaluation did not sufficiently consider tectonic-geological criteria and no re-evaluation using such criteria was conducted.

Prior to the earthquake, the Japan Trench was categorized as a subduction zone with a frequent occurrence of magnitude 8 class earthquakes; an earthquake of magnitude 9.0 off the coast of Fukushima Prefecture was not considered to be credible by Japanese scientists. However, similar or higher magnitudes had been registered in different areas in similar tectonic environments in the past few decades.

There were no indications that the main safety features of the plant were affected by the vibratory ground motions generated by the earthquake on 11 March 2011. This was due to the conservative approach to earthquake design and construction of nuclear power plants in Japan, resulting in a plant that was provided with sufficient safety margins. However, the original design considerations did not provide comparable safety margins for extreme external flooding events, such as tsunamis.

The vulnerability of the Fukushima Daiichi nuclear power plant to external hazards had not been reassessed in a systematic and comprehensive manner during its lifetime. At the time of the accident, there were no regulatory requirements in Japan for such reassessments and relevant domestic and international operating experience was not adequately considered in the existing regulations and guidelines. The regulatory guidelines in Japan on methods for dealing with the effects of events associated with earthquakes, such as tsunamis, were generic and brief and did not provide specific criteria or detailed guidance.

Before the accident, the operator had conducted some reassessments of extreme tsunami flood levels, using a consensus based methodology developed in Japan in 2002, which had resulted in values higher than the original design basis estimates. Based on the results, some compensatory measures were taken, but they proved to be insufficient at the time of the accident.

In addition, a number of trial calculations were performed by the operator before the accident, using wave source models or methodologies that went beyond the consensus based methodology. Thus, a trial calculation using the source model proposed by the Japanese Headquarters for Earthquake Research Promotion in 2002, which used the latest information and took a different approach in its scenarios, envisaged a substantially larger tsunami than that provided for in the original design and in estimates made in previous reassessments. At the time of the accident, further evaluations were being conducted, but in the meantime, no additional compensatory measures were implemented. The estimated values were similar to the flood levels recorded in March 2011.

Worldwide operating experience has shown instances where natural hazards have exceeded the design basis for a nuclear power plant. In particular, the experience from some of these events demonstrated the vulnerability of safety systems to flooding.
The assessment of natural hazards needs to be sufficiently conservative. The consideration of mainly historical data in the establishment of the design basis of nuclear power plants is not sufficient to characterize the risks of extreme natural hazards. Even when comprehensive data are available, due to the relatively short observation periods, large uncertainties remain in the prediction of natural hazards.

The safety of nuclear power plants needs to be re-evaluated on a periodic basis to consider advances in knowledge, and necessary corrective actions or compensatory measures need to be implemented promptly.

The assessment of natural hazards needs to consider the potential for their occurrence in combination, either simultaneously or sequentially, and their combined effects on a nuclear power plant. The assessment of natural hazards also needs to consider their effects on multiple units on a nuclear power plant site.

Operating experience programmes need to include experience from both national and international sources. Safety improvements identified through operating experience programmes need to be implemented promptly. The use of operating experience needs to be evaluated periodically and independently.

Application of the defence in depth concept

Defence in depth is a concept that has been applied to ensure the safety of nuclear installations since the start of nuclear power development. Its objective is to compensate for potential human and equipment failures by means of several levels of protection. Defence is provided by multiple and independent means at each level of protection.

The design of the Fukushima Daiichi nuclear power plant provided equipment and systems for the first three levels of defence in depth: (1) equipment intended to provide reliable normal operation; (2) equipment intended to return the plant to a safe state after an abnormal event; and (3) safety systems intended to manage accident conditions. The design bases were derived using a range of postulated hazards; however, external hazards such as tsunamis were not fully addressed. Consequently, the flooding resulting from the tsunami simultaneously challenged the first three protective levels of defence in depth, resulting in common cause failures of equipment and systems at each of the three levels.

The common cause failures of multiple safety systems resulted in plant conditions that were not envisaged in the design. Consequently, the means of protection intended to provide the fourth level of defence in depth, that is, prevention of the progression of severe accidents and mitigation of their consequences, were not available to restore the reactor cooling and to maintain the integrity of the containment. The complete loss of power, the lack of information on relevant safety parameters due to the unavailability of the necessary instruments, the loss of control devices, and the insufficiency of operating procedures made it impossible to arrest the progression of the accident and to limit its consequences.
The failure to provide sufficient means of protection at each of level of defence in depth levels resulted in severe reactor damage in Units 1, 2 and 3 and in significant radioactive releases from these units.

— The defence in depth concept remains valid, but implementation of the concept needs to be strengthened at all levels by adequate independence, redundancy, diversity and protection against internal and external hazards. There is a need to focus not only on accident prevention, but also on improving mitigation measures.

— Instrumentation and control systems that are necessary during beyond design basis accidents need to remain operable in order to monitor essential plant safety parameters and to facilitate plant operations.

Assessment of the failure to fulfil fundamental safety functions

The three fundamental safety functions important for ensuring safety are: the control of reactivity in the nuclear fuel; the removal of heat from the reactor core and spent fuel pool; and the confinement of radioactive material. Following the earthquake, the first fundamental safety function, control of reactivity, was fulfilled in all six units at the Fukushima Daiichi nuclear power plant.

The second fundamental safety function — removing heat from the reactor core and the spent fuel pool — could not be maintained because the operators were deprived of almost all means of control over the reactors of Units 1, 2 and 3, and the spent fuel pools as a result of the loss of most of the AC and DC electrical systems. The loss of the second fundamental safety function was, in part, due to the failure to implement alternative water injection because of delays in depressurizing the reactor pressure vessels. Loss of cooling led to overheating and melting of the fuel in the reactors.

The confinement function was lost as a result of the loss of AC and DC power, which rendered the cooling systems unavailable and made it difficult for the operators to use the containment venting system. Venting of the containment was necessary to relieve pressure and prevent its failure. The operators were able to vent Units 1 and 3 to reduce the pressure in the primary containment vessels, however, this resulted in radioactive releases to the environment. Even though the containment vents for Units 1 and 3 were opened, the primary containment vessels for Units 1 and 3 eventually failed. Containment venting for Unit 2, was not successful, and the containment failed, resulting in radioactive releases.

— Robust and reliable cooling systems that can function for both design basis and beyond design basis conditions need to be provided for the removal of residual heat.

— There is a need to ensure a reliable confinement function for beyond design basis accidents to prevent significant release of radioactive material to the environment.

Assessment of beyond design basis accidents and accident management
Safety analyses conducted during the licensing process of the Fukushima Daiichi nuclear power plant, and during its operation, did not fully address the possibility of a complex sequence of events that could lead to severe reactor core damage. In particular, the safety analyses failed to identify the vulnerability of the plant to flooding and weaknesses in operating procedures and accident management guidelines. The probabilistic safety assessments did not address the possibility of internal flooding, and the assumptions regarding human performance for accident management were optimistic. Furthermore, the regulatory body had imposed only limited requirements for operators to consider the possibility of severe accidents.

The operators were not fully prepared for the multi-unit loss of power and the loss of cooling caused by the tsunami. Although TEPCO had developed severe accident management guidelines, they did not cover this unlikely combination of events. Operators had therefore not received appropriate training, had not taken part in relevant severe accident exercises, and the equipment available to them was not adequate in the degraded plant conditions.

- Comprehensive probabilistic and deterministic safety analyses need to be performed to confirm the capability of a plant to withstand applicable beyond design basis accidents and to provide a high degree of confidence in the robustness of the plant design.

- Accident management provisions need to be comprehensive, well designed and up to date. They need to be derived on the basis of a comprehensive set of initiating events and plant conditions and also need to provide for accidents that affect several units at a multi-unit plant.

- Training, exercises and drills need to include postulated severe accident conditions to ensure that operators are as well prepared as possible. They need to include the simulated use of actual equipment that would be deployed in the management of a severe accident.

Assessment of regulatory effectiveness

The regulation of nuclear safety in Japan at the time of the accident was performed by a number of organizations with different roles and responsibilities and complex interrelationships. It was not fully clear which organizations had the responsibility and authority to issue binding instructions on how to respond without delay to safety issues.

The regulatory inspection programme was rigidly structured, which reduced the regulatory body’s ability to verify safety at the proper times and to identify potential new safety issues.

The regulations, guidelines and procedures in place at the time of the accident were not fully in line with international practice in some key areas, most notably in relation to periodic safety reviews, re-evaluation of hazards, severe accident management and safety culture.

- In order to ensure effective regulatory oversight of the safety of nuclear installations, it is essential that the regulatory body is independent and possesses legal authority, technical competence and a strong safety culture.
Assessment of human and organizational factors

Before the accident, there was a basic assumption in Japan that the design of nuclear power plants, and the safety measures that had been put in place, were sufficiently robust to withstand external events of low probability and high consequences.

Because of the basic assumption that nuclear power plants in Japan were safe, there was a tendency for organizations and their staff not to challenge the level of safety. The reinforced basic assumption amongst the stakeholders about the robustness of the technical design of nuclear power plants resulted in a situation where safety improvements were not introduced promptly.

The accident at the Fukushima Daiichi nuclear power plant showed that, in order to better identify plant vulnerabilities, it is necessary to take an integrated approach that takes account of the complex interactions between people, organizations and technology.

- In order to promote and strengthen safety culture, individuals and organizations need to continuously challenge or re-examine the prevailing assumptions about nuclear safety and the implications of decisions and actions that could affect nuclear safety.

- A systemic approach to safety needs to consider the interactions between human, organizational and technical factors. This approach needs to be taken through the entire life cycle of nuclear installations.

EMERGENCY PREPAREDNESS AND RESPONSE

Initial response in Japan to the accident

At the time of the accident, separate arrangements were in place to respond to nuclear emergencies and natural disasters at the national and local levels. There were no coordinated arrangements for responding to a nuclear emergency and a natural disaster occurring simultaneously.

The arrangements to respond to nuclear emergencies envisaged that, following the detection of relevant adverse conditions at a nuclear power plant (e.g. loss of all AC power supplies for more than five minutes or loss of all capabilities to cool the reactor), a notification would be sent from the plant to local and national governments. The national government would then assess and determine whether the situation was to be categorized as a ‘nuclear emergency’6. If the situation was categorized as a nuclear emergency, a declaration to that effect would be issued at the national level, and decisions about necessary protective actions would be taken on the basis of dose projections.

Based on a report from the Fukushima Daiichi nuclear power plant, the Prime Minister declared a nuclear emergency on the evening of 11 March and issued orders for protective

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6 The Act on Special Measures Concerning Nuclear Emergency Preparedness, hereafter referred to as the Nuclear Emergency Act.
actions for the public. The response at the national level was led by the Prime Minister and senior officials at the Prime Minister’s Office in Tokyo.

The consequences of the earthquake and tsunami, and increased radiation levels, made the on-site response extremely difficult. The loss of AC and DC electrical power, the presence of a huge amount of rubble that hindered on-site response measures, aftershocks, alerts for further tsunamis and increased radiation levels meant that many mitigatory actions could not be carried out in a timely manner. The national government was involved in decisions concerning mitigatory action on the site.

The activation of the emergency Off-site Centre, located 5 km from the Fukushima Daiichi nuclear power plant, was difficult because of extensive infrastructure damage caused by the earthquake and tsunami. Within a few days, it became necessary to evacuate the Off-site Centre due to adverse radiological conditions.

— In preparing for the response to a possible nuclear emergency, it is necessary to consider emergencies that could involve severe damage to nuclear fuel in the reactor core or to spent fuel on the site, including those involving several units at a multi-unit plant possibly occurring at the same time as a natural disaster.

— The emergency management system for response to a nuclear emergency needs to include clearly defined roles and responsibilities for the operating organization and for local and national authorities. The system, including the interactions between the operating organization and the authorities, needs to be regularly tested in exercises.

Protecting emergency workers

At the time of the accident, the national legislation and guidance in Japan addressed measures to be taken for the protection of emergency workers, but only in general terms and not in sufficient detail.

Many emergency workers from different professions were needed to support the emergency response. Emergency workers came from various organizations and public services. However, there were no arrangements in place to integrate those emergency workers who had not been designated prior to the accident into the response.

Implementation of the arrangements for ensuring the protection of workers against radiation exposure was severely affected by the extreme conditions at the site. In order to maintain an acceptable level of protection for on-site emergency workers, a range of impromptu measures was implemented. The dose limit for emergency workers undertaking specific tasks was temporarily increased to allow the necessary mitigatory actions to continue. Medical management of emergency workers was also severely affected and major efforts were required to meet the needs of on-site emergency workers.

Members of the public, referred to as ‘helpers’, volunteered to assist in the off-site emergency response. National authorities issued guidance on the type of activities that helpers could carry out and on measures to be taken for their protection.
Emergency workers need to be designated, assigned clearly specified duties, regardless of which organization they work for, given adequate training, and be properly protected during an emergency. Arrangements need to be in place to integrate into the response those emergency workers who had not been designated prior to the emergency, and helpers who volunteer to assist in the emergency response.

Protecting the public

National emergency arrangements at the time of the accident envisaged that decisions on protective actions would be based on estimates of the projected dose to the public that would be calculated when a decision was necessary using a dose projection model — the System for Prediction of Environmental Emergency Dose Information (SPEEDI). The arrangements did not envisage that decisions on urgent protective actions for the public would be based on predefined specific plant conditions. However, in response to the accident, the initial decisions on protective actions were made on the basis of plant conditions. Estimates of the source term could not be provided as an input to SPEEDI owing to the loss of on-site power.

The arrangements prior to the accident included criteria for sheltering, evacuation and iodine thyroid blocking in terms of projected dose, but not in terms of measurable quantities. There were no criteria for relocation.

Protective actions for the public implemented during the accident included: evacuation; sheltering; iodine thyroid blocking (through the administration of stable iodine); restrictions on the consumption of food and drinking water; relocation; and the provision of information.

The evacuation of people from the vicinity of the Fukushima Daiichi nuclear power plant began in the evening of 11 March 2011, with the evacuation zone gradually extended from a radius of 2 km from the plant to 3 km and then to 10 km. By the evening of 12 March it had been extended to 20 km. Similarly, the area in which people were ordered to shelter extended from within 3–10 km of the plant shortly after the accident to within 20–30 km by 15 March. In the area within a 20–30 km radius of the nuclear power plant, the public was ordered to shelter until 25 March, when the national government recommended voluntary evacuation. Administration of stable iodine for iodine thyroid blocking was not implemented uniformly, primarily due to the lack of detailed arrangements.

There were difficulties in evacuation due to the damage caused by the earthquake and tsunami and the resulting communication and transportation problems. There were also significant difficulties encountered when evacuating patients from hospitals and nursing homes within the 20 km evacuation zone.

On 22 April, the existing 20 km evacuation zone was established as a ‘restricted area’, with controlled re-entry. A ‘deliberate evacuation area’ was also established beyond the ‘restricted area’ in locations where the specific dose criteria for relocation might be exceeded.

Once radionuclides were detected in the environment, arrangements were made regarding protective actions in the agricultural area and restrictions on the consumption and distribution of food and consumption of drinking water. In addition, a certification system for food and other products intended for export was established.
Several channels were used to keep the public informed and to respond to people’s concerns during the emergency, including television, radio, the Internet and telephone hotlines. Feedback from the public received via hotlines and counselling services identified the need for easily understandable information and supporting material.

- Arrangements need to be in place to allow decisions to be made on the implementation of predetermined urgent protective actions for the public, based on predefined plant conditions.

- Arrangements need to be in place to enable urgent protective actions to be extended or modified in response to developing plant conditions or monitoring results. Arrangements are also needed to enable early protective actions to be initiated on the basis of monitoring results.

- Arrangements need to be in place to ensure that protective actions and other response actions in a nuclear emergency do more good than harm. A comprehensive approach to decision making needs to be in place to ensure that this balance is achieved.

- Arrangements need to be in place to assist decision makers, the public and others (e.g. medical staff) to gain an understanding of radiological health hazards in a nuclear emergency in order to make informed decisions on protective actions. Arrangements also need to be in place to address public concerns locally, nationally and internationally.

Transition from the emergency phase to the recovery phase and analysis of the response

Specific policies, guidelines, criteria and arrangements for the transition from the emergency phase to the recovery phase, were not developed until after the Fukushima Daiichi accident. In developing these arrangements, the Japanese authorities applied the latest recommendations of the International Commission on Radiological Protection.

Analyses of the accident and of the emergency response were performed and presented in the form of reports, including those issued by the Government of Japan, the operating organization (TEPCO), two investigation committees created by the government and the Parliament, respectively.

After the accident, national emergency preparedness and response arrangements in Japan were, in many cases, revised to take account of the findings of these analyses and of relevant IAEA safety standards in the area of emergency preparedness and response.

- Arrangements need to be developed at the preparedness stage for termination of protective actions and other response actions, and transition to the recovery phase.

- Timely analysis of an emergency and the response to it, drawing out lessons and identifying possible improvements, enhances emergency arrangements.
Response within the international framework for emergency preparedness and response

An extensive international framework for emergency preparedness and response was in place at the time of the accident, comprising international legal instruments, IAEA safety standards and operational arrangements. At the time of the accident, the IAEA had four roles in the response to a nuclear or radiological emergency: (1) notification and exchange of official information through officially designated contact points; (2) provision of timely, clear and understandable information; (3) provision and facilitation of international assistance on request; and (4) coordination of the interagency response.

The international response to the accident involved many States and a number of international organizations. The IAEA liaised with the official contact point in Japan, shared information on the emergency as it developed, and kept States, relevant international organizations and the public informed. Communication with the official contact point in Japan in the early phase of the emergency response was difficult. The IAEA Director General's visit to Japan, and the subsequent deployment of liaison officers in Tokyo, improved communication between the IAEA and the contact point. The IAEA also sent expert missions to Japan and coordinated the interagency response.

Different States either took, or recommended, different protective actions for their nationals in Japan in response to the accident. These differences were generally not well explained to the public and occasionally caused confusion and concern.

Relevant organizations participating in the Inter-Agency Committee on Radiological and Nuclear Emergencies regularly exchanged information. Joint press releases were also issued.

- The implementation of international arrangements for notification and assistance needs to be strengthened.
- There is a need to improve consultation and sharing of information among States on protective actions and other response actions.

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7 The primary international legal instruments are the Convention on Early Notification of a Nuclear Accident and the Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency. The international safety standards in the area of emergency preparedness and response at the time of the accident were IAEA Safety Standards Series No. GS-R-2 and No. GS-G-2.1. IAEA Safety Series No. 115 also included elements related to emergency preparedness and response. The international operational arrangements comprised the Emergency Notification and Assistance Technical Operations Manual (ENATOM), IAEA Response and Assistance Network (RANET) and Joint Radiation Emergency Management Plan of the International Organizations (JPLAN).

8 The primary responsibility for emergency preparedness and response for a nuclear or radiological emergency rests with the State, as does the primary responsibility for the protection of human life, health, property and the environment.
RADIOLOGICAL CONSEQUENCES

Radioactivity in the environment

The accident resulted in the release of radionuclides to the environment. Assessments of the releases have been performed by many organizations using different models. Most of the atmospheric releases were blown eastward by the prevailing winds, depositing onto and dispersing within the North Pacific Ocean. Uncertainties in estimations of the amount and composition of the radioactive substances were difficult to resolve for reasons that included the lack of monitored data on the deposition of the atmospheric releases on the ocean.

Changes in the wind direction meant that a relatively small part of the atmospheric releases were deposited on land, mostly in a north-westerly direction from the Fukushima Daiichi nuclear power plant. The presence and activity of radionuclides deposited in the terrestrial environment were monitored and characterized. The measured activity of radionuclides reduces over time due to physical decay, environmental transport processes and cleanup activities.

In addition to radionuclides entering the ocean from the atmospheric deposition, there were liquid releases and discharges from the Fukushima Daiichi nuclear power plant directly into the sea at the site. The precise movement of radionuclides in the ocean is difficult to assess by measurements alone, but a number of oceanic transport models have been used to estimate the oceanic dispersion.

Radionuclides, such as iodine-131, cesium-134 and cesium-137, were released and found in drinking water, food and some non-edible items. Restrictions to prevent the consumption of these products were established by the Japanese authorities in response to the accident.

— In case of an accidental release of radioactive substances to the environment, the prompt quantification and characterization of the amount and composition of the release is needed. For significant releases, a comprehensive and coordinated programme of long term environmental monitoring is necessary to determine the nature and extent of the radiological impact on the environment at the local, regional and global levels.

Protecting people against radiation exposure

Following the accident, the Japanese authorities applied conservative reference levels of dose included in the recent ICRP recommendations. The application of some of the protective

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9 International recommendations on radiation protection are issued by the International Commission on Radiological Protection (ICRP). These recommendations are taken into account in the establishment of international safety standards, including radiation protection standards (the International Basic Safety Standards for Protection Against Ionizing Radiation and for the Safety of Radiation Sources (the Basic Safety Standards, or BSS)), which were developed and established by several international organizations and issued under the aegis of the IAEA. The BSS are used worldwide in the development of national regulations for the protection of people and the environment from the potential detrimental effects of exposure to ionizing radiation. The 2007 ICRP recommendations provided a revised framework for radiation protection. These included introducing reference levels for protection strategies. At the time of the accident, the BSS were being revised, inter alia to take account of these recommendations.
measures and actions proved to be difficult for the implementing authorities and very demanding for the people affected.

There were some differences among the national and international criteria and guidance for controlling drinking water, food and non-edible consumer products in the longer term aftermath of the accident, once the emergency phase had passed.

- Relevant international bodies need to develop explanations of the principles and criteria for radiation protection that are understandable for non-specialists in order to make their application clearer for decision makers and the public. As some protracted protection measures were disruptive for the affected people, a better communication strategy is needed to convey the justification for such measures and actions to all stakeholders, including the public.

- Conservative decisions related to specific activity and activity concentrations in consumer products and deposition activity led to extended restrictions and associated difficulties. In a prolonged exposure situation, consistency among international standards, and between international and national standards, is beneficial, particularly those associated with drinking water, food, non-edible consumer products and deposition activity on land.

Radiation exposure

In the short term, the most significant contributors to the exposure of the public were: (1) external exposure from radionuclides in the plume and deposited on the ground; and, (2) internal exposure of the thyroid gland, due to the intake of iodine-131, and internal exposure of other organs and tissues mainly due to the intake of caesium-134 and caesium-137. In the long term, the most important contributor to the exposure of the public will be external radiation from the deposited caesium-137.

The early assessments of radiation doses used environmental monitoring and dose estimation models, resulting in some overestimations. For the estimates in this report, personal monitoring data provided by the local authorities were also included to provide more robust information on the actual individual doses incurred and their distribution. These estimates indicate that the effective doses incurred by members of the public were low, and generally comparable to the range of effective doses incurred due to global levels of natural background radiation.

In the aftermath of a nuclear accident involving releases of iodine-131 and its intake by children, the uptake and subsequent doses to their thyroid glands are a particular concern. Following the Fukushima Daiichi accident, the reported thyroid equivalent doses of children were low because their intake of iodine-131 was limited, partly due to restrictions placed on drinking water and food, including leafy vegetables and fresh milk. There are uncertainties concerning the iodine intakes immediately following the accident due to the scarcity of reliable personal radiation monitoring data for this period.

By December 2011, around 23 000 emergency workers had been involved in the emergency operations. The effective doses incurred by most of them were below the occupational dose limits in Japan. Of this number, 174 exceeded the original criterion for emergency workers
and six emergency workers exceeded the temporarily revised effective dose criterion in an emergency established by the Japanese authority. Some shortcomings occurred in the implementation of occupational radiation protection requirements, including during the early monitoring and recording of radiation doses of emergency workers, in the availability and use of some protective equipment and in associated training.

— Personal radiation monitoring of representative groups of members of the public provides invaluable information for reliable estimates of radiation doses and needs to be used together with environmental measurements and appropriate dose estimation models for assessing public dose.

— While dairy products were not the main pathways for the ingestion of radiiodine in Japan, it is clear that the most important method of limiting thyroid doses, especially to children, is to restrict the consumption of fresh milk from grazing cows.

— A robust system is necessary for monitoring and recording occupational radiation doses, via all relevant pathways, particularly those due to internal exposure that may be incurred by workers during severe accident management activities. It is essential that suitable and sufficient personal protective equipment be available for limiting the exposure of workers during emergency response activities and that workers be sufficiently trained in its use.

Health effects

No early radiation induced health effects were observed among workers or members of the public that could be attributed to the accident.

The latency time for late radiation health effects can be decades, and therefore it is not possible to discount the potential occurrence of such effects among an exposed population by observations a few years after exposure. However, given the low levels of doses reported among members of the public, the conclusions of this report are in agreement with those of the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) to the UN General Assembly.\(^\text{10}\) UNSCEAR found that “no discernible increased incidence of radiation-related health effects are expected among exposed members of the public and their descendants” (which was reported within the context of the health implications related to “levels and effects of radiation exposure due to the nuclear accident after the 2011 great east-Japan earthquake and tsunami\(^\text{11}\)). Among the group of workers who received effective doses of 100 mSv or more, UNSCEAR concluded that “an increased risk of cancer would be expected in the future. However, any increased incidence of cancer in this group is expected


\(^{11}\) The World Health Organization (WHO) also published a health risk assessment in 2013 on the basis of preliminary estimated doses. The results are presented in the report.
to be indiscernible because of the difficulty of confirming such a small incidence against the normal statistical fluctuations in cancer incidence\textsuperscript{12}.

The Fukushima Health Management Survey was implemented to monitor the health of the affected population of Fukushima Prefecture. This survey is aimed at the early detection and treatment of diseases, as well as prevention of lifestyle related diseases. At the time of writing, an intensive screening of children’s thyroid glands is taking place as part of the survey. Highly sensitive equipment is being used, which has detected asymptomatic thyroid abnormalities among a significant number of surveyed children (which would not have been detectable by clinical means). The abnormalities identified in the survey are unlikely to be associated with radiation exposure from the accident and most probably denote the natural occurrence of thyroid abnormalities in children of this age. The incidence of thyroid cancer in children is the most likely health effect after an accident involving significant releases of radioiodine. Because the reported thyroid doses attributable to the accident were generally low, an increase in childhood thyroid cancer attributable to the accident is unlikely. However, uncertainties remained concerning the thyroid equivalent doses incurred by children immediately after the accident.

Prenatal radiation effects have not been observed and are not expected to occur, given that the reported doses are well below the threshold at which these effects may take place. Unwanted terminations of pregnancy attributable to the radiological situation have not been reported. Concerning the possibility of parents’ exposures resulting in hereditary effects in their descendants, UNSCEAR concluded that, in general, “although demonstrated in animal studies, an increase in the incidence of hereditary effects in human populations cannot at present be attributed to radiation exposure\textsuperscript{13}.

Some psychological conditions were reported among the population affected by the nuclear accident. Since a number of these people had suffered the combined impacts of a major earthquake and a devastating tsunami as well as the accident, it is difficult to assess to what extent these effects could be attributed to the nuclear accident alone. The Fukushima Health Management Survey’s Mental Health and Lifestyle Survey shows associated psychological problems in some vulnerable groups of the affected population, such as increases in anxiety and post-traumatic stress disorders. UNSCEAR estimated that “the most important health effect [from the accident] is on mental and social well-being, related to the enormous impact of the earthquake, tsunami and nuclear accident, and the fear and stigma related to the perceived risk of exposure to ionizing radiation\textsuperscript{14}.

\textsuperscript{12} See footnote 10.  
The risks of radiation exposure and the attribution of health effects to radiation need to be clearly presented to stakeholders, making it unambiguous that any increases in the occurrence of health effects in populations are not attributable to exposure to radiation, if levels of exposure are similar to the global average background levels of radiation.

After a nuclear accident, health surveys are very important and useful, but should not be interpreted as epidemiological studies. The results of such health surveys are intended to provide information to support medical assistance to the affected population.

There is a need for radiological protection guidance to address the psychological consequences to members of the affected populations in the aftermath of radiological accidents. A Task Group of the ICRP has recommended that “strategies for mitigating the serious psychological consequences arising from radiological accidents [should] be sought.”

Factual information on radiation effects needs to be communicated in an understandable and timely manner to individuals in affected areas in order to enhance their understanding of protection strategies, to alleviate their concerns and support their own protection initiatives.

Radiological consequences for non-human biota

No observations of direct radiation induced effects in plants and animals have been reported although limited observational studies were conducted in the period immediately after the accident. There are limitations in the available methodologies for assessing radiological consequences but, based on previous experience and the levels of radionuclides present in the environment, it is unlikely that there would be any major radiological consequences for biota populations or ecosystems as a consequence of the accident.

During any emergency phase, the focus has to be on protecting people. Doses to the biota cannot be controlled and could be potentially significant on an individual basis. Knowledge of the impacts of radiation exposure on non-human biota needs to be strengthened by improving the assessment methodology and understanding of radiation-induced effects on biota populations and ecosystems. Following a large release of radionuclides to the environment, an integrated perspective needs to be adopted to ensure sustainability of agriculture, forestry, fishery and tourism and of the use of natural resources.

POST-ACCIDENT RECOVERY

Off-site remediation of areas affected by the accident

The long term goal of post-accident recovery is to re-establish an acceptable basis for a fully functioning society in the affected areas. Consideration needs to be given to remediation of the areas affected by the accident in order to reduce radiation doses, consistent with adopted reference levels. In preparing for the return of evacuees, factors such as the restoration of infrastructure and the viability and sustainable economic activity of the community need to be considered.

Prior to the Fukushima Daiichi accident, policies and strategies for post-accident remediation were not in place in Japan, and it became necessary to develop them in the period after the accident. The remediation policy was enacted by the Government of Japan in August 2011. It assigned responsibilities to the national and local governments, the operator and the public and created the necessary institutional arrangements for the implementation of a coordinated work programme.

A remediation strategy was developed and implementation began. The strategy specifies that priority areas for remediation are residential areas, including buildings and gardens, farmland, roads and infrastructure, with emphasis on the reduction of external exposures.

External dose from radionuclides deposited on the ground and other surfaces is the main pathway of exposure. The remediation strategy is therefore focused on decontamination activities to reduce the levels of radiocaesium present in priority areas, thereby reducing the potential for such exposures. Internal doses continue to be controlled by restrictions on food, as well as through remediation activities on agricultural land.

Following the accident, the authorities in Japan adopted a ‘reference level’ as a target level of dose for the overall remediation strategy. This level was consistent with the lower end of the range specified in international guidance. The application of a low reference level has the effect of increasing the quantity of contaminated materials generated in remediation activities, and thereby increasing the costs and the demands on limited resources. The experience obtained in Japan could be used in developing practical guidance on the application of international safety standards in post-accident recovery situations.

Two categories of contaminated areas were defined on the basis of additional annual doses estimated in the autumn of 2011. The national government was assigned responsibility for formulating and implementing remediation plans in the first area (the ‘special decontamination area’) — within a radius of 20 km of the Fukushima Daiichi site and in

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16 Post-accident recovery includes: remediation of areas affected by the accident; the stabilization of damaged on-site facilities and preparations for decommissioning; the management of contaminated material and radioactive waste arising from these activities; and community revitalization and stakeholder engagement.

17 Remediation is defined as any measures that may be carried out to reduce the radiation exposure from existing contamination of land areas through actions applied to the contamination itself (the source) or to the exposure pathways to humans.

18 The ‘Act on Special Measures Concerning the Handling of Environment Pollution by Radioactive Materials Discharged by the Nuclear Power Station Accident Associated with the Tohoku District—Off the Pacific Ocean Earthquake that Occurred on March 11, 2011’.
areas where additional annual doses arising from contamination on the ground were projected to reach 20 mSv in the first year after the accident. The municipalities were given responsibility for implementing remediation activities in the other area (the ‘intensive contamination survey area’), where the additional annual doses were projected to exceed 1 mSv but to remain below 20 mSv. Specific dose reduction goals were set, including a long term goal of achieving an additional annual dose of 1 mSv or less.

- Pre-accident planning for post-accident recovery is necessary to improve decision making under pressure in the immediate post-accident situation. National strategies and measures for post-accident recovery need to be prepared in advance in order to enable an effective and appropriate overall recovery programme to be put in place in case of a nuclear accident. These strategies and measures need to include the establishment of a legal and regulatory framework; generic remediation strategies and criteria for residual radiation doses and contamination levels; a plan for stabilization and decommissioning of damaged nuclear facilities; and a generic strategy for managing large quantities of contaminated material and radioactive waste.

- Remediation strategies need to take account of the effectiveness and feasibility of individual measures and the amount of contaminated material that will be generated in the remediation process.

- As part of the remediation strategy, the implementation of rigorous testing and controls on food is necessary to prevent or minimize ingestion doses.

- Further international guidance is needed on the practical application of safety standards for radiation protection in post-accident recovery situations.

On-site stabilization and preparations for decommissioning

A comprehensive, high level strategic plan for stabilization and decommissioning of the damaged nuclear power plant was developed jointly by TEPCO and the relevant Japanese Government agencies. The plan was first issued in December 2011 and subsequently revised twice to reflect the experience gained and an improved understanding of the conditions of the damaged nuclear power plant, as well as the magnitude of the future challenges. The strategic plan addresses the complex nature of on-site work and includes: the approach to ensure safety; measures toward decommissioning; systems and environments to facilitate the work; and research and development requirements.

At the time of writing, safety functions had been re-established and structures, systems and components were in place to reliably maintain stable conditions. However, there was a continuing need for control of ingress of groundwater to the damaged and contaminated reactor buildings. The resulting contaminated water was being treated to remove radionuclides to the extent possible and stored in more than 800 tanks. More sustainable solutions are needed, considering all options, including the possible resumption of controlled discharge to the sea. Final decision making will require engaging relevant stakeholders and consideration of socioeconomic conditions in the consultation process, as well as implementation of a comprehensive monitoring programme.
Plans for the management of spent fuel and fuel debris were developed and removal of fuel from spent fuel pools began\textsuperscript{19}. A conceptual model of future activities for removing fuel debris was developed, which takes account of the many preliminary steps required, including visual confirmation of the configuration and composition of the debris. The high radiation dose levels in the damaged reactors meant that no such confirmation had been possible at the time of writing.

Japanese authorities have estimated that the timescale for completing decommissioning activities is likely to be in the range of 30–40 years. Decisions regarding the final conditions of the plant and site will be the subject of further analysis and discussions.

- Following an accident, a strategic plan for maintaining long term stable conditions and for the decommissioning of accident-damaged facilities is essential for on-site recovery. The plan needs to be flexible and readily adaptable to changing conditions and new information.

- Retrieving damaged fuel and characterizing and removing fuel debris necessitate solutions that are specific to the accident and special methods and tools may need to be developed.

**Management of contaminated material and radioactive waste**

Stabilization of a damaged nuclear power plant and the on-site decontamination and remediation efforts in the surrounding areas results in large quantities of contaminated material and of radioactive waste. The management of such material — with its varying physical, chemical and radiological properties — is complex and requires significant efforts.

Following the Fukushima Daiichi accident, there were difficulties in establishing locations to store the large amounts of contaminated material arising from off-site remediation activities. At the time of writing, several hundred temporary storage facilities had been established in local communities and efforts to establish an interim storage facility were continuing.

- National strategies and measures for post-accident recovery need to include the development of a generic strategy for managing contaminated liquid and solid material and radioactive waste, supported by generic safety assessments for discharge, storage and disposal.

**Community revitalization and stakeholder engagement**

The nuclear accident and radiation protection measures introduced in both the emergency and post-accident recovery phases have had significant consequences for the way of life of the affected population. Evacuation and relocation measures and restrictions on food involved hardships for the people affected. The revitalization and reconstruction projects introduced in Fukushima Prefecture were developed from an understanding of the socioeconomic

\textsuperscript{19} Removal of fuel from the Unit 4 spent fuel pool was completed in December 2014.
consequences of the accident. These projects address issues such as reconstruction of infrastructure, community revitalization and support and compensation.

Communication with the public on recovery activities is essential to build trust. To communicate effectively, it is necessary for experts to understand the information needs of the affected population and to provide understandable information through relevant means. Communications improved in the aftermath of the accident and the affected population became increasingly involved in decision making and remediation measures.

— It is necessary to recognize the socioeconomic consequences of any nuclear accident and the subsequent protective actions, and to develop revitalization and reconstruction projects that address issues such as reconstruction of infrastructure, community revitalization and compensation.

— Support by stakeholders is essential for all aspects of post-accident recovery. In particular, engagement of the affected population in the decision making processes is necessary for the success, acceptability and effectiveness of the recovery and for the revitalization of communities. An effective recovery programme requires the trust and the involvement of the affected population. Confidence in the implementation of recovery measures has to be built through processes of dialogue, the provision of consistent, clear and timely information, and support to the affected population.
THE FUKUSHIMA DAIICHI ACCIDENT

SUMMARY REPORT

1. INTRODUCTION

The Great East Japan Earthquake occurred on 11 March 2011. It was caused by a sudden release of energy at the interface where the Pacific tectonic plate forces its way under the North American tectonic plate. A section of the Earth's crust, estimated to be about 500 km in length and 200 km wide, was ruptured, causing a massive earthquake with a magnitude of 9.0 and a tsunami which struck a wide area of coastal Japan, including the north-eastern coast, where several waves reached heights of more than ten metres. The earthquake and tsunami caused great loss of life and widespread devastation in Japan. More than 15 000 people were killed and over 6000 injured and, at the time of writing of this report\(^{20}\), around 2500 people were still reported to be missing \[1\]. Considerable damage was caused to buildings and infrastructure, particularly along Japan's north-eastern coast.

At the Fukushima Daiichi nuclear power plant (NPP), operated by the Tokyo Electric Power Company (TEPCO), the earthquake caused damage to the electric power supply lines to the site and the tsunami caused substantial destruction of the operational and safety infrastructure on the site. The combined effect led to the loss of off-site and on-site electrical power. This resulted in the loss of the cooling function at the three operating reactor units\(^{21}\) as well as at the spent fuel pools. The four other NPPs\(^{22}\) along the coast were also affected to different degrees by the earthquake and tsunami. However, all operating reactor units at these plants were safely shut down.

Despite the efforts of the operators at the Fukushima Daiichi NPP to maintain control, the reactor cores in Units 1–3 overheated, the nuclear fuel melted, and the three containment vessels were breached. Hydrogen was released from the reactor pressure vessels, leading to explosions inside the reactor buildings in Units 1, 3 and 4 that damaged structures and equipment and injured personnel. Radionuclides were released from the plant to the atmosphere and were deposited on land and on the ocean. There were also direct releases into the sea.

People within a radius of 20 km from the site and in other designated areas were evacuated, and those within a radius of 20–30 km were instructed to shelter before later being advised to voluntarily evacuate. Restrictions were placed on the distribution and consumption of food and the consumption of drinking water. At the time of writing, many people are still living outside the areas from which they were evacuated.

\(^{20}\) March 2015.

\(^{21}\) Of the six units of the Fukushima Daiichi NPP, Units 1, 2 and 3 were operating at the time of the accident; Units 4, 5 and 6 were in planned shutdown.

\(^{22}\) Higashidori, Onagawa, Fukushima Daini and Tokai Daini NPPs.
Following stabilization of the conditions of the reactors at the Fukushima Daiichi NPP\(^2\), work began to prepare for their eventual decommissioning. Efforts toward the recovery of the areas affected by the accident, including remediation and the revitalization of communities and infrastructure, began in 2011.

1.1. 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” [2].

The report on the Fukushima Daiichi accident 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 of the report. Additional internal and external review mechanisms were also instituted, as illustrated in Fig. 1.1.

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\(^2\) On 16 December 2011, the Government–TEPCO Integrated Response Office announced that the conditions for a ‘cold shutdown state’ had been achieved in Units 1–3. The term ‘cold shutdown state’ was defined by the Government of Japan at the time specifically for the Fukushima Daiichi NPP. Its definition differs from the terminology used by the IAEA and others.
This 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 Report provides a description of the accident and its causes, evolution and consequences, based on the evaluation of data and information from a large number of sources available up to March 2015, including the results of the work carried out in implementing the IAEA Action Plan on Nuclear Safety (the Action Plan)\textsuperscript{24}, and it highlights the main observations and lessons. Significant amounts of data were provided by the Government of Japan and other organizations in Japan.

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

This Report by the Director General comprises the following six sections:

- Section 1: Introduction.
- Section 2: The accident and its causes, including a description of the sequence of events and an assessment of how extreme natural events led to the severe nuclear accident.
- Section 3: Emergency preparedness and response, including the arrangements for the protection of emergency workers and the public, and the implementation of these arrangements during and immediately after the accident.
- Section 4: The radiological consequences of the accident, including radiation exposure of workers and the public, and health and environmental effects.
- Section 5: Post-accident recovery activities, including decommissioning of the plant, remediation strategies for the off-site areas affected, waste management and strategies for revitalization.
- Section 6: An overview of the activities of the IAEA and the Contracting Parties to the Convention on Nuclear Safety in response to the accident.

Key observations and lessons arising from specific features of the accident are included in Sections 2 to 5.

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\textsuperscript{24} 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 Section 6.1.
TABLE 1.2. Structure of the Summary Report and its relationship to the content of the technical volumes.

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FIG 1.2. Structure of the Summary Report and its relationship to the content of the technical volumes.
2. THE ACCIDENT AND ITS ASSESSMENT

This section provides a brief description of the accident at the Fukushima Daiichi NPP, followed by an assessment of factors that are considered to have contributed to its causes and consequences.

Section 2.1 describes the main events in chronological order, including the impact of the earthquake and tsunami and the subsequent events.

Section 2.2 assesses the causes of the accident. It begins with an evaluation of the vulnerability of the Fukushima Daiichi NPP to external hazards and deals with its design, the accident progression, the efforts of the operators to maintain fundamental safety functions and the actions taken by them. This section also considers the effectiveness of the regulatory framework in Japan as well as the impact of human and organizational considerations on nuclear safety.

2.1. DESCRIPTION OF THE ACCIDENT

The description that follows is mainly based on information provided by the Government of Japan to the IAEA [3, 4], reports of the investigation committees established by the Japanese Government [5, 6], the Japanese Diet [7] and TEPCO [8], including updates and supplements by TEPCO [9, 10], the regulatory body [11] and the IAEA missions listed in Section 6. Other sources from which information has been taken are cited separately.

Events are presented in chronological order. Some of the main events occurred in parallel or had an impact on actions taken in other locations on-site.

2.1.1. Initiating event and response

The earthquake and the loss of off-site power

The Great East Japan Earthquake of 11 March 2011 occurred at 14:46 Japan Standard Time (JST), 05:46 UTC\textsuperscript{25}, off the eastern coast of Japan. It was caused by a sudden release of energy at the interface where the Pacific tectonic plate forces its way under the North American tectonic plate (Fig. 2.1). The main shock, with a magnitude of 9.0 [12], lasted for more than two minutes, with several significant pulses and aftershocks. This event was among the largest recorded earthquakes, most of which also occurred in areas along the Pacific tectonic plate: the earthquakes of 1960 and 2010 in Chile, with a magnitude of 9.5 and 8.8, respectively, and those in Alaska (1964) and Sumatra (2004), both with a magnitude of 9.2.

\textsuperscript{25} Coordinated Universal Time, which is nine hours behind JST. Unless indicated, the report uses JST for all times.
When the earthquake occurred, three of the six boiling water reactors (Box 2.1) at the Fukushima Daiichi NPP [13] were operating at full power and three were shut down for refuelling and maintenance. 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. This automatic action achieved control of reactivity.

When shut down, the reactor cores continued to generate heat (known as 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. 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. The on-site replacement power facilities — emergency diesel generators — which were designed to deal
with such loss of off-site power situations, automatically started in order to restore AC power in all six units.

**Box 2.1. 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, 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.

Units 1–3 were automatically isolated from their turbine systems due to the loss of off-site power, resulting in increases in the temperature and pressure of the reactors due to the decay heat. The cooling of these reactors following isolation was accomplished by means of the following design and operational provisions (Box 2.2):

- In Unit 1, as the reactor pressure increased, both loops of the isolation condenser system started automatically and continued to cool the reactor. The operation of both isolation condenser 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 reactor pressure vessel. Afterwards, only one of the loops was used by the operators to control the cooling rate in a range prescribed by the procedures.

- In Units 2 and 3, the increase in reactor pressure automatically activated safety relief valves, which were designed to protect the reactor from over-pressurization by releasing steam from the reactor vessel to the suppression pool section of the primary containment vessel. This resulted in a decrease in the reactor water levels. In
response, the operators manually activated the reactor core isolation cooling system in accordance with procedures.

**Box 2.2. 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 2.1). However, when the reactor is isolated, this 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.

*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.

![Diagram of isolation condenser](image)

*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.
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 spent fuel pool water stopped working as a result of the loss of off-site power. The Unit 4 spent fuel pool, containing more than 1300 spent fuel assemblies, had the largest amount of decay heat to be removed among all the spent fuel pools 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 loss of off-site power. 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 safety relief valves.

- In Unit 6, the reactor was near atmospheric pressure and room temperature with fuel in the core, and the decay heat was low.

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26 The spent fuel pools, 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 fuel stops when the water level falls and exposes the fuel. Overheating and exposure causes damage to the fuel and the release of radionuclides.
In the spent fuel pools of all units and the common spent fuel pool\(^{27}\), which lost cooling and refilling capabilities upon the loss of off-site power, the temperatures of the pool water continued to increase due to decay heat.

In response to the earthquake and the loss of off-site power, the operators activated the 'event based' abnormal operating procedures in all three main control rooms of the six units\(^{28}\). An earthquake emergency response team was activated at the on-site emergency response centre located within the 'seismically isolated building'\(^{29}\). 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 emergency response centre. 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.

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 (except for some operator actions that were restricted or delayed by the aftershocks) (Fig. 2.2).

\(^{27}\) 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.

\(^{28}\) Each pair of units shared a common control room, i.e. Units 1 and 2, Units 3 and 4, and Units 5 and 6.

\(^{29}\) 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.
The tsunami and the station blackout

In addition to causing the strong ground motion, the earthquake displaced a massive amount of water, giving rise to a series of large tsunami waves [14]. When these tsunami waves reached the coast, they had a devastating effect over a wide area (Fig. 2.3).
The tsunami waves started reaching the Fukushima Daiichi NPP site about 40 minutes after the earthquake. The site was protected from the first wave, which had a 4–5 m run-up height, by the tsunami barrier seawalls that were designed to protect against a maximum tsunami height of 5.5 m [16]. However, about 10 minutes after the first wave, the second and largest wave, with a run-up height of 14–15 m, 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\(^{31}\) (Fig. 2.4), causing the following sequence of events:

\(^{30}\) Inundation is the inland limit of wetting and run-up is the crest height of a wave compared to sea level.

\(^{31}\) The administration buildings and the seismically isolated building that contained the on-site emergency response centre 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).
— 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 emergency diesel generators, could not be cooled to ensure their continuous operation.

— The wave flooded and damaged the dry cask storage building located near the seashore between Units 1–4 and Units 5–6. 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 emergency diesel generators or their associated power connections, which resulted in the loss of emergency AC power. Only one of the air cooled emergency diesel generators — that of Unit 6 — was unaffected by the flooding. 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.

Because of the station blackout in Units 1–5, the emergency operating procedures for “loss of all AC power” [18] were initiated. A ‘specific event’, as defined in the regulations associated with the Act on Special Measures Concerning Nuclear Emergency Preparedness [20] based on the condition of “some safety systems becoming unavailable”, was declared by the site superintendent, who was the head of the on-site emergency response centre of the operating organization, TEPCO. Consequently, the relevant off-site agencies were informed in accordance with the requirements of the Nuclear Emergency Act.

Footnotes:
32 Each unit had a pair of emergency diesel generators, and Unit 6 had an additional generator. Of those 13 emergency diesel generators, 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.
33 Unlike the components (i.e., switchgears) of the air cooled emergency diesel generators of Units 2 and 4, which were located on the ground floor of the common spent fuel building, the components of the air cooled emergency diesel generator of Unit 6, which was located on the first floor of a separate diesel generator building at a higher elevation, did not suffer water damage.
The Fukushima Daiichi Accident
Report by the Director General

The accident and its assessment

The Fukushima Daiichi NPP units, similar to other plants of the same age, were designed to withstand a station blackout for eight hours, based on the capacity of the DC batteries in the reactor units\(^\text{35}\).

\(^{35}\) NPPs are generally equipped with on-site DC and additional backup AC power sources (i.e. gas turbine generators or diesel engines) to withstand a station blackout for a limited period of time, varying between 4 and 72 hours. The
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, 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 station blackout.

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 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 a station blackout under these conditions. The operators and emergency response centre staff started reviewing available options and establishing possible ways to restore power and thereby regain the ability to monitor and control the plant.

Response in Units 3, 5 and 6

Units 3, 5 and 6 maintained power enabling the operators to observe the plant status as the main control room indications and controls were functioning. This allowed the operators to continue with their 'symptom based' emergency operating procedures in response to the events:

— In Unit 3, the safety relief valves automatically opened to protect the reactor vessel from over-pressurization, and the operators manually restarted the reactor core isolation cooling 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 station blackout.

— DC power was also available in Unit 5. The reactor was not generating steam, so residual heat removal by a high pressure cooling system was not possible. Alternative options to depressurize the reactor vessel to enable coolant injection by low pressure systems were tried unsuccessfully, and the reactor vessel, which was pressurized and filled with water, continued to heat up and pressurize.

— Unit 6 did not experience a station blackout, since AC power was available from one operating emergency diesel generator. Here, the efforts focused on maintaining fundamental safety functions in response to the loss of off-site power. The reactor was

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.
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.

2.1.2. Progression of the accident

The nuclear emergency in Units 1 and 2

As all electrical power was lost in Units 1 and 2, there were no indications available to the operators to determine whether the safety systems were operating properly, or operating at all, in order to maintain the fundamental safety functions. Unable to determine the water level in the reactor and the operational status of the cooling systems, plant operators declared that the core cooling fundamental safety function was lost. Consequently, the on-site emergency response centre reported to the off-site organizations, TEPCO headquarters and relevant government authorities, that nuclear emergency conditions for Units 1 and 2 existed on the basis of the “inability of water injection of the emergency core cooling system”, as defined in regulations [19].

Establishing the severe accident management strategy

The staff in the on-site emergency response centre started following the established severe accident management guidelines, and the operators in the common main control room of Units 1 and 2 activated the severe accident operating procedure. 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. 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, which required the restoration of AC power.

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

The on-site emergency response centre adopted a core cooling strategy that used the stationary diesel driven fire pump and the fire engines via the fire protection system to inject water into the reactors, in addition to connecting temporary power sources.

This accident 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 action

36 The fundamental safety function of reactivity control had been confirmed before the station blackout by indications showing that the control rods were inserted and the fission reaction had stopped.

37 The fire protection system was designed primarily for fire suppression and flooding of the containment vessel, not for injection of water into the reactor.
was to restore AC power using the available interconnecting line\textsuperscript{38} to the operating emergency diesel generator in Unit 6.

**Status of core cooling in Units 1 and 2**

Just before the tsunami struck, the Unit 1 isolation condenser was stopped by the operators in accordance with established operating procedures to control the reactor cooling rate. This was accomplished by closing the control valves (located outside the primary containment vessel and DC-operated, as shown in Box 2.2). About 2.5 hours after the loss of indications, 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. The operators attempted to start the isolation condenser by opening those valves. However, the isolation condenser did not function, indicating that the AC powered isolation valves inside the primary containment vessel were closed\textsuperscript{39}. Thus, the fundamental safety function of core cooling at Unit 1 was lost when the isolation condenser was stopped by the operators just before the tsunami, and the Unit 1 core heated up from that time.

Additionally, local measurements (in the reactor building) at 20:07 indicated that the reactor was still near the operating pressure of 70 bar (7 MPa), which prevented water injection by alternative methods that would only be possible below 8 bar (0.8 MPa).

After several reports from the on-site emergency response centre 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\textsuperscript{40}.

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 reactor core isolation cooling system was not operating and the Unit 2 core was heating up. At 21:01, the on-site emergency response centre 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\textsuperscript{41}.

The uncovering of the Unit 1 core was indicated when high radiation levels\textsuperscript{42} encountered in the Unit 1 reactor building by a team that was dispatched at 21:51 to confirm the status of the operation of the isolation condenser. This was an indication of the severity of the conditions at the Unit 1 reactor and of possible core damage.

\textsuperscript{38} 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.

\textsuperscript{39} 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 status of isolation valves. All the isolation condenser valves would keep their position when the AC power was lost, but the AC powered isolation valves would close, by design, if the control power (i.e. DC power) was lost.

\textsuperscript{40} At the same time, the Nuclear Emergency Response Headquarters, 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.

\textsuperscript{41} 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.

\textsuperscript{42} Their personal dosimeters recorded levels as high as 0.8 mSv in about ten seconds of their stay in the building.
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 containment vessel pressure became possible at 23:50 on 11 March. The containment vessel pressure had exceeded the maximum pressure considered in its design, and this information prompted the site superintendent to order preparations for venting of the Unit 1 containment vessel. This situation also warranted an emergency notification, based on an “abnormal rise in primary containment vessel pressure”, as defined in the regulations associated with the Nuclear Emergency Act [20].

The measurements of Unit 1’s containment pressure recorded the highest values at 02:30 and 02:45 on 12 March.

Confirmation of Unit 2’s status and focus on recovery of Unit 1’s safety function

At 02:10 on 12 March, a team was able to enter the room where Unit 2’s reactor core isolation cooling system equipment was located and read the parameters to determine the system’s status. The operating status was communicated to the on-site emergency response centre at 02:55 on 12 March and served to clarify the previously unknown condition of Unit 2 core cooling about 11 hours after the loss of monitoring in the control room. On confirmation of Unit 2 core cooling, and with the acute challenge to the confinement function of Unit 1, the site superintendent decided to focus the accident management on venting efforts at Unit 1.

While the venting plans were being developed, the accident management strategy to restore Unit 1’s core cooling using the fire pump 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 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, was then put into action.

Heating up of Unit 5 and restoration of AC power

At a similar time, a Unit 5 safety relief valve automatically opened for the first time approximately 10 hours after the station blackout 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 because the Unit 5 reactor had continued to heat up in the absence of heat removal measures.

The safety relief valves were operating automatically to limit pressure, but could not be used to reduce pressure since most of them had 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 reactor vessel was considered as an alternative because DC power was available for this purpose. Later, at 06:06 on 12 March, approximately 14.5 hours after the station blackout, the head vent nozzle was remotely opened and left open to depressurize the water-filled reactor vessel. In addition, the power connection between Unit 5 and the operating emergency diesel generator in Unit 6 was completed nearly 16.5 hours after the station blackout, enabling some AC power to be connected to the Unit 5 equipment, such as the pumps and valves needed for reactor heat removal.
Alternative cooling of the Unit 1 core

Meanwhile, the Unit 1 reactor pressure became low enough\textsuperscript{43} to allow alternative water injection. An alternative cooling method, namely fresh water injection from the fire engines into the Unit 1 reactor to restore core cooling, started at 04:00 on 12 March, about 12.5 hours after the station blackout. 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. Later, just over 17.5 hours after the station blackout, continuous fresh water injection to Unit 1 started directly from the tank.

Venting of the Unit 1 containment

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 shortly afterwards showed an increase\textsuperscript{44}. This was also an indication of some uncontrolled radioactive release from the primary containment, i.e. degraded confinement. The deteriorating radiological conditions at the site, combined with the elevated containment pressure in Unit 1, caused the Government to expand the evacuation zone to 10 km at 05:44 on 12 March.

The activities to configure venting of Unit 1’s containment were set to start at 09:00 on 12 March. As soon as confirmation was received from the Fukushima Prefecture authorities, at 09:02, of the completion of evacuation of the town of Okuma\textsuperscript{45}, the teams were activated to start manipulation of the valves in order to arrange the path for the venting of Unit 1’s containment. After 5.5 hours of efforts, the venting path (Box 2.3) 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 pressures, as measured at 14:30\textsuperscript{46}, 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\textsuperscript{47} by one of the site monitors located near the site boundary to the north-west of Unit 1.

\textsuperscript{43} Reactor depressurization had occurred without any operator or plant systems actions indicating that an unknown path provided pressure relief.

\textsuperscript{44} An increase of around ten-fold (0.000 069 mSv/h measured at 04:00 versus 0.000 59 mSv/h at 04:23).

\textsuperscript{45} Completion of evacuation to start the venting was agreed with the Fukushima Prefecture authorities.

\textsuperscript{46} Overall, it took 14.5 hours from the site superintendent’s order (around midnight) to start venting. This was a result of high radiation levels around the suppression chamber where valves had to be manually manipulated, and the lack of compressed air supply to operate the valves.

\textsuperscript{47} At 16:17, it was noted by the emergency response centre 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 the 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).
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 [22, 23]. The aim was to prevent over-pressurization of the primary containment by allowing venting (see the figure below). 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 main control room, 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 break when the containment pressure exceeded the design 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.
Loss of normal core cooling and start of emergency core cooling in Unit 3.

While the containment venting of Unit 1 was being established, the station blackout response in Unit 3 had to be modified when the reactor core isolation cooling 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, and the water in the reactor therefore continued to boil and evaporate and the reactor water level continued to decrease.

When the water level reached the point at which the high pressure coolant injection system — an emergency core cooling system — was activated automatically, at 12:35, this system automatically maintained the reactor water level in the pre-determined range. However, the operators took manual control to avoid repeated automatic starts and stops of the system in order to preserve DC power for longer, in accordance with station blackout response procedures.

Seawater injection and power supply line-up for Unit 1

After approximately 11 hours of water injection into the Unit 1 core, the fresh water in the fire protection water tank was almost completely depleted. As a result, freshwater injection to Unit 1 was stopped at 14:53 on 12 March. The site superintendent then decided to inject seawater 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. The arrangements for seawater injection were completed in just over half an hour.

Around the same time, work to connect the mobile voltage power supplies 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 at 15:30 on 12 March.

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

Explosion in the Unit 1 reactor building

At 15:36 on 12 March, an explosion occurred on the service floor of the Unit 1 reactor building, causing damage to the upper building structure and injuring workers. Although the explosion did not seem to damage the primary containment, there was extensive damage to the secondary containment (the reactor building). 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 emergency response centre requested evacuation of staff from the areas in and around Units 1–4, including the two main control rooms, except for the three most senior level staff.

48 Almost one hour after the station blackout 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 around 22:00 on 11 March, i.e. nearly six hours after the station blackout. More vehicles from other TEPCO and Tohoku Electric facilities and the Japan Self Defense Force arrived at the sites throughout the night. By 10:15 on 12 March, a total of 23 vehicles were at the site.
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.

Injection of seawater into Unit 1

The explosion in Unit 1 not only caused serious damage to the seawater injection and temporary electrical power line assemblies, but also hindered their repair because of the rubble scattered around the site and the locally high dose rates from contaminated rubble. After an evacuation lasting about two hours, teams returned to repair or replace damaged equipment.

After the repair and replacement of damaged equipment, water injection into the Unit 1 reactor, using fire engines and seawater from the Unit 3 backwash valve pit, started at 19:04 on 12 March and continued afterwards. Boric acid was added later to address re-criticality concerns for ensuring 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.

Loss of Unit 3 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 after the earthquake and the tsunami, the core cooling situation in Unit 3 became a cause of concern on the morning of Sunday, 13 March.

After 14 hours of continued operation of the emergency high pressure coolant injection 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 operating at low reactor steam pressure. The concern was related to the possibility of turbine damage and the creation of a release path from the reactor vessel. This would result in an uncontrollable release of radioactive steam, directly outside primary containment. 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.

Consequently, the operators decided to stop the high pressure coolant injection system and instead use the alternative means of injection at low pressure (the diesel driven fire pump). 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 pressure relief valves. The Unit 3 emergency high pressure core injection system was therefore turned off by the operators, who then started their attempts to open the pressure relief valves.

On one occasion, according to the investigations [7], 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.