Fukushima Daiichi Nuclear Power Plant Accident, Ten Years On

Progress, Lessons and Challenges

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NEA No. 7558

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NUCLEAR ENERGY AGENCY

The OECD Nuclear Energy Agency (NEA) was established on 1 February 1958. Current NEA membership consists of 34 countries: Argentina, Australia, Austria, Belgium, Bulgaria, Canada, the Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Korea, Luxembourg, Mexico, the Netherlands, Norway, Poland, Portugal, Romania, Russia, the Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States. The European Commission and the International Atomic Energy Agency also take part in the work of the Agency.

The mission of the NEA is:

– to assist its member countries in maintaining and further developing, through international co-operation, the scientific, technological and legal bases required for a safe, environmentally sound and economical use of nuclear energy for peaceful purposes;

– to provide authoritative assessments and to forge common understandings on key issues as input to government decisions on nuclear energy policy and to broader OECD analyses in areas such as energy and the sustainable development of low-carbon economies.

Specific areas of competence of the NEA include the safety and regulation of nuclear activities, radioactive waste management and decommissioning, radiological protection, nuclear science, economic and technical analyses of the nuclear fuel cycle, nuclear law and liability, and public information. The NEA Data Bank provides nuclear data and computer program services for participating countries.

Cover photo: Street planted with cherry trees in the Yonomori district of Tomioka Town (Tomioka Town City Council).

Foreword

The purpose of the OECD Nuclear Energy Agency (NEA) is to foster co-operation among its member countries and many partners around the world to advance policy, safety, technology, and science related to nuclear technology. The NEA serves as a forum for sharing and analysing information and experience; supports the development and maintenance of knowledge and the development of human resource capacities; and provides policy analyses relevant to nuclear energy. The NEA has supported its members in understanding and responding to new developments in the nuclear field for more than 60 years. Typically, this work involves addressing changes in technology and policy; and often it involves absorbing operating experiences related to nuclear facilities around the world. The 11 March 2011 accident at the Fukushima Daiichi Nuclear Power Plant is but one example, but it is an experience with significant global policy and regulatory impact.

The NEA published reports on the accident in 2013 (*The Fukushima Daiichi Nuclear Power Plant Accident: OECD/NEA Nuclear Safety Response and Lessons Learnt*) and in 2016 (*Five Years after the Fukushima Daiichi Accident: Nuclear Safety Improvements and Lessons Learnt*). Those mainly discuss safety improvements and legal matters. This new report covers more comprehensively the effects of the accident and future perspectives. It provides information about the achievements of the international community and the NEA, gives analyses on current challenges and suggests future activities of international programmes of co-operation. As the work of decommissioning the power station and remediating radiological effects and socio-economic impacts on the affected areas continues, there are many areas for international communities to learn, assist Japan and support each other.

This report is intended to provide clear information to policy makers involved in providing clean energy, a clean environment and healthy societies through the peaceful use of nuclear energy, as well as any member of the general public wishing to engage and understand the accident and its aftermath.

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Nuclear Energy Agency

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List of acronyms and abbreviations

AC	alternating current
ADS	automatic depressurisation system
ALARA	as low as reasonably achievable
ALARP	as low as reasonably practicable
AM	accident management
ATENA	Atomic Energy Association (Japan)
ATF	accident tolerant fuel
BWR	boiling water reactor
CNRA	NEA Committee on Nuclear Regulatory Activities
CRPPH	NEA Committee on Radiological Protection and Public Health
CSC	Convention on Supplementary Compensation for Nuclear Damage
CSNI	NEA Committee on the Safety of Nuclear Installations
CSSCF	Country-Specific Safety Culture Forum
CST	condensate storage tank
DAROD	decommissioning and remediation of damaged nuclear facilities
DBA	design basis accidents
DC	direct current
DiD	defence-in-depth
DOE	Department of Energy (US)
EOP	emergency operating procedure
ERC	emergency response centre
FDEC	Fukushima Daiichi Decontamination and Decommissioning Engineering Company (TEPCO)
HPCI	high-pressure coolant injection
IAEA	International Atomic Energy Agency
IAM	integrated accident management
ICRP	International Commission on Radiological Protection
ICSA	intensive contamination survey area
INES	International Nuclear Event Scale
IRID	International Research Institute for Nuclear Decommissioning (Japan)
ISF	interim storage facility
ISOE	Information System on Occupational Exposure
JAEA	Japan Atomic Energy Agency

JANSI	Japan Nuclear Safety Institute
JRC	Joint Research Centre (European Commission)
MAFF	Ministry of Agriculture, Forestry and Fisheries (Japan)
METI	Ministry of Economy, Trade and Industry (Japan)
MEXT	Ministry of Education, Culture, Sports, Science and Technology (Japan)
MoE	Ministry of the Environment (Japan)
MHPSS	mental health and psychosocial support
mSv	millisievert
NDF	Nuclear Damage Compensation and Decommissioning Facilitation Corporation (Japan)
NEA	Nuclear Energy Agency
NLC	NEA Nuclear Law Committee
NRA	Nuclear Regulation Authority (Japan)
NRRC	Nuclear Risk Research Center (Japan)
MSIV	main steam isolation valve
OECD	Organisation for Economic Co-operation and Development
PBq	petabecquerel (equal to 1 015 becquerels)
PCV	primary containment vessel
PSA	probabilistic safety assessment
R&D	research and development
RCIC	reactor core isolation cooling system
RHR	residual heat removal system
RPV	reactor pressure vessel
SA	severe accident
SAM	severe accident management
SAMG	severe accident management guidelines
SBO	station blackout
SDA	special decontamination area
SFP	spent fuel pool
SiD	strength-in-depth
SOER	Significant Operating Experience Report
TBq	terabecquerel (equal to 1 012 becquerels)
TEPCO	Tokyo Electric Power Company
TMI	Three Mile Island
TSS	temporary storage sites
UHS	ultimate heat sink
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation
WANO	World Association of Nuclear Operators
WHO	World Health Organization

Executive summary

On 11 March 2011, Japan was struck by a massive earthquake, which initiated a tsunami that inundated a large portion of the east coast of Japan. The tsunami caused significant devastation and loss of life. The tsunami also led to a severe accident at the Tokyo Electric Power Company (TEPCO) Fukushima Daiichi Nuclear Power Plant. Post-accident analyses have verified that the radiation from the accident has not led to any direct impact on human health. However, the health and well-being of more than 150 000 people living in surrounding areas was affected to different degrees (including some early deaths) as a result of evacuations from the area due to both the tsunami and the nuclear accident, lack of access to health care or medicines, stress-related problems, and other causes. The accident also caused disturbance to the daily life of many people and businesses and other activities.

In the immediate aftermath and during the ten years since the accident, Japanese authorities have undertaken very challenging work to address the on-site and off-site consequences, and rebuild the social and economic fabric of the areas impacted by the earthquake and resulting tsunami and the nuclear accident. The global community has come together with Japan to both offer assistance and draw lessons to further improve nuclear safety worldwide. This endeavour has been greatly facilitated by the openness of the Japanese government and industry leaders as well as the co-operation of international organisations, governments and companies. The present report, the third in a series of major studies on the aftermath of the Fukushima Daiichi accident by the Nuclear Energy Agency (NEA), surveys the research initiatives and the expanding knowledge and action made possible by such openness and co-operation.

The operating reactors at the Fukushima Daiichi nuclear power plant quickly and effectively shut down as designed when the earthquake struck on 11 March 2011. However, the tsunami generated by the earthquake inundated the site approximately 50 minutes later to devastating effect. Primary and auxiliary reactor cooling circuits and electrical power were lost. Over the course of three days the cores of Units 1, 2 and 3 (which had been in full operation before the earthquake) overheated and much of the nuclear fuel in the reactor cores melted. The high temperatures led to chemical reactions that released significant amounts of hydrogen gas, which exploded and caused structural damage to Units 1, 3 and 4 (the latter of which on 11 March was in a planned outage). The accident was categorised at Level 7 of the International Nuclear Event Scale due to high radioactivity releases.

Addressing the considerable challenge of decommissioning the complex nuclear clean-up site, the Japanese government's flexible Mid-and-Long-Term Roadmap reflects both the priority for safety and the implementation system. The 2019 (fifth) revision focusses on managing the contaminated water and the treated water stored on site and other radioactive waste, as well as on removal of both stored fuel and fuel debris. Environmental remediation is performed to allow wherever possible the safe return of the population to affected off-site areas; the decontamination in the Special Decontamination Area had been performed as planned by the end of March 2017, and the work in the Intensive Contamination Survey Area was completed in March 2018.

Institutional shortcomings uncovered in the aftermath of the accident prompted the government of Japan to completely redesign its approach to nuclear regulation and oversight. It established the Nuclear Regulation Authority (NRA) and assured its organisational, cultural, financial and political independence. The NRA quickly established new regulatory requirements to assure the safe operation and improved resilience of Japanese facilities in the face of conceivable events. The NRA continues to learn and is currently adopting a new risk-informed oversight process whose implementation includes essential discussions and interactions with operators. Japan has also adapted or supplemented legislation as needed in order to enhance safety, emergency preparedness and the nuclear liability framework enabling compensation.

At the international level too, much has been learnt. NEA projects supported by participating member countries and the government of Japan, as well as other NEA joint efforts, have delivered cross-cutting safety research. A common understanding of the accident has led to improved tools to support decommissioning and a better quantification and understanding of plant safety margins. Potential improvements have been identified in several areas such as fuel designs that are more tolerant of accidents and electrical power systems that are more robust. Comprehensive safety reviews were done across NEA countries to assess readiness for severe accident conditions, and have identified plant and process improvements to mitigate the potential impact of external hazards. As highlighted in the 2016 NEA report *Five Years after the Fukushima Daiichi Accident: Nuclear Safety Improvements and Lessons Learnt*, many such measures have been implemented.

To address near-term challenges in handling very low-level post-accident radioactive waste, the NEA examined how to develop a complex waste characterisation and categorisation process. NEA activities have also focussed on post-accident recovery management, including balancing decisions in radiological protection, as an important pillar of ensuring public health and well-being. Human aspects of nuclear safety, such as regulatory safety culture and broader stakeholder involvement in decision making, have been a significant focus of NEA activities. This report details the range of such initiatives and the lessons learnt. The activities of other international organisations are acknowledged and referenced as well.

Significant issues remain to be faced as Japan continues the difficult, long-term effort to clean up the Fukushima Daiichi site and revitalise the surrounding communities impacted by the earthquake and resulting tsunami and nuclear accident. Technical challenges concern, inter alia: fuel debris removal; decontamination methods; environmental remediation; and related waste issues. Regulatory and legal challenges include, inter alia: regulation under uncertainty; reinforcing institutional nuclear safety systems; legal preparedness; holistic optimisation decisions; and effective regulatory engagement with a broad range of stakeholders including licensees and the public. The ongoing task of rebuilding and revitalising communities and local economies should benefit from a guidance framework outlining a consensual process to facilitate recovery and enable the communities to develop greater societal resilience. Reflection and action will be needed on preserving intergenerational knowledge and experience, and also on clarifying ethical values and challenges.

This report finds that significant progress was achieved by Japan in vigorously addressing the accident through actions and reforms at both the technical and institutional levels. With co-operation from the NEA and other international organisations, the technical understanding of the accident event has progressed significantly, thereby aiding all countries to improve safety and preparedness. Environmental, social, political and economic aspects, including safety culture, must be a continued focus if nuclear power is to play its part in addressing the world's need for clean, safe, reliable energy.

This report concludes by noting that the NEA will continue its strong support for the long process ahead to address the aftermath of the Fukushima Daiichi accident and continue developing knowledge that can be gleaned from the experience the accident has generated. Recommendations are offered in nine areas, with advice on how to pursue and enhance:

- effective and balanced regulatory transparency, openness and independence;
- systematic and holistic approaches to safety;
- participation in international development of decommissioning technologies;
- well-planned waste management and disposal;

- improvements to damage compensation practices;
- stakeholder involvement and risk communication;
- recognition of mental health impacts in protective action and recovery;
- opportunities for economic redevelopment; and
- knowledge management.

These key areas highlight the many opportunities for Japan to provide important and needed leadership on the international level.

1. Introduction

On 11 March 2011, Japan was struck by a massive earthquake, which initiated a tsunami that inundated a large portion of the east coast of Japan. The tsunami caused massive devastation and approximately 20 000 people were killed or were declared missing. The tsunami also led to one of the most severe nuclear power site accidents in history, at the Tokyo Electric Power Company (TEPCO) Fukushima Daiichi Nuclear Power Plant. Three of the station's six reactors suffered core melts and the entire facility was severely damaged. The Great East Japan Earthquake, the tsunami, the nuclear accident, and the resulting release of radioactive material led local authorities to initiate an evacuation of approximately 150 000 people. By deposition, the radioactive releases contaminated a large area of both the Fukushima Prefecture and others. While post-accident analyses have verified that the radiation from the accident has not led to any direct impact on human health,[1] the series of events impacted the well-being of individuals and the community, and the evacuation is reported to have resulted in early deaths from the lack of health care or medicines, stress-related problems, etc. (ICRP, 2016).

After nine months, the immediate risks posed by the damaged reactors were brought under control by achieving cold shutdown of the facility. In the years since, Japanese authorities have undertaken very challenging work to address the on-site and off-site consequences, take forward the decommissioning of the site, conduct the remediation of the affected areas in the Fukushima Prefecture and neighbouring prefectures, and rebuild the social and economic fabric of the areas impacted by the earthquake, the tsunami and the nuclear accident. During and after the accident, the global community has come together with Japan to both offer any needed assistance and draw lessons to further improve nuclear safety worldwide. This endeavour has been greatly facilitated by the openness of the Japanese government and industry leaders as well as the co-operation of international organisations, governments and companies.

This is the third major report by the Nuclear Energy Agency (NEA) on the Fukushima Daiichi accident. In 2013, the NEA published its first report, *The Fukushima Daiichi Nuclear Power Plant Accident* (NEA, 2013d). This document focused on the NEA's and its member states' immediate response to the accident. The second major NEA report, *Five Years after the Fukushima Daiichi Nuclear Power Plant Accident* (NEA, 2016b), discussed the measures taken or in progress in NEA member states to improve

1. The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) assessed radiation exposures of the public, workers and non-human biota that resulted from the accident at the Fukushima Daiichi Nuclear Power Plant. Findings, including discussion of health implications, were presented to the General Assembly of the United Nations in 2013 (UNSCEAR, 2014; (www.unscear.org/unscear/en/fukushima.html, accessed 22 October 2020). UNSCEAR has gone on to discuss more detailed analyses and new information that subsequently became available (UNSCEAR, 2015; 2016; 2017); a revised report is in preparation (UNSCEAR, forthcoming).

further the safety of nuclear facilities in line with the underlying principle of "continuous learning and improvement." All high-risk industries, including nuclear, strive to learn and improve from all experience. The accident at Fukushima Daiichi has highlighted the need to ensure the lessons learnt are broadly shared and addressed now and in the future.

This report is intended to assist Japan's recovery from the accident for a better future for all, and more generally enhance the safe use of nuclear energy worldwide. It summarises, in a ten-year retrospective: the circumstances of the accident, the initial response in Japan and worldwide, and the societal impact (Chapter 2); the current status of the Fukushima Daiichi site, including the progress on its decommissioning and the environmental remediation of the surrounding areas, the technical issues associated with these combined activities, and the wider social and political aspects (Chapter 3); the activities of the NEA, other international organisations and NEA member countries (Chapter 4); the global impact and lessons learnt (Chapter 5). Looking forward, Chapter 6 addresses further challenges and, finally, Chapters 7 and 8 identify conclusions and make policy recommendations.

This report, as did the other major reports, seeks to complement the work of other international and national organisations including the International Atomic Energy Agency (IAEA) and the World Association of Nuclear Operators (WANO) which have also contributed greatly to further understanding and safety improvements stemming from the accident at Fukushima Daiichi. This report has been written using available information and the insights gained from interviews conducted with a broad group of experts and nuclear leaders in Japan and from around the world.

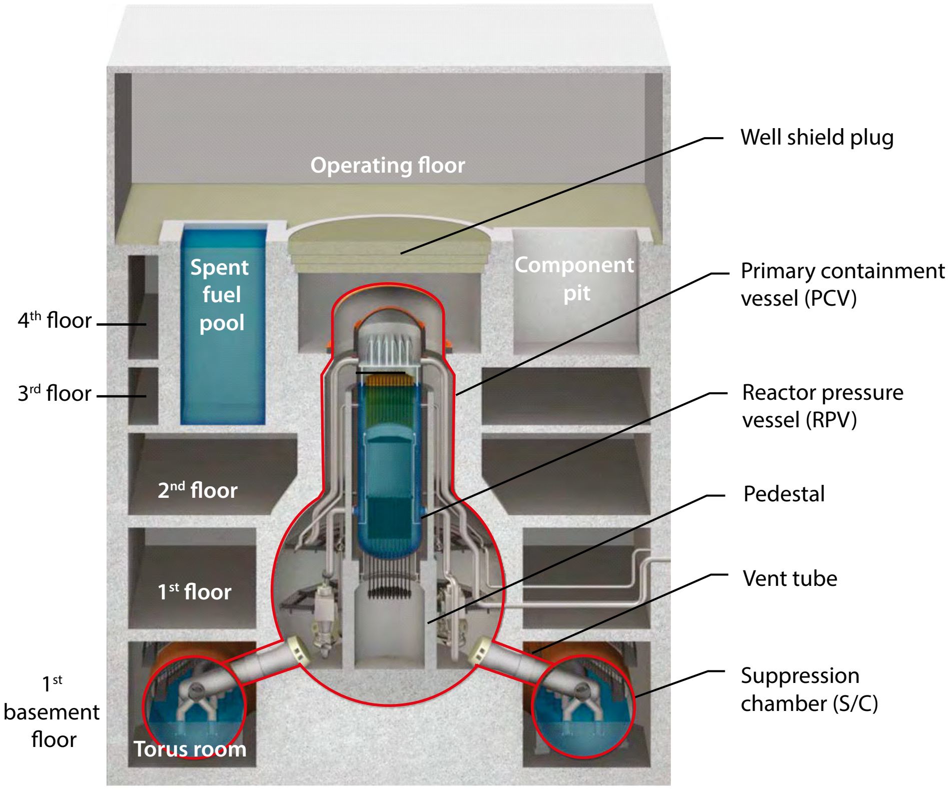
While the report may be of interest to a wide range of individuals and organisations, including the general public, it is intended to be useful in particular to policy makers and leaders involved in assuring a healthy and safe society through the peaceful use of nuclear energy. Even more fundamentally, this report may assist those leading the rebuilding of society and communities after major catastrophic events, such as the Fukushima Daiichi nuclear accident, and in developing effective recovery plans.

2. The accident at the Fukushima Daiichi Nuclear Power Plant

2.1. Basic information about the design and safety characteristics of the Fukushima Daiichi reactors

Understanding the accident and the responses to it does not require a deep technical knowledge of nuclear technology, but rather an understanding of the basic design of the Fukushima Daiichi reactors and of how to keep such technology safe.

Figure 1.1: Basic design of Fukushima Daiichi boiling water reactors



Source: NDF.

Figure 1.1 outlines the characteristics of the boiling water reactors (BWRs) on this site. They have five main elements relevant to this discussion:

- the reactor core, which includes nuclear fuel assemblies clad in zirconium alloy, as well as control rods;
- the reactor pressure vessel (RPV), which encloses the reactor core and water/steam used to transfer the heat;
- the primary containment vessel (PCV), consisting of: a robust free-standing bulb-shaped steel drywell backed by a reinforced concrete shell, which acts as a further containment, and the wetwell;
- the suppression chamber (SC), a torus-shaped steel tank holding water inside to absorb steam and thus reduce or "suppress" pressure;
- the spent fuel pool (SFP), where fuel removed from inside the reactor is held for cooling over a period of years, while it emits high levels of heat and radiation.

These elements support the three essential safety functions:

- to control the nuclear reactions in the reactor core as well as harmful chemical reactions that may occur in materials at high temperatures;
- to cool the reactor fuel;
- to contain the radiation and radioactive material.

These safety functions are interrelated: if the fuel is not cooled to remove decay heat,[1] it can begin to melt, leading to chemical reactions that can result in overpressurisation of the PCV and breach of the containment barrier.

To ensure that these three functions are maintained, the design and engineering of BWRs includes several safety systems that rely on the following principles: defence in depth; diversity; redundancy; physical separation and functional independence; and so forth. The safety systems in BWRs normally require electricity or other energy sources to operate effectively.[2]

In simple terms, at Fukushima Daiichi a loss of electrical power caused the cooling systems to stop functioning, which caused the fuel assemblies to overheat and melt, in turn causing the zirconium fuel cladding to react with high temperature steam, releasing hydrogen and overpressurising the PCV. The released hydrogen ignited, causing large explosions that damaged the reactor buildings.

The complex sequence of events that led to this nuclear accident is explained below.

2.2. Synopsis of the accident, the on-site damage, and the local effects

The Japan Meteorological Agency reported that on 11 March 2011 at 2:46 p.m. (Japan Standard Time), the Great East Japan Earthquake[3] (often dubbed "Tohoku Earthquake") occurred and shook the eastern part of Japan with a highest point intensity of 7 (the maximum point of the Japanese intensity scale). The earthquake, of 9.0 magnitude on the Richter scale, was centred about 130 km east of Oshika Peninsula, Miyagi Prefecture, Japan, at a hypocentre depth of 24 km. The seismic source area of the earthquake was in the plate boundary between the North American tectonic plate and the Pacific tectonic plate. The displacement in the seabed caused by the seismic event generated a chain of tsunamis which inundated hundreds of square kilometres of the Japanese coastline, destroyed or damaged over a million buildings in coastal ports and towns, and resulted in the death of approximately 19 729 people, with a further 2 559 people missing and 6 233 injured.[4]

1. The heat produced by the decay of radioactive fission products after a reactor has been shut down.
2. In many newer nuclear plant designs, often referred to as "Generation III or IV" technologies, plant safety relies less on electricity and, instead, applies natural forces such as gravity and convection to prevent a nuclear accident. Some Generation III reactors rely on electricity with increased diversity and redundancy, while others rely on passive features.
3. Website of the Japan Meteorological Agency, www.jma.go.jp/jma/en/2011_Earthquake/2011_Earthquake.html (accessed 22 October 2020).
4. Website of the Reconstruction Agency of the Government of Japan (accessed 22 October 2020), www.reconstruction.go.jp/

The Fukushima Daiichi Nuclear Power Plant, owned and operated by TEPCO, has six BWRs and is located just on the border of the towns of Okuma and Futaba, in the Fukushima Prefecture of northeast Japan. The earthquake caused no damage to the reactor safety systems, and the three operating units (Units 1, 2 and 3) responded as designed and automatically shut down upon indication of high vibratory ground motion. Unit 4 was in a planned outage, and all nuclear fuel assemblies had been placed in the SFP for a scheduled inspection; Units 5 and 6 were both under preparation for restart after periodic fuel change. However, earthquake damage caused the loss of all external power supply sources, i.e. six separate sets of electricity transmission lines; as designed, the emergency diesel generators started to provide electrical power to emergency equipment.

At this stage of the event, cooling for the Unit 1 reactor was initially maintained through the undamaged automatic functioning of two isolation condensers[5] returning condensed water to the RPV. However, due to overcooling of the reactor cooling system, operators in the main control room reverted to cycling only one of the isolation condensers. Cooling for the Unit 2 and 3 reactors was initially maintained automatically using the reactor core isolation cooling (RCIC) system in Unit 2 and both RCIC and the high-pressure coolant injection (HPCI) systems in Unit 3. At this point, the reactors were in a safe condition and the cores were cooling as designed.

Approximately 50 minutes after the earthquake, the tsunami that struck a large portion of north-eastern Japan inundated the Fukushima Daiichi site, bringing a huge wave of water and debris crashing into the facility, particularly Units 1, 2, 3 and 4 and their supporting systems. The tsunami submerged and damaged the seawater pumps for both the main condenser circuits and the auxiliary cooling circuits, notably the residual heat removal (RHR) cooling system. The emergency diesel generators, the electrical switchgear and the direct current[6] (DC) batteries, almost all of which were located in the basements of the turbine buildings, were inundated. Note that two diesel generators for Units 2 and 4 and DC batteries at Unit 3 survived the tsunami, before the diesel generators became inoperable due to a switchgear failure and the depletion of DC batteries. An air-cooled emergency generator dedicated to Unit 6 had been installed on higher ground and survived the tsunami.

These events led to a complete loss of electrical power (a scenario known in the nuclear sector as a “station blackout”) at Units 1, 2 and 3 which had all been in full operation before the earthquake. While Unit 4 was not in operation and no fuel was in the reactor, the loss of power left the operators without instrumentation, controls, or lighting and unable to monitor the condition of the used fuel in the reactor’s SFP nor deliver any needed cooling to the pool.

Conditions at the site were very difficult. As described above, the loss of electrical power and disabling of multiple systems prevented operators from cooling the reactors and the SFPs. Further, the earthquake and tsunamis damaged and obstructed roads, which made it difficult for off-site emergency services to gain access to the site.

Without cooling water, the cores of Units 1, 2 and 3 overheated and much of the fuel melted over the first three days. Many official reports document and catalogue the core damage, which include zirconium structures in the core reacting with high temperature water/steam and releasing hydrogen through the resulting chemical reaction. The highly flammable hydrogen gas generated by this high-temperature process caused explosions on 12 March at Unit 1, 14 March at Unit 3, and 15 March at Unit 4. In Units 1 and 3, these explosions significantly damaged the reactor buildings, destroying the upper structures of the buildings.

At Unit 1, the return valves of the isolation condenser closed after the loss of power, meaning that the ability to manipulate the cooling function of the isolation condenser was lost. This occurred unknown to the Unit 1 shift supervisor. Reactor decay heat accumulated in the suppression chamber

english/topics/GEJE/index.html.

5. The isolation condenser in a boiling water reactor is a safety system that removes decay heat when for any reason the connection between the reactor and the main condenser is disrupted, i.e. the reactor is isolated. The isolation condenser has a smaller heat sink capacity than the main condenser.

6. In DC systems, electric current moves in one direction with constant strength. DC is obtained from storage sources such as batteries.

with no capability to remove heat via the RHR to the ultimate heat sink of the ocean. Core melting began about 5 hours later, which led to pressurisation of the PCV from the accumulation of hydrogen gas and steam within the PCV. This high containment pressure is estimated to have produced a leak at the containment upper head, which released fission products and hydrogen gas into the upper operating floor of the reactor building, resulting after about 24 hours in the hydrogen explosion at the Unit 1 reactor building.

At Unit 2, the RCIC system continued to operate for nearly three days, providing makeup water to the reactor from the outside-of-containment condensate storage tank (CST) and later from the in-containment suppression chamber water. Eventually the Unit 2 RCIC failed and pressure in the RPV increased until the operators opened a safety relief valve to release the pressure in an attempt to allow water to be injected using fire trucks. The action was ultimately unsuccessful and the Unit 2 reactor core melted as well. However, the three days of cooling using the RCIC and the attempt to inject water may have reduced the severity of the meltdown, given that much of the Unit 2 fuel material was retained in the lower head of the vessel (according to post-accident RPV imaging). In addition, the Unit 2 reactor building did not suffer a hydrogen explosion. This was likely due to the dislodgement of the Unit 2 blowout panel caused by the Unit 1 reactor building explosion; with this building panel removed, hydrogen gas was able to escape the Unit 2 building before a flammable mixture could form.

The second reactor to suffer fuel melting was Unit 3, where the RCIC system was started following closure of the main steam isolation valves (MSIVs). In Unit 3, some battery power remained available for more than 24 hours and the RCIC system was initially used to move heat from the reactor to the suppression chamber. However, as in Unit 1 there was no RHR available to move suppression chamber heat to the ultimate heat sink of the ocean, and temperatures and pressures in the suppression chamber and PCV increased continuously. The RCIC system stopped on 12 March and the HPCI system automatically started. The HPCI system was unable to inject water under the degrading RPV conditions and operators shut down the HPCI system to alter the injection route. However, operators were not successful in establishing the alternative injection line or reactivating the RCIC system. RPV pressure returned to the SRV cycling pressure until an unintended activation of the automatic depressurisation system (ADS) occurred. Before that, core damage and hydrogen generation occurred, resulting in an accumulation of hydrogen and subsequent explosion in the reactor building upper floor area, destroying the upper reactor building. Structural debris from the reactor buildings of both Units 1 and 3 fell into their respective SFPs.

As noted above, Unit 4 was undergoing a scheduled outage; it had been shut down prior to the accident and the reactor fuel had been placed in the SFP. However, Unit 4 experienced a hydrogen gas explosion on 15 March that was subsequently determined to be caused by gas backflow from Unit 3 to Unit 4 via the common stack and the standby gas treatment system (SGTS) pipes. At the time, however, because operators lacked the ability to monitor SFP water level and temperature, they thought the explosion might have been caused by overheated, uncovered fuel in the SFPs of Units 3 and/or 4. This concern prompted several mitigation efforts, including remote visual inspection via helicopter which confirmed the presence of sufficient water in the Unit 4 SFP, but was inconclusive regarding the level in the Unit 3 SFP. As a result, initial airdrops of water from helicopters, and intermittent water spray from fire engines and concrete pump trucks, were used until the end of March. Further analyses conducted by TEPCO confirmed later that an adequate water level was maintained in each of the SFPs of Units 1 to 4 throughout the aftermath of the accident, and that the concentrations of radioactive materials in the pool water indicated that the fuel in the pools had been kept in sound condition. TEPCO also restored circulating cooling and purification systems of the pool water in late 2011.

The complete loss of electrical power to the damaged units extinguished all control room lighting and instrumentation, and severely limited the ability of operators to communicate with others outside the control room. Units 1, 2, 3 and 4 remained without alternating current (AC)[7] electrical power for between nine and fourteen days respectively after the station blackout. Stable cooling (or cold shutdown) of all the reactors and SFPs was not fully confirmed until December 2011. This delay in

7. AC current is that used for the transmission of electricity on grids which is generated by various types of power systems, including diesel generators.

restoration of safety functions required plant operators to carry out mitigative actions in the power station amidst challenging and hazardous conditions, including debris from the tsunami, darkness, high temperatures, high radiation, and repeated aftershocks and tsunami warnings. Operators worked heroically for many days under great stress and fatigue to restore safety functions and attempt to mitigate the damage to the plant.

The Nuclear and Industrial Safety Agency of the Ministry of Economy, Trade and Industry (METI) categorised the accident at Fukushima Daiichi as a Level 7 event on the International Atomic Energy Agency's (IAEA) International Nuclear Event Scale. This highest point on the IAEA scale was assigned due to high radioactivity releases, eventually totalling as follows: approximately 100-500 PBq (I-131) and 6-20 PBq (Cs137) as atmospheric releases (80% of which was deposited over the ocean); 10-20 PBq (I-131) and 3-6 PBq (Cs137) released directly to the ocean (UNSCEAR, 2014); 60 TBq to ground water; and an additional 0.5 TBq/y to plant harbour water stemming from the implementation of measures to prevent groundwater entering into the ocean. In view of these releases, the Fukushima Daiichi accident is considered the worst civil nuclear accident since the severe accident at Chernobyl in 1986.

While post-accident analyses have verified that the radiation from the accident has not led to any direct impact on human health, the evacuation of more than 150 000 people living in surrounding areas is reported to have resulted in early deaths associated with the evacuation of citizens from the area, lack of access to health care or medicines, stress-related problems, and other causes. The series of events – the earthquake, the resulting tsunami and nuclear accident, and later the evacuation and some other post-accident recovery measures – impacted the well-being of individuals and the community.

2.3. The initial emergency response in Japan

Approximately 15 minutes after the Great East Japan Earthquake, the Emergency Response Centre (ERC) headed by the Site Superintendent at Fukushima Daiichi was activated. The ERC was located in a seismically isolated building, outfitted with an autonomous electrical power supply and ventilation systems with filtration devices. The use of this building enabled mitigatory actions to continue at the site during the response to the accident. Although arrangements existed prior to the accident for the on-site ERC to request support (e.g. additional staff and equipment) from TEPCO Headquarters, the extensive damage to the transportation infrastructure from the earthquake and tsunami, as well as insufficient pre-planning, hindered the timely delivery and deployment of such support at Fukushima Daiichi.

In response to the emergency, personnel from TEPCO, contractors, and staff from other Japanese nuclear power plants (not operated by TEPCO) were dispatched to the site to assist with various tasks, including restoring power and monitoring instruments, injecting cooling water into reactors, removing rubble and monitoring radiation levels. Personnel from national government agencies and organisations – such as the Japan Self-Defence Force, police and firefighters – were also dispatched to the site to assist in mitigation and recovery activities, including operating the large equipment needed to spray water onto the spent fuel and to move debris.

Among the many actions to protect the public living near Fukushima Daiichi, the national government declared a nuclear emergency and an evacuation order was issued on 11 March for people within a 3 km radius of the site. As the situation at the site worsened, the decision was made on 12 March to extend the evacuation zone to 20 km.

From the beginning, Japan worked closely with other countries and international organisations, sharing information and reports. Many countries[8] offered assistance including the United States whose Armed Forces stationed in and around Japan provided humanitarian assistance and disaster relief as well as direct support to Fukushima Daiichi Nuclear Power Plant in Operation "Tomodachi (Friends)."

8. The government and TEPCO received goods and supplies (pumps, fire engines, remote controlled robots, dosimeters, personal protection equipment, germanium semiconductor detectors and other tools) from many countries and international organisations.

2.4. The initial response worldwide

All NEA member countries took early actions to ensure, improve and confirm the safety of their existing and planned nuclear power plants and the protection of people from the hazards of exposure to radiation (NEA, 2013; ENSREG, 2013; IAEA, 2014b). Preliminary safety reviews represented an essential part of these actions. The reviews concluded that there was no technical basis for requiring the currently operating plants to shut down. The reviews also found that short-term actions taken by plant operators (where necessary) provided assurance of the continued safe operation of the plants, while more thorough evaluations of the accident and of the impact on continued safe operation were performed.

The accident also highlighted a number of other issues, including the importance of a strong nuclear safety culture; the challenges to supporting reliable human performance under extreme conditions; communications and stakeholder involvement in decision making; and management of the impact of post-accident contamination on food and goods (NEA, 2016b).

One important and beneficial outcome of the global response was the development of much greater international discussion and co-operation to enhance nuclear safety, particularly through institutions such as the NEA, IAEA and the World Association of Nuclear Operators. There exists today more international co-ordination in the nuclear safety area than at any previous time.

3. Current status of technical and policy responses to the accident at Fukushima Daiichi

3.1. Decommissioning the Fukushima Daiichi site: Initial state, strategy and progress

Decommissioning may be defined in the nuclear sector as "achieving the goal of carrying out all administrative, technical and societal actions to allow the removal of a nuclear site from regulatory control."[1] The process may target different end state degrees of the former nuclear site's availability for other activities, ranging from "brown field" to "green field" status. Decommissioning, which includes many component activities ranging from reactor shutdown to site decontamination, is a complex multi-year process in the best of cases.

Decommissioning of the Fukushima Daiichi site is a unique challenge given the initial state of the site after the accident and limited experience in Japan with the decommissioning of complex nuclear clean-up sites. In addition, decommissioning activities are inherently different from operating a nuclear power plant and, therefore, constitute a challenge for both the site operator and the regulator. Further, the clean-up activities began as Japan and its people were still recovering from the largest earthquake and tsunami that Japan had suffered in recorded history. Plans and analyses undertaken since the accident indicate that decommissioning of the site will take several decades and the end state has not been determined. When considering the decommissioning progress to date this context has to be taken into account.

3.1.1. Initial state of the site after the accident

The initial state of the Fukushima Daiichi Nuclear Power Plant immediately after the earthquake and tsunami was one of devastation. Inundation of the site by the tsunami blocked roads and access routes, and caused extensive damage to the buildings. In this early stage, only Units 5 and 6 retained alternating current (AC) power. The diesel generators for Units 1-4 had failed and no off-site power sources were yet available.

The devastation was subsequently increased by the hydrogen explosions in Units 1, 3 and 4. Moreover, the fuel in three reactors (1, 2 and 3) had melted and some of the resulting corium material had migrated from the reactor pressure vessels into the containment vessels. Importantly, there were high radiation levels around the site both from direct radiation shine and from airborne radioactive contamination. This hampered recovery operations, limiting the amount of time workers could spend close to high radiation sources, and work in all areas required the use of protective clothing and respiratory protection.

1. NEA (2020), *Decommissioning and legacy management*, www.oecd-nea.org/decommissioning (accessed 22 October 2020).

The first priority during an initial recovery stage was to stabilise the site to reduce potential risks to the site personnel and the surrounding communities. Only when the site was made sufficiently safe could consideration be given to decommissioning. This stabilisation included the following: restoring electrical power to the site from off-site sources; arranging robust cooling of the reactor cores and spent fuel pools (SFPs); establishing criticality monitoring and protection; clearing access routes; reinforcing structures where necessary to ensure they were safe; installing air filtration units in buildings; stabilising contamination on surfaces to reduce re-suspension of radioactive particles. A particular problem for site personnel during the initial phase of the accident was the increasing volume of highly contaminated water accumulating on site and overflowing to the sea.

The operators faced a daunting task to stabilise the reactors to reach what was deemed to be a "cold shutdown condition"[2] where the reactor pressure vessel (RPV) temperature at the bottom generally was below 100°C and the public radiation exposure from any additional release was significantly minimised.[3] This condition, which was achieved in December 2011, was an important milestone. Decommissioning was begun in earnest at this point.

3.1.2. Decommissioning responsibilities and strategy

To respond to the complexities and uncertainties associated with decommissioning the multiple damaged reactors at Fukushima Daiichi, the decommissioning organisational structure has added aspects to those found in nominal circumstances. Five main elements have been involved:

- the national government, predominately the Ministry of the Economy, Trade and Industry (METI) and the Ministry of Education, Culture, Sports, Science and Technology (MEXT) – establishing necessary policies and legislation, authorising funding, and setting major milestones;
- the independent regulator for the site (the Japanese Nuclear Regulation Authority, NRA) – setting rules for decommissioning and regulating the activities on the site;
- the Nuclear Damage Compensation and Decommissioning Facilitation Corporation (NDF) – establishing the technical strategy for decommissioning, overseeing and managing the decommissioning programme in line with the strategy, deciding the amount of funds that the Tokyo Electric Power Company (TEPCO) should hold in reserve with NDF in each fiscal year and jointly establishing the plan for fund withdrawal to meet decommissioning needs;
- the responsible operator/decommissioning company, TEPCO – developing the Mid-and-Long-Term Decommissioning Action Plan in line with the Roadmap set by the government and the NDF Strategy and undertaking the decommissioning on the site;
- the Japan Atomic Energy Agency (JAEA) – implementing research and development (R&D) programmes and human resource development programmes in accordance with the technical strategy for decommissioning established by the NDF.

Decommissioning of a complex radiological contaminated site such as Fukushima Daiichi implies a considerable number of unknowns, some of which will arise or be resolved only with time. Thus, decommissioning must be conducted using a cautious, stepwise approach without the benefit of an established detailed safety case covering the entire process. A flexible plan, reflecting both the priority for safety and co-ordinated resource allocations, was first established in December 2011 as the Japanese government's Mid-and-Long-Term Roadmap (METI, 2011)[4], and it was revised five times. The latest revision (METI, 2019) lays out the following technical aspects for action: i) the contaminated water management; ii) removal of fuel from SFPs; iii) retrieval of fuel debris; and iv) the management of

2. This is different from the normal definition of cold shutdown when after normal shutdown and cooling the reactor pressure vessel is at atmospheric pressure and the water temperature is sufficiently below boiling point to allow the reactor pressure vessel to be opened up e.g. for refueling. Several of the Fukushima Daiichi reactor pressure vessels had been breached and hence would not hold water as would be normal for cold shutdown conditions.

3. After this effort, the exposure of the public by additional release is being significantly held down as well, and a target of not greater than 1 mSv/year at the site boundary was achieved in March 2016.

4. The Mid-and-Long-Term Roadmap is set and revised by "the Inter-Ministerial Council for Contaminated Water and Decommissioning Issues" for which METI provides the secretariat.

radioactive wastes. Human resource development, technical research and development, international co-operation programmes and symbiosis with local communities are covered as well.

The initial strategy for decommissioning in 2011 had to take into account the following considerations:

- Damage to fuel in the reactor building SFPs of Units 1, 3 and 4 potentially may have been caused by debris.
- Containment of the buildings was breached. In the case of Units 1 and 3 there was extensive damage to the top of the reactor building (on the fifth floor and above), such that the SFPs were substantially open to the environment. For the case of the reactor building of Unit 4, the explosion damaged and compromised the structural robustness of the third and fourth floors.
- Heavily contaminated water had accumulated in some of the buildings, particularly the turbine and reactor buildings, and underground conduits connected to the buildings. The water that was being used to continuously cool reactors Units 1, 2 and 3 was escaping and mixing with ground water and rain water entering the buildings.

Fuel debris was and is very highly radioactive, of unknown form and properties, and with a potential (albeit remote) risk of re-criticality. After extensive investigations, using robotic cameras inside the primary containment vessels (PCVs), accident progression analysis and muon radiography, a general understanding of the location of the fuel debris is now established.

The initial strategy has been reviewed periodically and refined by the incorporation of further knowledge and technical understanding. The NDF has established five guiding principles[5] for the decommissioning giving substance to the priority for safety or reducing risk. It has also developed a risk reduction and safety assurance strategy for decommissioning, and an extensive technical programme. The NDF's activities and work programmes, as well as these principles, are specified in its strategic plan (NDF, 2020).

3.1.3. Progress in decommissioning

In co-operation with TEPCO, METI updates information monthly in regard to the progress of decommissioning, including the situation of fuel removal from the four units, on-site storage and retrieval of fuel debris (METI, 2020b).

Many enablers to successful safe decommissioning have been put into place, including:

- maintaining the safety of the reactors;
- reducing the dose levels on site;
- optimising workers' use of personal protective equipment to enable on-site work to progress more efficiently and with better attention to industrial hazards;
- providing welfare and other structures such as canteens and rest centres;
- creating company structures such as TEPCO's Fukushima Daiichi Decontamination and Decommissioning Engineering Company (FDEC);
- introducing project management processes reflecting the project nature of the decommissioning programme;
- research and development;
- local community engagement;
- international co-operation.

Alongside the specific decommissioning activities described below, other activities to improve safety have included using remote heavy equipment to secure the removal of the upper portions of the reactor 1 and 2 exhaust stack which was contaminated and partially damaged. This work was completed by a local business, illustrating the operator's strong intention to co-operate with local enterprise as much as possible.

5. Namely: safe, proven, efficient, timely and field-oriented (NDF, 2020).

Fuel removal from reactor building SFPs

Fuel removal is a process to transfer fuel assemblies in the SFPs of reactor buildings of the Units 1 to 4 to more stable storage in the site. Before starting the transfer, the units need complete preparatory works, such as removal of rubble and debris in the SFPs especially in Units 1 and 3, reduction of dose levels of the operation floors, installation of weather shielding, and installing the fuel handling machines and cranes that must handle the required casks containing the fuel which, loaded, weigh some 50 to 100 metric tonnes.

Recovered fuel storage

There are two centralised spent fuel storage facilities on the site: a common pool, where the fuel is stored under water to provide shielding and cooling; and an interim cask storage area, where the spent fuel is stored dry in storage casks. This latter area has a much smaller capacity compared to the common pool. The interim cask storage area receives spent fuel from the common pool, thereby releasing space for the fuel recovered from the reactor SFPs. At the time of the accident, there were nine existing dry casks of fuel stored on site. The area of cask storage is planned to be expanded in the future.

Initially, the common pool had to be restored to a condition sufficient for it to handle fuel. This was achieved in November 2012. The operation of the interim dry cask storage area started in April 2013 with the receipt of the nine existing dry casks. In the middle of 2013, spent fuel started to be removed from the common pool for storage in dry casks. Later that year the interim area commenced storing spent fuel from Unit 4.

Fuel debris retrieval

Retrieval of fuel debris relies on an understanding of its actual distribution in reactors 1 to 3. The current understanding remains uncertain and efforts are ongoing to try to refine it. It has been built up from measurements during the accident, muon radiography, analytical modelling and understanding of the progression of the accident from tests and in-situ surveys using robotic equipment. The surveys have been hampered by the high radiation dose rates in the access routes to the ports in the PCVs and by the very high dose rates in the PCVs. Direct surveys inside the RPVs are still not possible. R&D projects are underway to establish access routes and investigation technologies inside the RPVs.

NDF has undertaken considerable work on the technical basis for fuel debris retrieval, as shown by its Technical Strategic Plan (NDF, 2020). Its 2019 Technical Strategic Plan was used as a basis for TEPCO's Mid-and-Long-Term Decommissioning Action Plan issued in March 2020. This is the foundation for the next TEPCO Mid-and-Long-Term Decommissioning Action Plan detailing the work to fulfil the Roadmap.

Unit 2 has been chosen as the first unit to start fuel debris retrieval. It is intended to be conducted in a stepwise approach commencing by the experimental retrieval of debris using a long-reach (approximately 22 metre) robotic arm[6] going through a sealed opening in the side of the PCV to obtain gram quantities for analysis. This first step was planned to start in 2021 in line with the current Roadmap. In December 2020, however, TEPCO and the International Research Institute for Nuclear Decommissioning (IRID) announced that the start would be postponed due to the delay in the development of equipment, due mainly to the impact of the COVID-19 pandemic. The first step will be followed by a gradual increase of the scale of retrieval. Further safety and process analysis will be conducted throughout operations to help refine the approach and maximise safety. Considerations include maintaining adequate cooling, criticality monitoring and control, containment (especially of any dusts generated), and providing adequate shielding.

Further work is in hand to determine the requirements and provide the appropriate facilities for handling, analysing and storing the fuel debris retrieved.

6. A suitable robotic arm is being procured from a company in the United Kingdom experienced in the production of such equipment.

Contaminated water management

A large quantity of contaminated water was created during the accident and additional water became contaminated and accumulated as it contacted radioactive material or reactor fuel debris. The contaminated water is from three main sources, arising from: the continuing cooling of the reactors; ground water flowing into the buildings; and rain falling onto and into buildings. Currently, measures ensure that the level of water, some heavily contaminated, in the basement of the buildings remains below the level of surrounding groundwater.

Measures to manage the accumulation of contaminated water have been based on three policies:

- remove the source of the water contamination;
- redirect and hence reduce the amount of clean water interacting with contamination sources;
- retain contaminated water and prevent it from leaking out to the environment.

A substantial number of measures in line with these policies have been put in place, including groundwater bypass, subdrains, and the installation of impermeable walls under the ground. The engineering measures associated with this effort have been impressive and progress has been continual. The amount of contaminated water generated has decreased from an average of approximately 470 m^3/day during the twelve months until March 2015 when the measures went into operation, to an average of approximately 180 m^3/day during the twelve months until March 2020 (METI, 2020b). In addition, facilities using existing technologies for treating the contaminated water were put in place early on. These are of two main types:

- KURION and SARRY, mainly for removing caesium and strontium from the water accumulated in building basements;
- ALPS, a multi-nuclide removal system.

Secondary waste generated by the water treatment facilities is stored in robust containers while the processed water is accumulated in large tanks. Originally, many tanks were of a bolted panel design and were deemed more vulnerable to leakage, especially from potential future seismic events that could challenge the integrity of the tanks, and required maintenance. All of these tanks for storing the treated water have been replaced with smooth welded panel tanks. This tank replacement achieved a reduction in risk associated with leakage and reduced the regular maintenance and inspection requirements that placed additional demands on the workforce.

These processes have been very effective in removing nearly all the radioactivity from the contaminated water, with the exception of tritium[7] and carbon-14. For the case of treated water with a high concentration of radioactivity, TEPCO will process the water to reduce further the concentration.[8] The difficulties in resolving the issue of treated water with residual tritium illustrate the need for effective risk communication and stakeholder engagement.

Solid waste management

Radioactive solid waste has been and will be accumulated on the site in many forms and with levels of radioactivity ranging from slightly contaminated trees and rubble to very highly radioactive material from inside the reactors. This waste needs to be characterised, and suitable treatment and conditioning options and storage have to be determined. Appropriate facilities must be put in place and operated. Additionally, long-term storage or disposal arrangements must be established.

Basic policies for solid waste management on the site were established in the 2017 NDF Technical Strategic Plan and summarised in that year's revision of the Roadmap. Further technical and R&D work has been defined and will be implemented in accordance with the NDF Technical Strategic Plan (NDF, 2020).

7. Tritium is a radioisotope of hydrogen. When existing in the form of tritiated water (i.e. composition hydrogen-tritium-oxygen), it is not accumulated in marine biota and shows a very low dose conversion factor. It therefore presents a very minor contribution to radiation exposure to individuals.

8. METI (2018), *Briefing Session on the current status of Multi-nuclide removal equipment (ALPS) treated water at Fukushima Daiichi Nuclear Power Station*, www.meti.go.jp/english/press/2020/1028_002.html (accessed 15 February 2021).

Some facilities related to waste management facilities have been brought into operation on the site, including: interim tentative storage areas of solid waste; an incinerator for combustible waste; a solid waste storehouse; and analytical laboratories.

3.2. Remediating surrounding areas: Initial state, plans and progress

3.2.1. Initial state of the surrounding areas after the accident

The Fukushima Daiichi accident caused off-site releases that led to the evacuation of people from a 20 km radius around the site and some high dose areas, as well as to sheltering over a wider area up to 30 km within which voluntary evacuation was recommended by the Japanese government. Additionally, radioactive particles fell into the surrounding ocean and large quantities of radioactive water migrated from the site directly into the ocean. Restrictions were placed on food and water consumption and distribution. Initial dose rates in the evacuation zones were high: from 50 to 100 mSv/year, estimated from measurements in November 2011, in Iitate Village, 35 km north-west from the site; closer to the site, annual dose rate estimates increased by over 100 mSv/year (IAEA, 2013).[9] Aerial survey data regarding the extent of land contamination may be found in IAEA (2015; figure 4.4, from end of April 2011 up to November 2014) or on the NRA website[10] (from 2011 to 2020).

3.2.2. Remediation plans and targets

In August 2011 the Japanese Diet enacted the Act on Special Measures concerning the Handling of Environmental Pollution by Radioactive Materials. The act establishes that the government will be in charge of the decontamination and provides explicitly that TEPCO will bear the costs of the program of remediation of the areas affected by the accident. The following two categories for the remediation of land were specified:

- a Special Decontamination Area within a 20 km radius of the Fukushima Daiichi site and other areas where annual doses above normal in the year after the accident were predicted to be greater than 20 mSv;
- an Intensive Contamination Survey Area where annual doses were predicted to be between 1 and 20 mSv.

The national government took responsibility for determining and implementing the remedial plans in the Special Decontamination Area, whereas the local government implemented plans in the Intensive Contamination Survey Area.

A balance has to be struck in any remediation plans between i) lowering contamination, and hence radiation exposure to people in the affected area; ii) the time, risk and resources to reduce contamination; and iii) the amount of waste created. Initially, the government set the local public exposure target to 20 mSv per year, but after the public expressed concern, this was reduced to 1 mSv per year[11] (The National Diet of Japan, 2012). The targets set are onerous. The October 2013 IAEA international mission to review the remediation work noted that the government should explain to the public that an additional individual dose of 1 mSv/year due to the Fukushima Daiichi Nuclear Power Plant is a long-term goal, and that it cannot be achieved e.g. solely by decontamination work (IAEA, 2013). The IAEA review team considered, as did the international scientific community, that the stated targets were unrealistic and that an annual dose remaining under the value of 20 mSv/year would represent a more appropriate balance of situational factors, being in line with international standards and recommendations for protecting public health and safety.

9. The radiation levels decay with time from the initial high levels. These annual exposures are conservatively estimated using a constant assumed dose rate from initial hourly figures, without taking such decay into account.

10. NRA (2021), *Airborne Monitoring Survey Results*, https://radioactivity.nsr.go.jp/en/list/307/list-1.html (accessed 15 February 2021).

11. The exposure targets cited have a basis in international guidance. 20 mSv per year corresponds to the upper bound of reference-level recommended by ICRP Publication 146 (ICRP, 2020) for existing exposure situations such as areas in post-accident recovery.

3.2.3. Progress in remediation

In the Special Decontamination Area, contaminated housing and other buildings are demolished, and the contaminated lands are decontaminated by removing approximately 5 cm from the upper level of soil. The soil and waste removed from off-site decontamination works in Fukushima Prefecture (removed soils) are stored in an Interim Storage Facility (ISF) just outside of the Fukushima Daiichi site on land acquired for this purpose until the time of final disposal. As a result of remediation efforts, the decontaminated land has been gradually returned to use, many evacuation orders have been lifted, and people have been encouraged to return. Aside from Difficult to Return Zones (DRZ), the Japan Ministry of the Environment (MoE) completed the decontamination work in the Special Decontamination Area as planned at the end of March 2017. In DRZ, every municipality designates a certain area as Special Reconstruction and Regeneration Bases, in which the national government conducts an additional decontamination campaign. Six areas are currently designated as such since 2017. In the Intensive Contamination Survey Area, the survey campaign was completed in March 2018. Removed soils from this area of Fukushima are stored in the ISF until the time of final disposal.

3.3. Significant technical and non-technical issues

The following sections build upon the general decommissioning status presented above and focus on current and anticipated issues that are technical, logistical, or socio-political and non-technical in nature.

3.3.1. Decontamination of the Fukushima Daiichi site

As decontamination activities continue on the Fukushima Daiichi site new problems may arise. The way in which contamination can move across a site underground has been shown in other sites to be complicated by legacy site construction elements that are no longer in use, such as old roadways, abandoned piping, sealed off rooms and undocumented tunnels. International collaboration may usefully assist with anticipating and addressing the technical challenges, through for example compiling a database of techniques and experiences.

3.3.2. Radioactive water treatment and management and the tritium issue

The water reduction engineering measures noted above have been very effective in reducing the accumulation of contaminated water. However, the ion exchange technology used in the water treatment process produces an additional waste stream of radionuclide-contaminated slurry and spent adsorbent which require interim storage and ultimate disposal. While the disposal of such waste has yet to be resolved experience exists in other countries of applying solidification processes, thereby putting the waste into a more passively safe form.

Treated water still remains one of the most challenging sources of on-site risk owing to residual radioactive contamination, essentially due to tritium. There are no particularly effective and economical means of removal of tritium from water especially in large quantities and in relatively low concentration. The tank farm of accumulated treated water, around 1.2 million cubic metres, occupies a growing area of land that is needed for other decommissioning activities such as interim storage of decommissioning-related wastes. It also consumes resources that might otherwise be used for decommissioning. There is little land left for the storage of further water.

A government advisory committee has reported (METI, 2020a) on handling methods for the tritium-charged water and has advised that there are two technically feasible methods – vaporisation and release to the atmosphere, and discharge to the oceans after suitable dilution to ensure the release is well within safe discharge concentrations. The scientific assessment is that such disposal to the air and oceans is no more than one thousandth of the exposure impact of natural radiation. However, it is thought that any release has the potential to create public mistrust or lack of confidence regarding both government decision making and the safety of food products (mainly the marine and bottom feeding fishes). Consultation is ongoing to conclude on the preferred handling method. The transparency of the consultation on how to handle tritiated water could be enhanced through the involvement of international experts, including those of neighbouring countries.

3.3.3. Fuel removal from SFPs

The large inventory of radioactivity in the nuclear fuel assemblies stored in the pools in reactor buildings Units 1 through 4, and the damaged state of the reactor buildings as a result of the hydrogen explosions in Units 1, 3 and 4, made spent fuel removal from SFPs a priority. This has the aim of reducing Fukushima Daiichi site risks by transferring spent fuel from SFPs in the buildings to the common pool which is more reliable. The removal of spent fuel from the SFPs has proceeded slowly but methodically. The work was completed in December 2014 for Unit 4 and on 28 February 2021 for Unit 3. Significant building debris had to be removed first from the SFPs, along with damaged fuel handling equipment.

Fuel removed from the damaged units is stored in the large common pool where some fuel will subsequently be placed in dry cask storage units.[12] The SFPs in each reactor building also store damaged assemblies and highly irradiated and aged components, such as control blades, channel boxes and fuel support pieces, which add additional complexity to removal and storage processes. Emerging risks have been managed and workflow has been adjusted to accommodate new information regarding high dose rate areas and special debris handling requirements. Such new information sometimes requires work stoppages, situational evaluations, and placement of mitigating measures to manage risk optimally over the anticipated long duration of decommissioning activities.

3.3.4. Fuel debris removal from reactors

There are many challenging and novel aspects of decommissioning a nuclear site that has experienced the meltdown of three reactors, where the containment buildings are compromised, fuel materials melted and relocated, building structures are potentially compromised, and the site itself is contaminated from the release of fission products. The removal of the melted and relocated reactor fuel materials constitutes the most complex and hazardous technological challenge. First-of-a-kind technologies must be developed to address the extreme challenges of radioactive materials, unknown fuel debris properties, and environmental damage.

The experimental retrieval described in section 3.1.3 will provide knowledge and experience to provide a firmer basis for full-scale retrieval. Moreover, a great deal of scientific research and analysis has been undertaken, notably in benchmarking exercises and other studies initiated by the NEA. Outcomes will assist in anticipating and addressing challenges that may be encountered during the planned debris removal activities. The research and benchmarking activities furthermore are contributing to worldwide understanding of severe accident progression and the improvement of modelling and codes (NEA, 2015k; forthcoming m).

3.3.5. Solid waste management on site

Currently, areas of the Fukushima Daiichi site are dedicated to the temporary storage of various wastes such as concrete rubble, as well as newer vegetive matter such as trimmed trees. Solid waste streams currently exist for items such as contaminated clothing and soil. As noted above, an important solid waste stream is contaminated slurry and spent adsorbent from the campaign to decontaminate water of radioactive caesium and strontium. Radionuclide-contaminated slurry and spent adsorbent currently are being retained on site.

In the years to come, additional solid waste streams and other waste storage needs will be generated from new activities such as planned on-site facilities for incinerating combustible waste. Ultimate disposal remains a distant objective at this point.

3.3.6. Decontamination of off-site lands

Although much remediation work has been effectively completed, further attention is needed regarding the means for regulation and final disposal of removed soils. Table 3.1 provides some details on the amounts of wastes removed from the Special Decontamination Areas (SDAs) and Intensive

12. Part of new fuel (fresh fuel assemblies never used) is planned to be transported to a fuel manufacturer.

Contamination Survey Areas (ICSAs) in the course of clean-up, and the volumes of materials that have been moved from Temporary Storage Sites (TSS) to the Interim Storage Facility (ISF) or other means of waste management such as incineration or recycling, as well as the associated costs.

Table 3.1: Volume of soils removed from off-site locations and evacuated and costs associated with clean-up of SDA and ICSA (March 2018)

Classified area	Volume of soils removed (million m^3)	Decontamination cost (EUR billion)	Volume of soils evacuated by recycling or incineration (million m^3)
SDA	9.1	12.6	1.62
ICSA	7.9	11.8	1.20
Total	17.0	24.4	2.82

Source: NEA (forthcoming h).

3.4. Restructuring the nuclear legal framework in Japan

3.4.1. Reorganisation of regulatory and preparedness systems

One of the fundamental principles for ensuring nuclear safety within a country is the effective independence of the nuclear regulator, that is organisational, cultural, financial and political independence from both the nuclear industry and those parts of government that sponsor the nuclear industry (NEA, 2014a; forthcoming a; IAEA, 2006). A major lesson drawn from analysis of the Fukushima Daiichi accident was the importance of independent regulation of nuclear safety, not only structurally but also culturally (The National Diet of Japan, 2012).

Prior to 2012, the authorities responsible for the regulation of nuclear safety were the Nuclear Safety Committee and the Nuclear and Industrial Safety Agency. The latter was organised under METI which itself was responsible for the nuclear industry. To ensure a transparent separation of these two sectors, nuclear safety regulation was decoupled from METI. Following the Fukushima Daiichi accident, the Japanese government established in 2012 a new nuclear regulator with organisational and political independence, the NRA, as an external agency of the MoE with the mission to protect the general public and the environment through rigorous and reliable regulation of nuclear activities. The NRA assumes the roles and responsibilities of nuclear safety and security regulations for nuclear facilities and radioactive materials, as well as for nuclear non-proliferation safeguards. Formerly these were shared among several governmental organisations.

The NRA has faced a tremendous task not only in regulating the decommissioning of Fukushima Daiichi and the restart/decommissioning of the reactors shut down after the accident, but crucially in building a new independent expert regulatory body in a challenging environment. It has undergone an extensive period of development and will need to continue to develop and adapt given the changing circumstances. Initiatives to introduce new ways of working to the organisation include a risk-informed, performance-based reactor oversight process. Both the NRA and plant operators are becoming more familiar with this new process, including the effective interactions and discussions essential to implementing this new approach to regulation.

Based on the experiences and lessons learnt from the Fukushima Daiichi accident, the Japanese government furthermore revised the Atomic Energy Basic Act, the Nuclear Emergency Act, and related legislation in September 2012 to develop new nuclear accident emergency responses. A Nuclear Emergency Preparedness Commission was established within the Cabinet, with the Prime Minister serving as the Chairperson and the Chief Cabinet Secretary, the Minister of the Environment, and the NRA Chairperson serving as Vice Chairpersons. The goal of the Commission is to ensure unified nuclear emergency response policies are part of the routine work of the entire government. The Revision of the Nuclear Emergency Act enhanced measures to prevent nuclear disasters and strengthened the functions of the Nuclear Emergency Response Headquarters in any emergency.

3.4.2. Regulatory safety enhancements

When the NRA was established in 2012, it started to develop new regulatory requirements incorporating lessons learnt from the Fukushima Daiichi accident. The new requirements, which were enforced in July 2013, focused mainly on strengthening the assessment of natural hazards and establishing countermeasures to severe accidents. The measures accommodated by utilities included: i) measures to improve plant robustness and protection against tsunamis, including the installation of coastal levees, watertight doors and waterproofing of outside walls of buildings; ii) means to inject water following a station blackout, and alternative power sources (such as air-cooled gas turbine generators placed at a higher elevation); iii) supplemental battery capacity; iv) additional water reservoir sources for plant makeup water; and v) to mitigate core damage, the installation of top-vent facilities on reactor buildings, and filtered containment vent facilities.

Further, the new regulatory requirements reorganised the emergency-response organisations in Japan such that they are staffed and equipped to respond to simultaneous accidents in two or more reactors. The new regulatory requirements also require operators to construct backup facilities (a Specialised Safety Facility and a permanent DC power supply facility as the third power system) to further enhance reliability. These facilities were required to be operational within five years from the date of approval of the associated construction plan.

3.4.3. Efforts to improve the nuclear liability framework

Although Japan was not a party to any of the international nuclear liability conventions at the time of the accident,[13] its Act on Compensation for Nuclear Damage provided for the basic principles included in those conventions, such as the strict and exclusive liability of the nuclear operator for the nuclear damage caused to third parties and the obligation to maintain a financial security (such as insurance) to cover such liability.[14] Japan is one of the few countries providing for the unlimited liability of the nuclear operator. The Act on Compensation for Nuclear Damage, coupled with innovative mechanisms adopted to supplement it, fulfilled the purpose of allowing the nuclear operator, TEPCO, to compensate victims in a timely and adequate manner. Those innovative mechanisms are as follows:

- In August 2011 the Nuclear Damage Compensation and Decommissioning Facilitation Corporation (NDF)[15] was set up to provide under certain conditions financial support to Japanese nuclear operators in case they face nuclear damage compensation obligations beyond the required financial security amount of JPY 120 billion. As of 12 February 2021, TEPCO has paid almost JPY 10 000 billion.[16]
- Guidelines were drafted by the Dispute Reconciliation Committee for Nuclear Damage Compensation (DRC), established under MEXT, to define specifically the types of nuclear damage that would entitle to compensation and to assess the appropriate compensation for a given type of damage.[17]

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13. On 15 January 2015, Japan deposited its instrument of acceptance to the 1997 Convention on Supplementary Compensation for Nuclear Damage (CSC). The CSC entered into force for Japan on 15 April 2015. The reasons that led Japan to join this Convention are as follows: i) the need to adopt an international nuclear liability regime; ii) the need to address the legal concerns of the foreign suppliers participating in the decommissioning of the TEPCO Fukushima Daiichi Nuclear Power Plant; iii) the access to the CSC international fund; and iv) the improvement of the legal framework applicable to nuclear trade.

14. For more detailed information on the Japanese nuclear liability regime applicable at the time of the accident, see *Japan's Compensation System for Nuclear Damage: as Related to the TEPCO Fukushima Daiichi Nuclear Accident* (NEA, 2012c).

15. The Nuclear Damage Compensation Facilitation Corporation Act was amended in May 2014 and became the "Nuclear Damage Compensation and Decommissioning Facilitation Corporation Act" to include the decommissioning of the TEPCO Fukushima Daiichi NPP among the Corporation's activities.

16. TEPCO (2021), *Records of Applications and Payouts for Compensation of Nuclear Damage as of 12 February 2021*, www.tepco.co.jp/en/hd/responsibility/revitalization/pdf/comp_result-e.pdf (accessed 15 February 2021).

17. Guidelines from the DRC were introduced in the Act on Compensation for Nuclear Damage in 2009 following the 1999 Tokaimura nuclear accident.

- Voluntary out-of-court settlement of disputes relating to nuclear damage compensation claims were promoted by the Nuclear Damage Compensation Dispute Resolution Centre (ADR Centre), established by the DRC.[18] Most disputes have been settled out of court.[19]
- The three-year discovery period was extended to ten years.[20]

In December 2018, the Act on Compensation for Nuclear Damage was amended[21] to introduce the following changes that entered into force on 1 January 2020 and had already been implemented for the Fukushima Daiichi accident:

- Nuclear operators will have to publish their general policy to compensate nuclear damage, which should include a description of the claims handling process, of the financial security coverage and of the dispute resolution mechanism.[22]
- A governmental loan up to the amount of the operator's financial security (i.e. JPY 120 billion for each nuclear power plant site) will be available to promote the prompt payment of provisional compensation by the liable nuclear operator.
- The discovery period will be suspended during the mediation procedure of the ADR Centre.

These changes aimed at ensuring legal preparedness and the adequate and prompt compensation of potential victims in the future.

Finally, at the time of the accident Japan had not joined any of the international nuclear liability conventions; therefore it had no such treaty relations with other states,[23] including the United States, with regard to nuclear liability. A number of lawsuits have been filed by American and Japanese citizens before US courts against American suppliers and TEPCO. At the time of publishing this report, some of these suits have been dismissed by the courts, while others are ongoing.[24] This demonstrates the legal risks that may arise when countries are not in treaty relations that clearly establish which nuclear liability regime would apply in case of an accident.

18. The ADR Centre at one point in time employed more than 400 attorneys.

19. According to the written report of TEPCO to the DRC, about 2 941 000 applications for compensation were received by the end of July 2020, while 567 lawsuits were filed against TEPCO before the courts. Among these lawsuits, 165 cases are still pending. Source: TEPCO (2021), "Situation of the payouts of nuclear damage compensation and other information", www.mext.go.jp/content/20200924-mxt_san-gen01-000010296_03.pdf (accessed 15 February 2021).

20. Pursuant to Article 724 of the Civil Code, all rights of action are fully extinguished 20 years (prescription period) following the date of the tort (i.e. the nuclear accident) and the actions must be brought by the victims within three years (discovery period) from the date on which the person suffering damage had knowledge or should have knowledge of both of the damage and of the person liable (i.e., the operator of the nuclear installation where the accident occurred). In May 2013, the Act on the Interruption of Statute of Limitations for Settlement Mediation Procedure in the Dispute Reconciliation Committee for Nuclear Damage Compensation suspended the three-year discovery period and in December 2013, the Act on Sure and Prompt Compensation and the Special Exception on the Statute of Limitations for the Damage Caused by Nuclear Accident in 2011 extended the three-year discovery period to ten years. Both Acts are special acts that only apply to the Fukushima Daiichi accident.

21. Article 6 of the supplementary provisions to the Nuclear Damage Compensation Facilitation Corporation Act, enacted on 3 August 2011, obliged the government to establish an organisation to facilitate the process of resolving disputes. It also demanded the government to consider drastic revision of the Act on Compensation for Nuclear Damage.

22. TEPCO (2021), *Records of Applications and Payouts for Compensation of Nuclear Damage as of 12 February 2021*, www.tepco.co.jp/en/hd/responsibility/revitalization/pdf/comp_result-e.pdf (accessed 15 February 2021). In May 2013, TEPCO had almost 11 000 persons handling the claims, which entailed hiring and training the staff, providing for the necessary office space and equipment, and implementing effective processes within a very short period of time.

23. If two countries join the same nuclear liability instrument, they will be considered to have "treaty relations" and the common instrument will determine a number of legal issues, such as which nuclear liability regime would apply in case a nuclear accident occurs in one of those countries to compensate the population of the other state (i.e. which would be the applicable law and the competent court).

24. For more information on these lawsuits, see NEA (2020), *Nuclear Law Bulletin*, No. 103, OECD Publishing, Paris, pp. 47-49.

4. Safety improvements and other lessons learnt at the international level

4.1. Key activities and achievements of the Nuclear Energy Agency and member countries

Shortly after the 2011 accident, significant joint studies were initiated by the Nuclear Energy Agency (NEA), member countries and, importantly, the government of Japan. These included a benchmark study of the accident at the Fukushima Daiichi Nuclear Power Plant started in 2012, and post-Fukushima safety research started in 2013. Governments, regulators, technical organisations, operators and other stakeholders of the NEA and member countries, including Japan, moreover undertook organised safety-enhancing activities in response to the accident at Fukushima Daiichi. In general, these activities have contributed to establishing a common understanding of the accident and led to improved tools and a better quantification and understanding of plant safety margins.

Areas of study have included safety of multi-unit sites, the potential for common cause failures through external events, and mechanisms important in accident progression including ex-vessel phenomena. Potential improvements have been identified in several areas such as fuel designs that are more tolerant of accidents and electrical power systems that are more robust. The NEA also organised meetings and activities to learn lessons of public health aspects from the accident and share them with member countries, with an important focus on stakeholder involvement in decision-making. The reference section of this report lists pertinent NEA publications in these areas.

4.1.1. Safety reviews

Comprehensive reviews were undertaken across NEA countries to enable an evaluation of the safety and robustness of nuclear power plants, including evaluating their capacity to withstand major incidents beyond the existing design-basis capabilities for external hazards. The reviews, which were generally based on existing and new safety studies, as well as engineering judgment, examined the adequacy of design-basis assumptions as well as provisions for conditions more severe than design-basis events. Each NEA member country used its own approach and methods for the reviews, although some also conducted reviews within a regional framework (e.g. the European Stress Test Program). The reviews generally covered similar initiating events (e.g. earthquake, flooding and other extreme natural conditions challenging the specific site) and consequent or postulated loss of safety function (e.g. loss of electrical power, including station blackout [SBO]; loss of the ultimate heat sink [UHS]; or a combination of both), as well as the capability to cope with severe accidents.

Although diverse approaches and methods were used for the reviews, individual NEA member countries reached many similar conclusions regarding the needed safety improvements and enhancements. A shared insight is the need for diversity of equipment, enhancements in the robustness of safety functions and continuing efforts to improve organisational behaviour. Common activities have included a focus on plant and process improvements to mitigate the potential impact of external hazards. Areas under examination include: i) re-assessment of external hazards; ii) improvement of the robustness of the electrical systems; iii) an enhancement of the robustness of the UHS; iv) protection of the reactor containment system, v) protection of spent fuel in spent fuel pools (SFPs); vi) reinforced capability to rapidly provide diverse equipment and assistance from on-site or off-site emergency preparedness facilities; vii) reinforced safety culture, including human and organisational factors in decision making during emergencies; viii) continued safety research; and ix) consideration of events that could affect all the reactors at a single site simultaneously (multi-unit events). Many improvements have already been implemented in these areas.

Particularly in the context of safety culture, the Japanese industry, based on the lessons learnt from the accident, established the Atomic Energy Association (ATENA) to voluntarily pursue further safety enhancement potentially even beyond legal requirements. ATENA co-ordinates the activities of the entire nuclear industry and seeks to accomplish the higher level of safety for nuclear power plants. In addition to ATENA, the Japan Nuclear Safety Institute (JANSI) and the Nuclear Risk Research Center (NRRC) support nuclear operators through peer reviews of nuclear power plants and to conduct fundamental research activities for safety improvements. The important commitments of the nuclear operators and the industry to foster safety culture and to voluntarily pursue safety enhancement with nuclear facilities are endorsed by the policy of the national government through Japan's Strategic Energy Plan in 2018.

In addition, governments in several countries have taken action to reinforce the independence of their regulatory bodies.

4.1.2. Cross-cutting safety research and analysis on severe accidents and decommissioning

Following the accident at the Fukushima Daiichi Nuclear Power Plant in 2011, NEA research projects supported by participating member countries and the government of Japan, as well as other NEA joint efforts, have delivered cross-cutting safety research. These initiatives support both decommissioning research and development (R&D) activities in view of the extraction of fuel debris and waste processing, and the improvement of scientific understanding and modelling capabilities addressing severe accident progression and consequences. Some studies in particular have analysed information obtained from reactor buildings and containment vessels of Fukushima Daiichi Nuclear Power Plant. Overall the activities have revealed valuable insights, identified near-term and long-term R&D topics, and provided technical bases for planning decommissioning activities.

An analytical study in two phases has aimed at benchmarking internationally used severe accident computer codes against the known data and behaviour of the three accidents of reactor units 1, 2 and 3 (NEA, 2015k; forthcoming n). There were very encouraging results given the inherent challenges of the analyses. These provided code-generated estimates of the damage to the reactor fuel and the relocation and ultimate disposition of melted and relocated fuel materials which span the regions between the damaged cores, the reactor pressure vessel (RPV) lower head and the primary containment vessel (PCV) cavity regions. These damage estimates suggest where fuel materials are likely to be found and their likely compositions, and while these estimates likely differ from what is ultimately found during decommissioning, the estimates are nonetheless valuable in planning re-entry strategies and likely required fuel removal technologies and waste streams. Note that these analytical findings are also merged with other characterisations such as muon imaging of the reactors to determine location for high density core materials (i.e. fuel) and in-PCV robotic investigations which also provide information on fuel distribution end states to provide greater certainty concerning decommissioning methods.

Analytic studies and fuel debris physical characterisations are essential elements of an informed and efficient decommissioning campaign. With the support of the Japanese government, NEA member country institutions and the European Commission's Joint Research Centre (JRC) launched a preparatory study on the analysis of fuel debris. In follow-on activities, information derived from code is aggregated with physical information from robotic entries into the damaged PCVs, to support fuel debris characterisation and planning for fuel extraction and removal.

Another joint project (NEA, forthcoming j), again supported by the Japanese government, has enabled a deeper understanding of material behaviour in severe accident conditions, which will ultimately contribute to the improvement of the severe accident mitigation strategies. Such studies enable the improvement of reference thermodynamic databases and degradation models applied to the Fukushima Daiichi accident.

4.1.3. Characterisation and management of unconventional waste

Of radioactive waste resulting from the accident at the Fukushima Daiichi Nuclear Power Plant, low-level and very low-level waste represent the vast majority by volume while making up only a small fraction of the radiological inventory. An optimal approach to handling these large amounts of so-called unconventional waste has not yet been settled. This is due to the lack of availability of the appropriate long-term waste management infrastructure, which demands a robust process and procedures for managing waste, waste disposal routes including the siting of disposal facilities, and appropriate safety culture as well as public acceptance.

As Japan pursues the clearance and release of the very low-level post-accident radioactive waste in full respect of international standards, among the most difficult near-term challenges are characterisation and categorisation. An international activity (NEA, forthcoming k) examined how to develop a complex waste characterisation process. Case studies from NEA countries including France, Japan, the Russian Federation, Ukraine and the United Kingdom allowed the identification of strategic components for such a process.

Although the prime responsibility for ensuring safe management of radioactive waste rests with the operator, there is a need for the government to establish a basic framework for taking the interests of stakeholders into consideration when making decisions. The establishment of a regulatory framework and dialogues with stakeholders to implement the policy are encouraged; the framework should afford flexibility to address uncertainty in characterising unconventional and legacy waste, and enable the weighing of variables and prevailing circumstances in complex decision making.

4.1.4. Stakeholder involvement

The accident at Fukushima Daiichi transformed perceptions regarding the role of citizens in government decision-making about nuclear energy, especially at the local level. In Japan and in several other countries, the accident significantly undermined public trust in governmental oversight of, and communication about, nuclear energy. In some NEA member countries, it underscored the need to take into account the knowledge, values, interests and preferences of concerned communities in nuclear decision making, including for accident preparedness and recovery in affected areas. The years after Fukushima Daiichi have seen continued worldwide debate about the so-called "social licence" for nuclear energy-related decisions: "*is this to be granted by duly elected or appointed government officials, or by those individuals and communities who will be directly impacted?*" The accident had profound, wide-ranging and long-lasting repercussions for local communities, highlighting the democratic deficit in making consequential decisions without sufficient local ownership. In a trend started well before the 2011 accident, reflected in such international treaties as the 1998 Aarhus Convention, stakeholders in NEA member countries increasingly expect not merely to be informed about important environmental and infrastructure decisions affecting their lives, but to be directly and meaningfully involved in making those choices – beyond participating in democratic elections. In harmony with NEA work predating Fukushima Daiichi, the NEA considers stakeholder involvement an essential process for making sound and durable decisions. Lessons learnt from the accident at Fukushima Daiichi Nuclear Power Plant clearly highlight a dimension of societal acceptance in decision-making through stakeholder involvement. Earning trust is key for recovery.

Past practice demonstrates the feasibility of such engagement. In the aftermath of the accident at the Three-Mile Island Nuclear Power Plant Unit-2 in 1979, the US Nuclear Regulatory Commission (NRC) established a Citizen's Advisory Panel which was active between 1980 and 1993 (USNRC, 1994). This panel provided opportunities for the public, regulator, and licensee representatives to meet periodically in a public forum to discuss clean-up issues, solutions and plans. In addition, through periodic public meetings the panel helped maintain the NRC Commissioners' awareness of the importance to the citizens of the clean-up. Japanese government agencies have been holding meetings, public panels and advisory group discussions with local stakeholders in the area of the Fukushima Prefecture.

Following the accident at the Fukushima Daiichi Nuclear Power Plant, the NEA transitioned from discussing stakeholder involvement within the context of particular work areas to a holistic approach. An initial report on stakeholder involvement in nuclear emergencies published in October 2011 highlighted that sustainable post-accident recovery requires committed, long-term outreach to a range of stakeholders. Subsequently, growing recognition that stakeholder involvement in nuclear decision-making exists in a socio-political context of public trust and may extend beyond radioactive waste management or emergency response prompted a wider berth. In 2017 and 2019, the NEA organised stakeholder involvement workshops which integrated all NEA areas of international co-operation. The workshops established the interconnectedness of decision making and risk communication with stakeholder relationships and trust for long-term nuclear energy programmes.

4.1.5. Country-specific safety culture enhancements and safety culture of the regulatory body

Achieving and maintaining high levels of safety is the goal of all organisations involved in nuclear energy. Experience has shown that a healthy safety culture is essential to the overall safety performance of any organisation, and that safety culture is influenced by many factors including national context. Two NEA workshops have explored organisational and national influences on nuclear safety culture.

In 2018, the NEA and the World Association of Nuclear Operators (WANO) held a Country-Specific Safety Culture Forum (CSSCF) in Sweden to explore the impact of the national context on nuclear safety and identify approaches to sustain and improve nuclear safety culture. The forum demonstrated that the national context has a powerful impact on nuclear safety, suggesting it will be important for all countries to understand and potentially use the particular aspects present in their own cultures to enhance safety culture.

A separate workshop focussed on challenges and enhancements to the safety culture of the regulatory body was held in June 2015. The report (NEA, 2015j) emphasised that the manner in which a regulator oversees the industry greatly affects the safety culture within that industry and hence nuclear safety. Thus, the regulatory safety culture, which is the basis for its interactions with the industry, is a vital component of assuring a high level of national nuclear safety. The report also highlighted the influence that national culture can have on safety culture, emphasising that national characteristics and cultural strengths should be recognised and used to foster and develop a healthy safety culture.

4.1.6. Emergency and accident management

Off-site

The accident at the Fukushima Daiichi Nuclear Power Plant highlighted the importance of effective nuclear accident response, including reliable estimation of potential consequences and implementation of actions as appropriate in response to the anticipated consequences. However, the complexity of the accident, combined with the widespread effects of the earthquake and tsunami, greatly impacted the ability to provide timely and accurate information to national and international stakeholders. In fact, as stated in a NEA report (NEA, 2015c), organisations involved in the assessment of potential consequences from the Fukushima Daiichi accident in 2011 were predicting different outcomes, which occasionally led to a lack of clarity, delays in taking action or a non-optimised response. Regarding initial decisions on urgent protective actions, the arrangements in Japan were revised after the accident so that actual conditions at the nuclear power plant constitute the basis for taking urgent protection actions, rather than using dose projection models.[1] It was also observed that the measures given by

1. Callen and Homma, 2017.

many foreign governments to their citizens residing or staying in Japan occasionally differed, especially at the initial stages of the accident. Such variations, which may be attributed to factors such as the methods used to assess accident progression and to develop estimates of radionuclide releases to the environment, can affect the projected radiological dose to a member of the public.

NEA experts in the field of radiological protection and public health recently pointed to post-accident recovery management as an important pillar of ensuring public well-being. It is seen as a complex multidisciplinary process of multisectoral dimension, and all the NEA member countries have expressed the need for international co-operation to improve preparedness for recovery. (Further consideration is given in section 5.2.)

Emergency operating procedures (EOPs) and severe accident management guidelines (SAMGs)

In June 2012, the NEA's task group on accident management assessed member country's regulatory needs and challenges in light of the Fukushima Daiichi Nuclear Power Plant accident. The group identified measures that should be considered to enhance the regulations and regulatory guidance for operators' accident management activities.

In addition, the NEA Working Group on Analysis and Management of Accidents developed a report to address the topic of severe accident management guidelines (SAMGs) verification and validation, with a particular focus on the use of analytical simulations as one of the means to inform SAMGs in nuclear power plants. The report describes the current practices to ensure the correctness, adequacy, usability and efficiency of SAMGs, provides an overview of national examples of past and ongoing assessments of severe accident management (SAM) and summarises recommended practices with regard to the use of analytical simulations. That being said, every accident is likely to be unique and hence an overriding message is that SAMGs need to be flexible and focused on the basics rather than on detailed responses to a particular accident sequence.

Radiological protection for severe accident management

In 1992, the NEA and the International Atomic Energy Agency (IAEA) began to jointly sponsor the Information System on Occupational Exposure (ISOE) to foster the exchange of data, analysis, lessons learnt and experience in occupational radiological protection at nuclear power plants worldwide.

Following the Fukushima Daiichi accident, the ISOE focused on identifying the experience and information from the Chernobyl and Three Mile Island (TMI) accidents, looking at how the management of emergency worker/responder doses were legally and practically managed, as well as information about personal protective equipment for highly contaminated areas. This information was collected from the ISOE-participating nuclear utilities and regulatory authorities and made available for Japanese utilities. In May 2011, an expert group was established to discuss occupational radiological protection in severe accident management.

A report (NEA, 2014m) compiled best practices in radiological protection job coverage during response to a severe accident and identified the following major issues that should be considered and incorporated into an occupational radiological protection program: i) the development of extensive emergency response plans to protect emergency workers/responders and the public; ii) the development of anticipatory training related to severe accident management for all emergency workers/responders; iii) the effective implementation of a radiological protection programme during a severe accident (as this may be significantly impacted by the plant's facility configuration and access controls); iv) radiological protection of the emergency worker/responder, including the establishment of individual exposure reference levels, extensive work controls, and thorough radiological exposure controls to maintain emergency worker/responder radiation exposures as low as reasonably achievable (ALARA); v) extensive radiological controls of radioactive and contaminated materials released internally and externally from the affected facility during the emergency and post-accident mitigation phases to avoid or minimise radiation exposures to emergency workers/responders and the public; and vi) comprehensive emergency plan development, routine training and exercising (including stressful, time-limited activities) of all emergency workers/responders, remote radiological monitoring, high dose detection equipment, and robotic equipment.

Long-term accident management

Prior to the accident at the Fukushima Daiichi Nuclear Power Plant, the need for long-term accident management had not been foreseen. It was anticipated that some form of short-term intervention would be possible to stabilise the situation (e.g. reintroduction of off-site power).

Accident management exercises have typically been run as "tabletop exercises" of management strategies during some 24 hours of accident "simulation," after which the accident is typically declared concluded. The reality experienced at Fukushima Daiichi Nuclear Power Plant was that an accident lasts more than 24 hours, and indeed, must be managed over many months, and even years following the initial occurrence of the accident.

In a March 2000 report on the impact of short-term severe accident management actions in a long-term perspective (NEA, 2000), a survey of international practices was made with the aim of identifying means of preventing further plant damage and optimising long-term accident management. This study identified actions such as measures to preserve long-term containment function and means of mitigating long-term releases that are further reinforced by real-world experience at the Fukushima Daiichi Nuclear Power Plant. One action considered by the Boiling Water Reactor Owners Group is referred to as "anticipatory containment venting[2]".

A report on accident management of regulatory aspects reflected on insights for long-term accident management learnt from the accident at the Fukushima Daiichi Nuclear Power Plant (NEA, 2014j). This study describes the concept of integrated accident management (IAM) as a generalisation and extension of the reactor accident SAMGs that seeks harmonious optimisation of safety management, risk reduction, prevention and mitigation for all aspects of the Nuclear Power Plant including SFPs and interim waste management. This aim is approached from the standpoint of: i) procedures and guidelines, ii) equipment, components and instrumentation, and iii) human and organisational resources.

With respect to procedures and guidelines, the study recommends accident management procedures for all plant operating states such as full power, low power or shutdown, including SFPs taking consideration of portable equipment and improvised mitigations. Concerning equipment, components and instrumentation, a major challenge in long-term management is understanding plant status as indicated by potentially defective or damaged instrumentation and ability to monitor and manage the site from the main control room over varying conditions throughout the decommissioning duration and under potential future accident or external event challenges. Finally, the training and staffing of the long-term accident management infrastructure is a multi-generation requirement over the anticipated 30 years needed to complete decommissioning work. This is a challenging extension of accident management training given the already extensive training demands posed by other safety aspects such as training for emergency operating procedures. This field of safety practice has been furthered by the NEA activities undertaken since the Fukushima Daiichi accident.

4.1.7. Oversight for safety

Defence in depth

In June 2013, a joint NEA workshop considered the core theme of defence in depth (DiD). The participants examined key priorities for the application of the DiD concept and identified important topics to pursue in order to strengthen the application of DiD. The main conclusions were that the DiD concept remains valid, but strengthening and further work on implementation may be needed. A Regulatory Guidance Document on DiD (NEA, 2014i) was therefore developed, which identifies areas for further study including:

- the impact of human and organisational factors on DiD;

2. Anticipatory containment venting is a short-term accident management procedure to relieve the containment of steam pressure in the development of a severe accident before fuel damage and fission product release to the containment has taken place. Such action is taken to preserve containment safety margins and functionality at a later time when fission products and hydrogen are present and to ensure the many low pressure water injection sources do not encounter containment pressures that exceed the shutoff head of systems like fire suppression systems.

- improvements on the use of the DiD concept for multi-unit sites, fuel cycle facilities and research;
- reactors and new reactor designs;
- implementation of countermeasures for level 5 of DiD;
- benchmarking and further harmonisation of the regulatory use of DiD through training, workshops and other means;
- the impact of new technologies.

Characteristics of an effective regulator

In June 2012, regulatory experts gathered by NEA agreed that effective regulatory organisations are those that have good leadership and are able to transform strategic direction into operational programmes that achieve its fundamental purpose: ensuring that licensees operate their facilities and discharge their obligations in a safe manner, in accordance with international safety principles and with full respect of the environment. The report (NEA, 2014a) stated that an effective nuclear safety regulator:

- is clear about its regulatory roles and responsibilities, its purpose, mandate and functions;
- has public safety as its primary focus;
- has independence in regulatory decision making from any undue influence on the part of the nuclear industry and those sectors of government that sponsor this industry;
- has technical competence at its core, with other competencies built upon this fundamental and essential requirement;
- is open and transparent in its regulations and decisions;
- has a regulatory framework and requirements that are clear and easily understood by all stakeholders;
- makes clear, balanced and unbiased decisions, and is accountable for those decisions;
- has a strong organisational capability in terms of adequate resources, strong leadership and robust management systems;
- performs its regulatory functions in a timely and efficient manner;
- has and encourages a culture of continuous self-improvement and learning, including the willingness to subject itself to independent peer reviews.

4.1.8. Nuclear law

Since the occurrence of the accident, the Japanese delegation has been providing briefings at each meeting of the NEA Nuclear Law Committee (NLC) on the implementation of the Japanese legal framework and the legislative innovations. Dedicated sessions have regularly examined the legal framework and the actual implementation of Japan's compensation scheme in order to draw lessons for the benefit of the international community.

The Japanese government, in co-operation with the NEA Secretariat, prepared *Japan's Compensation System for Nuclear Damage: As Related to the TEPCO Fukushima Daiichi Nuclear Accident* (NEA, 2012c). This publication gathers the English translations of all major statutes, ordinances and guidelines adopted or issued by the Japanese government in order to establish and implement the compensation scheme necessary to respond to the Fukushima Daiichi nuclear accident, as well as several commentaries.

Encouraging broader adherence to the international nuclear liability conventions

Since the Fukushima Daiichi accident, the international community has encouraged broader adherence to the international nuclear liability conventions with the goal of achieving a global nuclear liability regime (IAEA, 2011; NEA, 2011d). Broader adherence would lead to greater harmonisation of national nuclear liability and compensation schemes, and thus promote a more similar treatment of victims and operators on a worldwide basis. In addition, greater adherence to any one of the international nuclear liability regimes would result in the extension of treaty relations between states, providing greater certainty both to nuclear industry investors and suppliers as well as to the general public regarding the liability regime that would apply in case of an accident.

The IAEA General Conference in September 2011, through its Action Plan on Nuclear Safety, and the NEA Steering Committee at its policy debate on "Progress Towards a Global Nuclear Liability Regime" in April 2014, encouraged their respective member countries to adhere to one of the nuclear liability regimes and to adopt consistent legislation, if they have not already done so.

The nuclear liability principles were implemented for the first time to compensate victims of a severe accident following the Fukushima Daiichi nuclear accident. If the legal framework demonstrated its effectiveness, it also revealed that the international community needed to continue exploring the practical application of the nuclear liability regimes.

The NEA organised for that purpose two international workshops:

- the Third Workshop on the Indemnification of Damage in the Event of a Nuclear Accident in 2017, which assessed the challenges of implementing the international nuclear liability conventions in case of a transboundary accident;
- the Fourth International Workshop on the Indemnification of Damage in the Event of a Nuclear Accident in 2019, which addressed the challenges of determining nuclear damage in practice, and of setting up a national or transboundary claims handling.

4.2. Key activities and achievements of other international organisations

This section identifies the main international organisations aside from the NEA that have been directly affected or involved in the response to the accident at Fukushima Daiichi, and summarises their undertakings in the past 10 years. This short summary is purely the view of the NEA and is not intended to substitute for the publications of specific international organisations.

The IAEA is a United Nations body with 172 member countries. It was created in the late 1950s as a means to support the safe and responsible use of nuclear technology. The IAEA's best-known mission is to implement the global non-proliferation regime to limit the spread of nuclear weapons, but it is also very active in the nuclear safety area. The IAEA provides assistance to countries newly entering the nuclear sector, conducts peer review missions, and publishes consensus safety standards that member states may use as references in establishing national regulations. The IAEA partners with the NEA and other international bodies to develop reports and analyses and to organise international conferences.

The primary role of the World Health Organization (WHO) is to direct international health within the United Nations system and to lead partners in global health responses. Membership in the WHO is open to all member countries of the United Nations.

The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) is mandated to undertake broad assessments of the sources, effects and risks of exposure to ionising radiation from human health (public, patients, workers) and the environment. In pursuit of its mandate, UNSCEAR thoroughly reviews and evaluates global and regional exposures to radiation. UNSCEAR also evaluates evidence of radiation-induced health effects in exposed groups and advances in the understanding of the biological mechanisms by which radiation-induced effects on human health or on non-human biota can occur. Those assessments provide the scientific foundation used, inter alia, by the relevant agencies of the United Nations system in formulating international standards for the protection of the general public and workers against ionising radiation; those standards, in turn, are linked to important legal and regulatory instruments.

The International Commission on Radiological Protection (ICRP) consists of eminent scientists, policy makers, practitioners, and other experts in the field of radiological protection. All members of the Main Commission, Committees, and Task Groups are volunteers, selected through a transparent process. The ICRP was established to advance the science of radiological protection for the public benefit, in particular by providing recommendations and guidance on all aspects of protection against ionising radiation.

WANO brings together every operator of commercial nuclear facilities in the world to co-operate in assuring that all nuclear plants strive for the highest standards of nuclear operations excellence and nuclear safety. It has over 120 members from all over the world.

4.2.1. Activities and achievements of the IAEA

Following the accident at Fukushima Daiichi, the IAEA engaged in dialogue with Japanese officials regarding on-site and off-site issues. The on-site assistance included: an International Fact-finding Mission in May-June 2011; four International Peer Review Missions in 2013 (twice), 2015 and 2018; and a Follow-up Review in 2020. The off-site assistance included: i) two international peer review missions in 2011 and 2013; and four IAEA-Ministry of Environment Experts Meetings (two each in 2016 and 2017). In 2011, the IAEA efforts focused on crisis management and understanding the emergency situation. Subsequent focus turned to stabilisation, storage of treated water, and creating a safe, predictable work environment. Ongoing efforts include focusing on decommissioning, solving the accumulation of treated water, removing spent fuel and debris, and planning for the next 50 years.

From the four IAEA Peer Review missions to Japan, the agency acknowledged significant improvement in working conditions at the site, water management and solid waste management. The missions also identified good progress towards removing spent fuel from the three damaged reactors, as well as progress in understanding the status of fuel debris in the reactors. The advice shared with Japanese counterparts following the missions included: i) the need for a decision on the disposition path for accumulated treated water; ii) preparation of an integrated plan for the completion of decommissioning, including waste treatment and management; iii) strengthening decommissioning and decontamination project management; and iv) the value of drawing upon the global diversity of international good practices. Other relevant ongoing IAEA work associated with the decommissioning of Fukushima Daiichi includes the Decommissioning and Remediation of Damaged Nuclear Facilities (DAROD) Project and the Coordinated Research Project (CR) on Management of Severely Damaged Spent Fuel and Corium.

Of particular note is the IAEA's comprehensive and detailed international technical review of the accident involving a very large number of international experts (*The Fukushima Daiichi Accident – Report by the Director General*, [IAEA, 2015]).

4.2.2. Activities and achievements of other United Nations bodies

World Health Organization (WHO)

Immediately after learning of the accident at Fukushima Daiichi, the WHO activated its emergency response procedure including liaison with the IAEA. WHO personnel worked to assess public health risks and provide technical assistance. WHO's response was supported by its Radiation Emergency Medical Preparedness and Assistance Network to provide authoritative advice on radioactive contamination and food consumption and trade. The WHO also provided travel advice and information on potential radiation risks to its member countries, the public and the media.

United Nations Scientific Committee on the Effects of Atomic Radiation

UNSCEAR issued a report on its 2013 assessment of the radiation exposures of the public, workers and non-human biota from the accident at Fukushima Daiichi and concluded that health risks resulting from the accident were far lower than those for Chernobyl (UNSCEAR, 2014). This assessment was due to the substantially lower doses received by the public and workers in Japan. The report also indicated that UNSCEAR did not expect discernible increased incidences of radiation-related health effects among those exposed.

UNSCEAR then published White Papers (UNSCEAR, 2015; 2016; 2017) covering six thematic areas: i) radionuclide releases to atmosphere, dispersion and deposition; ii) radionuclide releases to water, dispersion and deposition; iii) evaluation of doses for public; iv) evaluation of doses for workers; v) health implications for workers and public; and vi) evaluation of doses and effects for non-human biota. In its 2016 White Paper UNSCEAR also considered a new topic: the transfer of radionuclides in terrestrial and freshwater environments (UNSCEAR, 2016) An updated assessment of the levels and effects of radiation exposure due to the accident at the Fukushima Daiichi Nuclear Power Plant is in preparation (UNSCEAR, forthcoming).

4.2.3. Activities and achievements of the ICRP

After the Fukushima Daiichi Nuclear Power Plant accident, the ICRP compiled initial lessons related to the system of radiological protection. The ICRP is already taking action on this basis, including developing dose conversion coefficients for external exposures to environmental sources, and updating advice on emergency and existing exposure situations.

In late 2011 ICRP began a Dialogue Initiative between experts, authorities, professionals, NGOs, local communities and representatives of Belarusian, Norwegian and French organisations with direct experience in managing long-term consequences of the Chernobyl accident, to find ways to respond to the challenges of the long-term consequences of the Fukushima Daiichi accident. The NEA supported and participated in these dialogues and applied many important lessons into its work on stakeholder engagement.

In line with the experience from the dialogues, ICRP Publication 146 (dealing with radiological protection of people and the environment in the event of a large nuclear accident) underlined the added value of the co-expertise approach to assist the optimisation process and related decision making. Co-expertise is defined as “an approach in which authorities, experts, and stakeholders work together to share experience and information in affected communities, with the objective of developing a practical radiological protection culture to enable individuals to make informed decisions about their own lives.” (ICRP, 2020)

4.2.4. Activities and achievements of WANO

Following the accident at Fukushima Daiichi, WANO issued three Significant Operating Experience Reports (SOERs) and one Addendum:

- SOER 2011-2, Fukushima Daiichi Nuclear Station Fuel Damage Caused by Earthquake and Tsunami, and SOER 2011-2 Addendum 1;
- SOER 2011-3, Fukushima Daiichi Nuclear Station spent Fuel Pool/Pond Loss of Cooling and Makeup;
- SOER 2011-4, Near Term Actions to Address an Extended Loss of all AC Power.

Further to these, WANO published two revisions which together replaced the three SOERs listed above:

- SOER 2011-3 Rev. 1, Spent Fuel Facility Degradation, Loss of Cooling or Makeup;
- SOER 2013-2 Rev. 1, Post-Fukushima Daiichi Nuclear Accident Lessons Learned.

WANO also identified a number of important changes to strengthen WANO and its focus on nuclear safety, and it implemented all of them into its “business as usual” activities by October 2015. Added to the scope of WANO activities were: i) emergency preparedness; ii) severe accident management; iii) on-site fuel storage; iv) some aspects of design as it relates to plant operation. As well, the following areas were earmarked for development: i) implementing an integrated emergency response strategy; ii) improving visibility and transparency; iii) implementing a real-time event reporting process; iv) addressing equivalency of INPO, JANSI, IAEA and other peer reviews; v) conducting a corporate review of every member within six years; vi) increasing peer review frequency to every four years; vii) adding an assessment or grading process; and viii) conducting an internal assessment of WANO regional offices and headquarters.

5. Global impact of lessons learnt

The Fukushima Daiichi accident has affected nuclear energy strategy in different countries and regions in different ways and to different extents. It also highlighted the strong importance of human behaviour and organisational background for nuclear safety. The political, economic and social issues, including future energy supplies, global climate change, costs of alternatives and security of energy supply, have varied across regions and countries. A few countries, such as Germany, have made the decision to phase out their nuclear generating capacity. Elsewhere, low electricity prices and the difficulty of financing new nuclear construction (especially after the global financial crisis of 2008) have led to fewer new nuclear plant construction projects and some decisions to reduce generating capacity or close older reactors in particular. Some countries have continued to expand their nuclear generating capacity with the construction of new reactors and a growing list of "newcomer" countries are laying the groundwork to build new plants to meet future energy security and environmental goals.

Renewed interest has been shown in alternative fuel designs that are more resistant to fuel failure and hydrogen production. Several countries are conducting research and development on enhanced accident-tolerant fuels (ATFs; NEA, 2018b) and performing a lead test assembly or lead test rod irradiation in commercial reactors. One particular research area of interest is focused on the development of cladding and core internal materials that can survive higher temperatures before failure and that are less reactive with steam (thereby reducing the production of hydrogen such as was generated during the Fukushima Daiichi accident).

The accident has also contributed to the massive global surge in recent years in the development of new nuclear power technologies, including small modular reactors and Generation IV reactors with passive safety features. With about 70 development projects underway in countries around the world, industry intends that these new technologies will address public concerns about safety and help address the challenge of financing nuclear energy capacity.

In addition, many countries are placing more focus on fostering trust and confidence in their nuclear policies by engaging stakeholders more completely in decision making. The Nuclear Energy Agency (NEA) workshops on Stakeholder Involvement have been successful fora for exchanges of experiences and lessons learnt, and have benefited from the participation and perspectives of citizens of Fukushima Prefecture.

Over the past ten years, there has been tremendous improvement in the resilience of nuclear plants; however, more in-depth activities remain to be done – particularly in human aspects of nuclear safety. This chapter briefly reviews status and advancements in these areas.

5.1. Lessons learnt on organisational factors and safety culture in NEA member countries

5.1.1. Enhancing the understanding of human aspects of nuclear safety

As observed in the NEA report *Five Years After the Fukushima Daiichi Accident* (NEA, 2016b), continuous and innovative progress is fundamental to ensuring safety, even where many improvements have been made. Lessons learnt through operating experience and research will require continued attention. This is particularly true for complex areas such as the human aspects of nuclear safety as reflected in safety culture, training and organisational factors. Constant vigilance and effort are needed at national and international levels.

The NEA has supported activities and long-term initiatives on accident management, crisis communications, precursor events, defence in depth (DiD), regulatory effectiveness, safety culture and regulation of new reactors. This has resulted in best practices and guidance for countries with existing, mature regulatory organisations and can be used for improving policies and practices, benchmarking as well as training staff and ensuring knowledge and know-how transfer. Such activities are essential and fundamental in assisting countries to ensure the safe and effective deployment of nuclear technology.

Addressing the human aspects of nuclear safety, including organisational factors and safety culture, is fundamental for the safe operation of nuclear installations as well as for the effectiveness of regulatory authorities. These aspects also have an important impact on the potential future uses and regulation of nuclear technology. The NEA has continued to assist its member countries in their efforts to enhance focus and improve the understanding and the technical basis for treating these elements.

NEA member countries continued to implement measures in the area of safety culture, reinforcing their regulatory requirements and further developing their guidelines and guidance documents. They also carried out various activities to ensure human and organisational factors are addressed which have, for example, included the following:

- The Radiation and Nuclear Safety Authority in Finland has begun implementation of risk-based oversight of organisational factors. They are developing tools to look into the most important issues of safety concerned with organisational factors.
- The Man-Technology-Organisation of the Institute for Energy Technology in Norway conducted a study on Crew Decision Making with Degraded Information, to look at how human performance is affected when information is missing or degraded, as this is relatively common and can increase in severe situations or during cyber-attacks. This work focuses on the strategies operators use to determine that the indications from their instruments are degraded, under what conditions they fail to notice degraded information, and how operators handle situations with degraded information.
- Human factors are increasingly incorporated into many aspects of member countries' approaches to nuclear safety.

5.1.2. National culture and safety culture

Over the years, the importance of safety culture and its influence on nuclear safety has been increasingly recognised. It has become increasingly evident that safety culture is influenced by many factors, among these factors are elements reflecting the national cultures. This question is not new, but the Fukushima Daiichi accident brought it to the forefront and prompted a focussed response to the issue (NEA, 2016h). Hence, it is important that the nuclear community take time to uncover these national influences, realise their potential impacts on safety and develop a path towards sustaining a healthy safety culture. The Country-Specific Safety Culture Forum (CSSCF) is a step in this development, conceived and implemented jointly by the NEA and the World Association of Nuclear Operators (WANO) as a means of providing an arena to explore the impact of the national context on nuclear safety and derive approaches to sustain and improve nuclear safety culture.

The concept behind the CSSCF is to start out from the respective country's cultural realities and conduct a reflective dialogue about strengths and weaknesses, as well as what can be done to strengthen the safety culture within the authorities and operators concerned. In order to improve safety culture, the attributes that make up the national context must be understood. It is important to keep in mind that the national attributes are neither good nor bad. They can support a sound safety culture or, if disregarded, can in some instances counteract safety culture. The goal of the CSSCF is not to change the national attributes but rather to create awareness of how they manifest in organisational behaviours and, potentially, highlight areas that mat be further addressed in training programmes. The aim is to work within the national context for sustainable change.

The nuclear safety regulatory bodies of both Finland and Sweden have hosted CSSCFs (NEA, 2018e; NEA, 2019c) and all the organisations involved found them to have considerable benefit and to contribute towards enhancing the human and organisational factors of safety within a national context. Canada and the United Kingdom are scheduled to host CSSCFs in the coming years. Both the NEA and WANO are supportive of this approach and would recommend conducting CSSCFs in other member countries – including those with established nuclear safety institutions and those wishing to further strengthen/develop their nuclear safety institutions.

5.1.3. Defence and institutional strength in depth

Whereas rigorous and comprehensive safety standards and other tools may be in place, the Fukushima Daiichi accident has clearly shown that to deliver high levels of safety the overall nuclear safety system must ultimately ensure their diligent and effective application by the relevant institutions, taking into account human and organisational factors. In other words, to achieve high levels of safety in all circumstances and against all challenges, the nuclear safety system in its entirety must be robust.

Defence in depth (DiD) provides a systematic means to analyse and ensure layers of systems to prevent or mitigate accidents. Activities to strengthen and further develop DiD are reported in *Implementation of Defence in Depth at Nuclear Power Plants* (NEA, 2016a). The analogous concept of strength in depth (SiD), hinging on strong independent institutions, has been recognised as a powerful aspect of accident prevention and management (IAEA, 2017).

There are three main independent organisational sub-systems in the overall nuclear safety system: a strong licensee, a strong and independent regulator, and a strong set of public stakeholders. Each of these subsystems must possess the competence and capacity to fulfil its respective functions and duties. In addition, the subsystems should interact, encouraging and welcoming reciprocal questions and challenges, and taking into consideration others' options and advice. Within each subsystem there are multiple layers and components that provide the independence, diversity, redundancy and separation of function required to prevent single-point or common-cause failures. For example, within the licensee subsystem, the individual licensee is supported by peer layers at the national and international level, and a further layer of international institutions. Similarly, in the regulator subsystem the regulatory authority is supported by a layer of national and international technical groups, a layer of international peers, and a layer of international institutions.

In summary, the application of institutional strength in depth as part of the human and organisational approach to nuclear safety is a necessary building block to enhance and ensure nuclear safety on a national and global basis.

5.2. Accident, emergency and post-accident management: Resilience and balancing decisions

5.2.1. Resilience

A lesson reinforced by the Fukushima Daiichi Nuclear Power Plant accident is that it is necessary to provide accident management measures for conditions more complex and/or more severe than those postulated for design basis accidents (DBAs). Additionally, the accident has highlighted the need to ensure accident management measures are robust and diverse so that they are not likely to be completely defeated by a single event leading to a "cliff-edge" effect.

From this, the concept of strengthening resilience in emergency and accident management has emerged. Resilience is having the ability within local, national and international plans to deal with unprecedented events, and having the flexibility and agility to respond to the unexpected. This is an area of considerable challenge when considering that accidents may require the operator and the regulatory body to face a large number of “unknown unknowns.” Resilience also requires the ability to implement protection strategies that are effective, manageable and proportionate, and to have a plan for withdrawal of crisis-level intervention. Experience exists in non-nuclear areas and lessons have been drawn from emergency management of hazards emanating from a variety of sectors (NEA, 2018a). Similar challenges are seen in non-nuclear events today with the national and international responses to the COVID-19 pandemic.

5.2.2. A holistic approach to optimisation

Balanced decision making to help achieve an optimised outcome in terms of nuclear safety and risk has been fundamental to the operation and regulation of the nuclear industry. Optimisation weighs a risk against the resources (effort, time and money) needed to control it. When dealing with optimisation of protection, the ALARA principle is applied to ensure that doses all be kept “as low as reasonably achievable”, taking into account economic and societal factors. Safety measures are considered to be optimised if they provide a high level of safety across the industrial lifecycle without unduly limiting the functional activities of the facilities using radiation. Thus, this process of optimising the risk in carrying out activities, actions and programmes describes the limit to which society expects to see exposure controlled and the resources that society is willing to invest for control.

The ALARA principle applies also to post-accident management, where additionally the costs and benefits of countermeasures and the amount of waste created must be weighed. The accident at Fukushima Daiichi, its immediate and longer-term aftermath, and the tasks of decommissioning the site and dealing with the associated waste, have highlighted this point. Situations presenting potential exposure to radiation are in general complex and require multidisciplinary attention, both during an accident and in the post-accident management of the recovery. The experience has brought forward the need to consider in a holistic way the wider environmental, societal, psychological, technological and economic costs and benefits of radiation applications and associated (potential) exposures, but also, for recovery, of different options for protective action. Any given circumstance will have particular social, environmental, economic and political features that will influence the preferences of stakeholders. Focusing resources on the reduction of one single risk, for example health risk from radiation exposure, may lead to minimising exposure, but may not lead to well-balanced overall protection of well-being. The global nuclear community undertakes to develop better understanding of these features and preferences extending far beyond the site perimeter and to address their fuller integration into the process of balanced and optimised risk decision making.

The risks presented by the prevailing circumstances in the aftermath of the accident at Fukushima Daiichi are, in general, very difficult to compare in qualitative terms. While it is possible to put a monetary value on the costs and consequences of controlling certain risks, a common framework is needed in which significantly different aspects can be balanced to support risk-informed decision-making processes and determine the level of tolerability of risk and uncertainty.

Such complex decision making is inherently difficult, especially when outcomes affect a public who may not have a direct part in decision making. It typically requires the establishment of a position after taking multiple, sometimes contradictory factors into account, many characterised by uncertainty. Such positions and decisions are often required to be taken under time pressure and in confusing contexts where short-term emergent factors and long-term impacts cannot readily be predicted. The decision to evacuate members of the public in response to the potential releases from the Fukushima Daiichi accident should be viewed in this context.

How to reach a consensus optimum decision in such circumstances is a challenge that must be addressed, noting that international work can assist but each country must take into account differing cultural backgrounds, and different social, economic and political environments. This again points to the value of a more holistic and inclusive approach to decision making, considering a wider range of factors and inputs than radiological protection and nuclear safety decision routines may have used in the past. Moreover, an agreed process needs to be put in place to determine the basis for ending or reversing a decision once its primary purpose has been achieved (or when assessment shows that purpose cannot be fully achieved). This is a lesson re-emphasised by the difficulties encountered by authorities and communities in seeking to return to their home places and reconstruct after the temporary relocation decided at the time of the accident.

5.2.3. Balancing risks of decisions in emergency situations

After the onset of the Fukushima Daiichi accident, multiple evacuation orders were declared over several days, while decisions on voluntary evacuation took somewhat longer. The lessons learnt call for reconsideration of implementing immediate evacuation because of the mortality risks associated with evacuations. Immediate evacuation was unsafe for patients from hospitals and nursing homes and where preparation was insufficient led to higher mortality. These are also major lessons for accident preparedness, where it seems appropriate to consider specific actions for vulnerable groups such as elderly people to balance the risks of immediate evacuation against the possible benefits of sheltering in place with continuous care (if ad hoc resources and care takers are available). More generally, the Fukushima Daiichi accident experience suggests a need to better clarify and understand the direct causes and risk factors for evacuation-related deaths. It has also shown that advice by knowledgeable experts must be carefully integrated in post-accident decisions, regarding both health risks from radiation exposure (helping individuals or communities answer the question "*am I safe?*"), and the potential deleterious effects of protective actions.

As such, another crucial area relates to the mitigation of mental health and psycho-social impacts on populations when implementing protective measures. The NEA contributed to the development of the World Health Organization (WHO) framework on Mental Health and Psychosocial Support (MHPSS) in radiological or nuclear emergencies, adapting existing guidelines for non-nuclear emergency settings (WHO, 2020). Recent NEA webinars helped to explore how the experience and lessons from non-nuclear crises, such as the COVID-19 pandemic, could help countries to improve MHPSS in the event of a nuclear or radiological emergency (NEA, 2020c). The NEA is furthermore developing practical, feasible approaches to integrate MHPSS impacts in protective action decisions. The way forward should include: i) developing methods for balancing direct health risks against the indirect consequences of protective actions, by considering potential impacts on the most vulnerable groups (e.g., elderly, hospitalised population, etc.); ii) enabling more effective risk communication; iii) making the best use of international good practice examples of MHPSS operations and adapting them to the national/local plans and procedures; and iv) integrating logistical or other highly local aspects in preparedness (e.g. effective access to health care and public services, relationship of the community or groups to the natural environment and traditional areas).

6. Further challenges stemming from the accident

Japan and many other countries have successfully addressed many issues and difficulties arising from the accident and, importantly, identified and learnt lessons to make further improvements in global nuclear safety. The technical understanding of the accident is well established on the aspects of its cause and how to prevent similar events. Many technical and regulatory issues have now been resolved. However, scientific knowledge continues to evolve on how the accident progressed in each unit, and on some aspects related to the accident consequences including those which are of environmental, social, economic or political character. This chapter addresses ongoing and future challenges, noting their linkages. It revisits several aspects which have benefitted from discussion in the preceding chapters.

Nuclear power is likely to play an important role in addressing the world's energy future, particularly as more countries take serious action to dramatically reduce emissions of carbon into the atmosphere. Hence, ensuring that the lessons are embedded in future policies and practices is vital. This chapter also recalls the involvement of the international community, and the willingness of the Nuclear Energy Agency (NEA) and its member countries to continue lending their support and expertise.

6.1. Technical challenges

6.1.1. Fuel debris removal and associated forensic studies

The Japanese government, the Nuclear Damage Compensation and Decommissioning Facilitation Corporation (NDF), the Tokyo Electric Power Company (TEPCO), the Japan Atomic Energy Agency (JAEA) and other Japanese institutions continue to engage in significant work to determine how to remove the fuel debris from the three stricken reactors on the Fukushima Daiichi site, and to prepare for this unprecedented task. While the global scientific community is keen to learn from the effort, advancing the decommissioning programme must remain the central priority.

The programme includes safety assessments, research and development and engineering studies, as well as procurement of equipment, some of which represents novel, first-of-a-kind technology. The fuel debris analysis has to be broad ranging. Its primary purpose will be to optimise the safety of the decommissioning work and the safe treatment, storage, and eventual disposal of the fuel debris and associated structures and materials. Also, the analysis will enhance scientific understanding of the phenomena affecting the fuel under accident conditions. Of particular interest are the location and form of the fuel debris and the extent to which knowledge of these can refine predictive modelling using computer codes. Enhanced realism in such modelling provides a technical and simulation basis for improvements in technological plant-safety responses, as well as in Severe Accident Management Guidelines (SAMGs) and other procedures that can help prevent and/or mitigate the evolution of any future accident the world may encounter.

The NEA is well placed to support Japan and the international community in advancing this work. The NEA can co-ordinate the interests of scientists around the world to formulate a joint plan for forensic investigation work on fuel debris in partnership with Japanese work, avoiding duplication and fostering synergies. Such collaboration and refinement were discussed above in section 4.1.2.

Additionally, the NEA can assist Japan in its development of the basis for fuel debris retrieval by co-ordinating the gathering of information from member countries on important topics such as:

- release of various radioactive materials related to fuel retrieval operations (e.g. radioactive dusts);
- containment and ventilation systems for fine radioactive particles, especially alpha particles;
- criticality assessment and protection under uncertain configurations and form of fissile materials and moderators;
- material (especially elastomers, plastics, greases and fluids) behaviours and properties in highly radioactive environments;
- use of robotics in highly radioactive environments.

This list is not exhaustive; there will be other advanced engineering challenges in the safe and effective retrieval of fuel debris with which NEA and its members may be able to assist.

6.1.2. Decontamination methods, environmental remediation and related waste issues

The decommissioning of Fukushima Daiichi will require the capability to decontaminate areas, structures, equipment, etc., suitably and to create an inventory, condition, store and eventually dispose of the contaminated and radioactive material. Both the safety of workers undertaking decommissioning activities and the minimisation of radioactive waste are at stake (NEA, forthcoming k). Because there are many methods of decontamination commercially available from industry, it would be useful to have a central data bank of such methods, their use, feasibility, cost and effectiveness together with the science behind them. The NEA is already bringing together existing knowledge and information that can support ongoing decommissioning work and stimulate further technological development to enable future tasks to be conducted more safely and efficiently.

Japan has undertaken a massive programme to decontaminate and remediate extensive environmental areas affected by radioactive deposition from the accident. Some of these activities are unprecedented considering the volumes and complexities involved, and additional work remains to be done. Several NEA member countries have experience in such activities; assembling experts in this field to determine the state of the art, propose further scientific or other research, and draw lessons would be advantageous. Other areas of the Organisation for Economic Co-operation and Development (OECD) also could provide useful input, given that there are economic and other considerations in determining effective and efficient remediation.

Areas that could be considered include:

- tools to compare various remediation/clean-up options (including the do-nothing or zero option), assessment of options such as recycling of low-level contaminated materials (as considered in Japan), and identification of criteria to distinguish conventional waste from that which needs special consideration as radioactive waste;
- guidance for a sustainable remediation approach, including those related to legislative and policy frameworks, taking into account the sustainability pillars (environmental, social and ethical, and economic) and the impact of various end-state options;
- information systems to compile, manage and store data and other knowledge used for decision making and stakeholder engagement;
- stakeholder involvement and strategies to maintain and build trust with the authorities at the local and national levels in view of elaborating an environmental remediation plan, including designing and siting final waste storage facilities.

6.1.3. Solid waste management

Effective and efficient solid waste management is at the core of safe economic and timely decommissioning, and yet it remains one of the most challenging areas for nuclear programmes to demonstrate full lifecycle stewardship to the public. Many countries have struggled to establish disposal sites for spent nuclear fuel and highly radioactive waste and continue to face challenges in the scientific, engineering, societal and policy domains. This is true also for Japan where although studies on treatment and handling methods are underway at present, final plans for the disposal of radioactive waste from the decommissioning of Fukushima Daiichi cannot yet be established.

Japan is currently engaging with the difficult waste management issues associated with large-scale decommissioning posed by the Fukushima Daiichi site and surrounding area. The waste includes large quantities of materials ranging from lightly contaminated soil, trees and other natural products, to the very highly radioactive materials to be retrieved in future from inside the primary containment vessel (PCV). NEA has publications across the range of issues (see section 4.1.3, and NEA, 2015b; 2016c; 2018d; forthcoming m), but more work is required to assist Japan and advance the basis worldwide to effectuate closure of the nuclear fuel cycle. The NEA continues to gather experiences from around the world on handling and disposing of complex radioactive waste, and the following areas are highlighted for further development:

- application of advanced technologies (e.g. robotics, digitalisation);
- decommissioning cost evaluation practices (NEA, 2012f; 2014o; 2015l; 2017g; 2019i);
- waste decisions and stakeholder engagement (see section 6.4);
- strategy and approaches to the management of materials from decommissioning and territorial rehabilitation;
- multijurisdictional and multinational considerations for the safe storage, transport and disposal of waste;
- management of information, data and knowledge.

6.2. Regulation

A challenge of post-accident contexts such as Fukushima Daiichi is that their regulation cannot be identical to that adopted for operating reactor sites or planned end-of-life decommissioning. The Fukushima Daiichi site is in an uncertain state with many unknowns. Decommissioning of the nuclear power plant is very complex and a flexible, stepwise process is being employed to gradually build up knowledge and experience. The NEA has assisted by assembling regulatory experts from its member countries to determine common lessons (NEA, 2019d).

Japan's Nuclear Regulation Authority (NRA) and other member country regulators would be served by further insights into the following matters: regulation under uncertainty such as with special decommissioning projects; optimisation decisions (see sections 5.2.2 and 6.5); effective regulatory engagement with stakeholders and industry; and effective regulatory interactions with the licensees and public.

The NRA has made tremendous progress in developing into a technically and independent nuclear regulator over the last ten years. As is the case with many nuclear regulators, it has probably reached a transition point where the opportunity exists to adapt to the fast-moving changes in society and further enhance its effectiveness through open and constructive dialogue with industry, on all levels.

The NRA has the basis for such evolution in its guiding principles that include "independent decision making" and "openness and transparency." In effecting these principles, the NRA has implemented an external stakeholder engagement practice that includes a policy of strict distancing from the nuclear industry. While recognising the significant difficulties in Japan stemming from the accident at Fukushima Daiichi, it is important for regulators to strive, in keeping with the stated "characteristics of an effective regulator," for balance and reasonableness in their approach to demonstrating independence and openness. As other NEA member countries can attest, such balance can and should be achieved through multilateral and bilateral, public and non-public engagement between the regulator and external stakeholders, including nuclear industry representatives; care must be taken to conduct bilateral engagements with any stakeholder in a manner that avoids or minimises the perception of bias or compromise. This approach balancing independence and openness allows the regulator to avoid isolation, and to obtain the information needed to understand the relevant issues and develop sound, timely regulatory decisions.

Broader stakeholder engagement can be an important process to reach consensus on optimum decommissioning approaches for difficult activities or circumstances. Experience from NEA member countries has shown that adopting innovative approaches to involving stakeholders in such decisions can be of assistance. These processes can bring together regulators, government officials, local public representatives, decommissioning strategic bodies (such as the NDF), and the site operators to examine and agree on optimum decommissioning approaches. In situations where operators are exposed to an increased short-term risk, parties to the meeting, such as the regulator, may choose to favour a risk-informed approach over a prescriptive approach, so that reasonable actions can be undertaken that lead more directly to long-term hazard reduction.

6.3. Rebuilding and revitalising communities and local economies

Japan is in the midst of rebuilding the areas damaged and evacuated following the tsunami and the accident at Fukushima Daiichi, and revitalising that part of Japan. Among the excellent initiatives taken by the operator are the effort by TEPCO's FDEC to engage local business in the work at the site, thereby building up their knowledge and expertise; and proposals to set up local scientific/technical centres of excellence focused on decommissioning needs for Fukushima Daiichi.

A public/private organisation, Fukushima Soso Reconstruction Corporation, was established by the Japanese government in 2015 to assist restarting affected businesses. The main points pursued by the joint revitalisation team were to gain needed information locally, build trust with all economic actors, co-operate with professionals for responding to the various issues, and reflect local needs in government support measures. Although some businesses have restarted, there still remain many issues to be tackled, for example, business continuity or deep-rooted reputational damage caused by harmful rumours.

Revitalisation not only covers restarting business. Measures are also crucial for revitalisation of family and social bonds, of cultural links, and of social, environmental and economic linkages between "sub-communities" (e.g. those created by the zoning actions after the disaster). Access to support and services matching local needs must be reinforced. Ten years after the accident, food safety management strongly interacts with economic aspects through consumers trust, the issue of loss of image for a region and/or a product, and/or how to secure the market for emblematic food products.

There is some understandable apprehension among citizens regarding residual levels of radioactive contamination. Means have been provided in Japan for local citizens to exercise management in relation to these concerns through monitoring programmes and advice on protective actions.

These various issues must be embedded into a comprehensive and operational generic framework enabling preparedness for post-accident recovery. This framework should provide guidance on how to make the recovery decision-making process consensual, by involving a wide range of stakeholders who can bring local knowledge and expertise in order to achieve the best possible outcomes and provide insights on how to build national and community resilience to minimise the societal disruption and facilitate recovery.

The NEA is in a unique position to assist with its close connection to the wider expertise in the OECD. The NEA can access specific country-based experience in rebuilding deprived areas, whether or not these are characterised by widespread radioactive contamination and evacuation. Such synergistic work could potentially assist Japan, and also benefit other countries confronted by the need to rebuild local economies in a sustained and sustainable way. The NEA has already published several reports in this area (NEA, 2014n; 2019g; forthcoming h). Such work has to take into account ethical considerations (see section 6.7) such as respecting the rights and autonomy of individuals.

6.4. Public and stakeholder engagement

Stakeholder trust in the institutions and decision makers who operate and oversee nuclear energy programmes remains an ongoing issue in many NEA member states and was an overarching theme of the NEA's 2017 and 2019 stakeholder involvement workshops (NEA, forthcoming i). Building long-term relationships, especially between individuals, with a range of stakeholders, including local communities, is essential not only for navigating challenges but also for establishing the informed confidence in the institutions which is integral to a democratic society. Trust is built upon openness, transparency, effective communication and meaningful engagement, which are intertwined, resource-intensive, and often difficult to fully achieve. Nuclear-related communication is sometimes viewed solely as translating scientific and technical language into accessible public messaging. In fact, this is not the end goal, but instead the starting point for building meaningful, dialogue-based relationships informed not only by science, but also by public needs and concerns. When stakeholders experience their interactions and feedback being explicitly considered, being responded to openly and transparently and influencing policies, it builds confidence, trust, and value in the nuclear energy community, and increases robustness of policies.

At this tenth anniversary of the Fukushima Daiichi accident, next steps on the future of the site will require operationalising these lessons by bringing together civil society stakeholders and those across the Japanese government, regulatory bodies, industry, and regional entities in a co-ordinated and transparent policy decision-making process. Communication, stakeholder relationships and trust at the international, national and local levels have impacted societal responses and resiliency in the short and long term. Conscientious stakeholder relationships built on trust, openness, transparency, empathy, and communication offer pathways to policy decision making rooted in informed consent and optimisation (see section 6.5) across the full range of impacts. NEA member countries recognise that work in this area has broad applicability to the whole spectrum of nuclear policy and will continue to support international co-operation advancing stakeholder engagement.

6.5. Optimised holistic decision making

Experts in the radiological protection community and wider fora recognise that complex decision making in a context like the one found at Fukushima Daiichi benefits greatly from a holistic approach to optimisation and decision making through wider information gathering and engagement. NEA publications have reported the development of such an approach and offer guidance on how to exchange information to make better informed decisions (NEA, 2012e; 2015a; forthcoming g; forthcoming h). The role of a broadened range of stakeholders is actively discussed and experiences are exchanged regarding means for their involvement. To take this further forward will require a wider range of expertise that can involve other parts of the OECD.

Governments and regulators may also confront difficulties in establishing public support for policy decisions on the disposal of radioactive waste, or on power station life extensions. Such decisions may make sense based on scientific evidence, but may not be accepted socially or politically. Reaching a consensus optimum policy decision in such circumstances is a challenge that must be addressed, noting that international work can assist but each country must take into account differing cultural backgrounds as well as different social, legal, economic and political environments. This again points to the need for a more holistic and inclusive approach to policy decision making, and for considering a wider range of factors and inputs than radiological protection and nuclear safety may have used in the past.

Optimisation is one of the three protection principles of the international radiological protection system besides justification and limitation (as applicable). Briefly stated, doses should all be kept as low as reasonably achievable (ALARA), taking into account economic and societal factors, and:

- using an all-hazards approach – with optimisation of radiological exposure done by taking into account other risks;
- involving stakeholders where practical and appropriate – with stakeholder engagement being integral to the policy decision-making process and key for defining acceptance or tolerance;

- conducting structured analysis – proposing and comparing different options for protection, their costs and their benefits;
- referring to the need for proportionality – by implementing a graded approach.

There is a sense today that the approach to protection must evolve beyond the narrow optimisation of radiation exposure to place optimisation within the larger perspective of well-being. Methods and tools are needed to appropriately balance approaches to managing diverse risks, keeping in view stakeholders' needs and concerns, looking at the wider range of benefits beyond those to health, generating and assessing options on this basis. This will never be a one-size-fits-all approach; the human dimension is key and optimisation processes must integrate cultural and country-specific features, as they are found at the time of application. Post-accident recovery can be improved by making the recovery process a bridge to a "new normal" designed according to the desired outcomes of the stakeholders. Such new processes should also embrace environmental optimisation.

The NEA is examining multidisciplinary practices for optimising health and safety within wider environmental and socioeconomic contexts and under dynamic and uncertain conditions. However, more work is needed on how to achieve transparently accepted or tolerated and sustainable policy decisions through a stakeholder-inclusive process of balancing the various risk components (covering both benefits and detriments) towards the identification of the best-balanced optimal protection.

6.6. Institutional systems for ensuring nuclear safety

As the Japanese Diet independent report indicated (The National Diet of Japan, 2012), the Fukushima Daiichi accident had as a root cause[1] structural flaws in Japan's nuclear administration – institutional failure rather than technical failure. The failure of the system in place to ensure nuclear safety furthermore led to a breakdown of public trust in the industry, regulator and government in Japan, and raised concerns about other institutions elsewhere in the world. Understanding that the accident was a system failure rather than attributable to just one or more components in the system is key to ensuring that wider lessons are learnt. Looking at the technical aspects of the accident is necessary but not sufficient if nuclear accidents with different direct causes are to be prevented.

Thus, rather than just reviewing or changing one component (such as the regulator) in the system the whole nuclear safety system has to be considered, especially the interactions among components. Some work has been undertaken in this area, for example the INSAG 27 report (IAEA, 2017), but more is required to expand knowledge and understanding.

6.7. Ethics for leaders and participants

One of the major issues stemming from the accident at the Fukushima Daiichi Nuclear Power Plant was the loss of public trust. The accident demonstrated that trust is easily lost, and once lost very difficult to rebuild. One of the major components of rebuilding trust is the regard that the public have for what drives the professionals in a profession or organisation. Many leaders and professionals in the nuclear industry, regulators and other organisations have a sense of purpose and working for the greater good. This is reflected in professional bodies' required standards of behaviours. WANO has published a document on nuclear leadership in which it is stated:

> As leaders in the commercial nuclear industry, we carry a unique responsibility to uphold the highest standards of nuclear safety while producing electricity reliably. Our ability to effectively lead our organisations and teams is essential to fulfilling our obligations to all key stakeholders: our employees, the public, regulators and our colleagues in the global nuclear power community. (WANO, 2019, p. 2)

1. Accident investigators talk of direct causes and root causes. Direct causes (e.g. a tsunami) instigate the accident; root causes are the underlying problems that would eventually surface in an accident or "near miss".

The International Commission for Radiological Protection (ICRP) has published *Ethical Foundations of the System of Radiological Protection* (ICRP, 2018). The core ethical tenets are:

- beneficence and non-maleficence (doing good and avoiding causing harm);
- prudence (choosing carefully in cases where full knowledge is not available);
- justice (being fair in sharing advantages and disadvantages);
- dignity (respect to individuals – a human right).

These principles have foundations in the Hippocratic Oath that has been used to guide medical physicians through the centuries, and which may be the basis for the general trust that the public has in the medical profession.

Perhaps the time is ripe for the various strands of nuclear ethics, as indicated above, to be brought together in an overarching code of ethics for nuclear leaders and professions worldwide. This could be part of the basis of building sustained public trust and confidence in the peaceful use of nuclear energy. The NEA with its member countries could be the catalyst for such an initiative. Such an ethical code could then lead onto principles for policy decision processes enhancing an open dialogue among experts, authorities and citizens.

6.8. Intergenerational knowledge and experience

The hard-won experience and knowledge that comes from accidents such as that at the Fukushima Daiichi site, and from the ensuing work to understand and implement lessons, must not be lost to future generations. This is only one part of the nuclear knowledge and experience available. Various organisations and companies have their own knowledge management systems which in principle must preserve both essential documents and tacit know-how and experience. The world needs a mechanism of bringing all this together dynamically and making it accessible (respecting any security and commercial considerations) across generations and countries. The NEA has initiated some work in this area (NEA, 2019d), and its Radioactive Waste Management Committee established the Working Party on Information, Data and Knowledge Management in 2020.

It is noted that the NEA has a Data Bank service covering nuclear-related computer codes and data. This may be able to act as a basis for a wider world knowledge management system building on a Japanese system for knowledge management related to Fukushima Daiichi.

6.9. A global system of international organisations working together

The response to the Fukushima Daiichi accident has benefited greatly from the closer working together of international organisations (see section 4.2). Looking into the future, such collaborative work will be required as nuclear safety and radiological protection are continuously improved in an effective and efficient way as a basis for promoting nuclear power as a safe, robust, clean energy technology. Leaders of regulatory bodies meet periodically to learn from each other and address common issues, as do leaders of nuclear power companies to hold each other to account and promote excellence. Apart from some conferences, leaders of international organisations rarely get together to build mutually beneficial collaborations. The relationships formed when jointly responding to the Fukushima Daiichi accident could be used as a basis for further partnership to address other global issues including those of interest to other parts of the OECD.

6.10. Legal preparedness

The Fukushima Daiichi nuclear accident reminded the international community of the importance of having a clear and comprehensive legal framework in place to enable the relevant bodies to react quickly and adapt to the specific circumstances of the accident to ensure timely and financially adequate compensation to victims. Japan's Act on Compensation for Nuclear Damage was an adequate basis requiring only further supplement to adjust the legal framework to the context of the accident (see section 3.4.3 above).

The NEA has organised workshops to discuss the practical features of implementing a nuclear liability regime, whether at the national or international levels, and consequences of the absence of treaty relations. Such discussion should continue in order to support states with nuclear installations, and as many states as possible that may be affected by a nuclear accident, in adhering to one of the nuclear liability regimes and improving their national legislation as necessary.

7. Conclusions and perspectives

The accident at Fukushima Daiichi was a seminal event for both the Japanese and global nuclear sectors. Japanese governmental and industrial organisations have responded well to the accident, especially in containing the accident's effects and in being open and transparent with information. Globally, the accident proved to be a watershed moment that spurred greater exchange of information and best practices between nuclear regulators, the industry, and international organisations than had been seen previously.

In Japan, improvements have been made to the regulation and oversight of nuclear technology. A major focus is placed now on safely decommissioning the damaged reactors and remediating the site in a manner that accommodates the needs and concerns of stakeholders at the local, national and international level. The Fukushima Daiichi site entails unprecedented challenges – including four heavily damaged reactors with three melted cores. The decommissioning effort is being pursued with vigour in a structured manner with a focus on risk reduction and with a priority to ensure the safety of workers, the public and the environment. A large earthquake struck Fukushima Prefecture on 13 February 2021 and impacted the site. While analysis performed thus far indicates that this event caused no significant difficulties at the Fukushima Daiichi site, it serves as a clear reminder of the need to complete the decommissioning effort as soon as practical.

Off-site decontamination activities in the areas around the site have progressed well. Most evacuation orders have been lifted and public services have been restored in many of the affected areas. There is now a need to enhance the ongoing programme to rebuild and revitalise communities and local economies. This is a significant challenge that is situated more largely in the realm of communications and confidence-building than in that of radiological protection and nuclear safety.

Globally, lessons learnt have been applied to further enhance the safety of nuclear facilities, particularly in ensuring the availability of robust and diverse systems to respond to accidents and extreme events. International experts, many of whom have been engaged with Japanese partners since the early days of the accident to support Japan's response to and recovery from the accident, seek opportunities to enhance the world's knowledge base. The shared learning and co-operation benefit the global community, fuelling further progress in many areas of nuclear safety and radiological protection – including stakeholder engagement.

Going forward, efforts in Japan and around the world continue to rebuild and enhance public trust in nuclear operations. In this respect, new lessons continue to be learnt, such as enhancing post-accident recovery by placing the human and societal dimension at the core of planning through comprehensive stakeholder involvement. It is now widely understood that earning public trust is a key catalyst for recovery.

Decommissioning and management of radioactive wastes

The safe decommissioning of the site and surrounding areas and the careful management of wastes associated with these activities are the clear priority for the effort in Japan to recover from the Fukushima Daiichi accident. There is a need to develop a more comprehensive system to manage the unconventional wastes emerging from the decommissioning effort, including the development of characterisation methods and techniques for legacy and unconventional waste, for effective decommissioning and treatment, and for waste management. Fully engaging the global community will tap into worldwide experience in addressing highly contaminated sites and highlight both good practices and methods to be avoided.

The decommissioning effort also calls for effective application of robotics and remote technologies. This is another area ripe for international collaboration. Development at national and international level of strategic approaches to facilitate the implementation of such advanced systems in radioactive waste management, decommissioning and legacy management will support the Japanese decommissioning activities. In particular, there is a need for Japan and other countries to co-operate in addressing the unique challenges associated with the use of remote tools to progress the removal of fuel debris from the damaged reactors.

Nuclear safety and scientific knowledge

The technical understanding of the most significant aspects of the causes and progress of the accident has advanced significantly, providing a firm basis for the measures undertaken to further improve the safety of nuclear installations worldwide. In applying the lessons learnt, the specific situation in a country (geography, regulatory framework, etc.) must be taken into account. While the outcomes may be very similar, different priorities for enhancing safety and preventing and mitigating potential accidents are identified in each country. As the Fukushima Daiichi reactors are decommissioned, there will be opportunities to gain further understanding of the specifics of the accident progression that can enhance the scientific knowledge base. For example, information may be gained on core melt behaviour, fission products release, and the behaviour of nuclear power plant components and structures, including spent fuel pools, in a severe accident. Japan can assume a central role in the enhancement of safety and knowledge in some specific areas and Japanese research capabilities could be augmented to take the best advantage of opportunities to gather new scientific knowledge.

Worldwide operating experience combined with risk insights provides a source of potential improvement or innovations, as demonstrated in the course of several events over the history of global nuclear operations. The Fukushima Daiichi experience is adding significantly to this knowledge base. There remain opportunities for learning associated with the evaluation and mitigation of the technical, environmental, social, political and economic consequences of the accident. One main technical challenge is related to the removal of debris, and fuel debris in particular. Accordingly, the analysis of fuel debris must be broad-ranging, considering that its primary purpose will be to optimise the safety of the decommissioning work and the safe treatment, storage, and eventual disposal of the fuel debris and associated structures and materials. There is considerable international interest in this work and many insights to be gained.

Stakeholder involvement and risk communication

Since the general public has great interest in the work underway to remediate the Fukushima Daiichi site and surrounding areas, effective engagement with the citizens of Fukushima Prefecture is a very high priority. As has been observed in key fora in recent years, particularly the NEA Stakeholder Involvement Workshops, relating complex technical topics to public stakeholders is a difficult task that requires considerable attention and resources. This is a challenge in Japan and in many other countries.

In Japan, the Nuclear Damage Compensation and Decommissioning Facilitation Corporation (NDF) has made tremendous strides in developing effective public engagement. There is still a need in all countries, including Japan, to find better approaches to giving stakeholders more opportunities to make their views understood and to see them incorporated into the policy decision process.

The Fukushima Daiichi experience, over the last decade, has spurred considerable rethinking in Japan and in countries around the world as to how stakeholders should be involved in policy decision making. The more traditional approach, in which governments, industry, and regulators decide upon a course of action and simply inform stakeholders after the fact with limited public input, is giving way to far more inclusive approaches.

It is now well accepted that involvement of stakeholders – including local authorities, industry, nongovernmental organisations, government officials, and, of course, the general public – in policy decision making is appropriate and advisable to enhance the credibility, legitimacy, sustainability, and final quality of decisions related to the recovery effort.

It is particularly important for there to be continued enhancement of stakeholder engagement by regulatory bodies. Japan's nuclear safety regulator, the NRA, includes stakeholder engagement in its guiding principles. The regulator can further build and enhance its effectiveness in addressing the consequences of the Fukushima Daiichi accident through the conduct of an open and constructive dialogue with industry, at all levels.

Analysis has led to the recognition that stakeholder engagement is essential also for off-site emergency management planning decisions which have direct impact on the longer-term recovery and quality of life in areas affected by the accident. As a result of these considerations, efforts in Japan and globally are needed to develop better means for communicating and discussing risk with the general public, especially prior to any event. Such communication could potentially reduce the feelings of uncertainty and fear that often arise during radiological events. A clear, straightforward approach is needed and new thinking is required to develop it. The United Nations Sendai Framework for disaster risk reduction and promoting stakeholder involvement provides some insights to enhance community engagement and societal resilience (UNISDR, 2015).

In addition to communicating risk, it is also important to ensure that risks are assessed in their broadest sense. In Japan and in all other countries, the international nuclear community must enhance emergency preparedness, response and recovery after radiological events by taking into full account and mitigating mental health and psychosocial impacts of protective decisions. Events such as the Fukushima Daiichi accident may have serious long-term effects on people's mental health and well-being and these deserve as much consideration as potential radiation exposure. Overall, an all-hazards approach for preparedness, response and recovery is recommended.

Addressing these matters will require direct engagement with the public in exchanges of views and understanding. While this change in approach is challenging, it is necessary to achieve the needed improvements.

Damage compensation

Also related to societal recovery from any radiological accident is assuring prompt compensation of the affected population, which concerns the application and interpretation of the nuclear liability regime and the practical logistical matters relating to the processing of the claims received. It is crucial for all concerned parties (mainly the affected population, the liable operator and the insurers) to know exactly what nuclear damage will be compensated for and how to estimate the allocated compensation. This could ensure that the affected population will be adequately compensated without having to go before the courts, which is time consuming, stressful and costly. In addition, it is essential to have the foundations for an efficient claim handling process that would allow the affected population wherever they are situated (on national territory or abroad) to start receiving compensation immediately in the aftermath of a radiological event. The experience being gained in Japan in this area will have global relevance.

Knowledge management

Internationally co-operative, integrated knowledge collection, management, and analysis of the lessons emerging from the Fukushima Daiichi accident have benefits for the efforts underway in Japan and for nuclear safety around the world. A vast amount of valuable knowledge has been gained thus far and much more will be realised over the years to come. It is under the responsibility of Japan and of the international nuclear community to protect, share and make the most of this knowledge. It is important that every opportunity be taken to assemble, preserve and manage this vital information in a dynamic system accessible across generations and countries. This knowledge will facilitate the effective conclusion of the remediation of the Fukushima Daiichi and the recovery of affected areas. An integrative knowledge system will enhance severe accident management, waste management, decommissioning, societal/community preparedness and post-accident recovery. It will contribute to the improvement of nuclear operations around the world, and to the development of expertise in all countries today and for future generations.

8. Recommendations

The purpose of the Nuclear Energy Agency (NEA) is to support co-operation between countries with advanced nuclear technology infrastructures to address challenges both existent and future. The Agency and its membership have been very active in understanding, assessing, and responding to the Fukushima Daiichi accident since it occurred a decade ago. The NEA will continue its focused engagement with Japanese organisations to support this important member country in the years to come as the recovery effort continues, as well as support its global membership in sharing and applying the many lessons learnt from this experience.

The NEA's ability to convene the finest experts from around the world, to quickly establish co-operative frameworks between countries, and to disseminate lessons learnt has been and will continue to be applied to the unique and difficult challenges associated with recovery from the Fukushima Daiichi accident.

In particular, the NEA may apply its resources – and those of relevant OECD programmes – to explore many areas discussed in this report such as: the development of international co-operation to pursue forensic investigation work on fuel debris in partnership with Japanese counterparts; co-ordinating support to Japanese organisations in the development of the methods for the safe and effective retrieval of fuel debris; bringing together the experience of member countries to support efforts to manage and dispose of unconventional radioactive waste emerging from the accident and recovery; and supporting efforts in Japan and globally to develop optimised approaches for emergency response and decision making that fully involve stakeholders.

Over the last decade, Japan has demonstrated excellent co-operation with the NEA and other member countries, just as many NEA members have demonstrated strong interest in engaging with the Agency and Japan in relation to the accident. All have appreciated the openness and accessibility shown by Japanese officials. It will be important for the NEA – as well as other international organisations – to leverage the successful collaborations forged in the aftermath of the Fukushima Daiichi accident to seek further, experience-based enhancements in global nuclear safety and to continue modernising radiological protection. These efforts will be essential as all pursue a common goal of improving the lives of citizens across the world.

The concluding assessment that emerges from the analysis performed in the course of developing this report is that Japanese authorities and organisations have risen very effectively to the unprecedented challenges presented by the Fukushima Daiichi accident and subsequent recovery. The efforts to reduce risks at the site have been very successful and the way has been cleared for many people to at least consider returning to their homes.

As Japanese authorities have stated consistently, there are still many years of hard work ahead. In the course of writing this report, several areas for enhancement have been identified for consideration by relevant Japanese organisations, supported by the NEA and other member countries, that might enable improvements and efficiencies. This report concludes by highlighting these areas.

Recommendation area 1: Regulatory environment

Japan's regulatory environment was significantly reformed following the accident in 2011 to specifically address issues of transparency, openness, and independence, with the creation of the NRA in 2012. This has been a challenging transformation that has met with success in the implementation of plant improvements against natural phenomena such as tsunamis, and in safety improvements aimed at station blackout threats to core cooling and backup electrical power – all specific lessons learnt from the Fukushima experience. In accordance with NRA principles and a culture of continuous improvement, the NRA could take opportunities to further enhance its open interaction with licensees while maintaining its independence and integrity.

Recommendation area 2: Systematic approach to safety

Some international activities have undertaken to review the whole nuclear safety system, including the interactions among the component organisations. This is an area on which all countries involved in nuclear operations need to focus. However, additional effort could be given to expanding the knowledge and understanding of a systematic approach to safety, such as that provided by "defence in depth" or "strength in depth", to develop and institutionalise a system for nuclear safety that provides levels of protection and engages the industry, regulators and stakeholders. In adopting such an approach, Japan would benefit from a holistic consideration of national objectives for stakeholder involvement, ethics, and principles for intervention by all interested parties. Through this leadership Japan could spur similar action in countries around the world.

Recommendation area 3: Decommissioning technologies

Relevant Japanese organisations could benefit from enhanced participation in international collaborative efforts associated with areas such as: maintaining safety in difficult radiological environments; advanced robotics suitable for radioactive applications; the characterisation of complex wastes; and technologies needed to support the extraction of core debris.

Recommendation area 4: Waste management and disposal

For the decommissioning of Fukushima Daiichi Nuclear Power Plant to be successful, the unique waste management challenges must be met. While there are welcome signs that this subject is being addressed, the waste management challenges encountered in decommissioning Fukushima Daiichi Nuclear Power Plant are unique and demanding. Areas for intensified focus include: identifying and securing disposal options for the wide variety of identified wastes and, in particular, the handling of the treated water held on the site; continued research on characterisation of the unique and unconventional waste forms; and the safe and effective extraction, removal, stabilisation, and ultimate disposal of fuel debris.

Recommendation area 5: Damage compensation

The Japanese government has worked to establish and implement the compensation scheme necessary to respond to the Fukushima Daiichi nuclear accident. However, continuous improvement efforts are needed to address the application and interpretation of the nuclear liability regime as well as the practical logistical matters relating to the processing of the claims received. Such efforts include the arrangement for concerned people being able to know exactly what nuclear damage will be compensated for and how to calculate the allocated compensation; and implementation of an efficient claims handling process to allow the affected population, wherever they are situated, to start receiving compensation in a timely manner.

Recommendation area 6: Stakeholder involvement and risk communication

A principal goal of the restructuring of the nuclear safety framework in Japan has been to repair the damaged confidence of the public in the ability of institutions to communicate accurately risk information to the public and the world, and to engage meaningfully the public in policy and decision making that affects the public. This report has acknowledged several examples of notable progress in this area. Stakeholder involvement and public engagement are extremely important in transitioning to an environment of "informed consent" characterised by public participation and community ownership in such policy decision making. Here, Japan has the opportunity to demonstrate global leadership in this important aspect of the democratic implementation of nuclear energy policy.

Continued progress in developing means of informed public engagement leading to a unified national effort to regulate and manage the nuclear energy sector is strongly encouraged. Specifically, the openness, transparency, and engagement with the public by the institutions involved with decommissioning the Fukushima Daiichi site, environmental remediation and revitalisation of affected territories, are commendable and strongly encouraged. In keeping with the principle of optimisation, use of multi-stakeholder arrangements for risk-informed policy decisions on complex hazard reduction decommissioning activities is encouraged.

Recommendation area 7: Recognition of mental health impacts

The recovery from the Fukushima Daiichi accident has involved not only the physical and health sciences but also environmental, economic, social, philosophical/ethical and emotional considerations. It is recommended that additional consideration be given to how to take into account the mental health and well-being of the affected populations. Such considerations will contribute more broadly to continued improvement in nuclear or radiological accident preparedness and recovery management. This is a global challenge in which Japan has a unique opportunity to assume a leadership role.

Recommendation area 8: Opportunities for economic redevelopment

The work on and around the Fukushima Daiichi site will proceed for many years and require new technologies and methodologies. This is both a challenge and an opportunity. As has been seen in major radiological remediation activities around the world, this work could be embraced as an engine for creativity and economic growth. The need for new remote and robotic technologies for the decommissioning work has already been identified a potential area of economic development. The Japan Atomic Energy Agency's Naraha Center for Remote Control Technology Development is an excellent beginning. It may be possible to build on this success by incentivising global innovators to come to Fukushima and develop robots for both nuclear and broader applications. Other, more ambitious possibilities may exist. For example, examination of core debris, could draw academics and researchers from around the world and serve as the core of a university-based research centre. Authorities in Japan are encouraged to consider holding an international conference to highlight possible paths to leverage the Fukushima Daiichi decommissioning work to the maximum benefit of the people of the area.

Recommendation area 9: Knowledge management

The Fukushima Daiichi event which began on 11 March 2011 and persists to this day has been tragic and challenging to the people of Fukushima Prefecture, to the Japanese people and authorities, and to the global community. While it has been a difficult experience with many more hurdles to be overcome in the future, it is also a source of learning and exploration. It is essential that a system to capture lessons learnt from this event be established in order to secure the associated knowledge.

While safe and timely decommissioning is the clear priority, it is also important to seize the opportunity to extract new lessons that will contribute to nuclear safety and the design of future facilities – at the same time as reinforcing the success of the decommissioning operation. A clear opportunity lies in the scientific investigation of core debris materials that will be removed in the course of the decommissioning effort. Japan is uniquely positioned to take a global lead in knowledge management and invite interested partners to contribute to these examinations and to structuring their outcome.

More broadly, there are many aspects of the accident that can serve to enhance current expertise and develop a new generation of specialists both in Japan and around the world. This will benefit the global community well into the future and provide a strong incentive for Japan's international partners to remain engaged in the long-term decommissioning project. Accordingly, Japanese organisations are encouraged to aggressively pursue national and international frameworks that will preserve, analyse, and disseminate the hard-won experience from the accident at the Fukushima Daiichi Nuclear Power Plant.

References and further reading

The following includes both the documents cited in this report, and an extensive but not exhaustive list of pertinent documents by the Nuclear Energy Agency (NEA) and other Japanese or international bodies. The *NEA 2019 Annual Report* (NEA, 2020a) covers all aspects of the Agency's work and provides details of the many working parties and expert groups addressing topics of interest.

Callen J. and T. Homma (2017), "Lessons Learned in Protection of the Public for the Accident at the Fukushima Daiichi Nuclear Power Plant", *Health Physics: The Radiation Safety Journal,* Vol. 112 (6), pp. 550-559, Wolters Kluwer Health, Inc.. DOI: 10.1097/HP.0000000000000666.

ENSREG (2013), Report of the European Nuclear Safety Regulator's Group, HLG_p (2013-24)117, European Nuclear Safety Regulators Group. www.ensreg.eu/document/third-report-european-nuclear-safety-regulators-group-july-2013

IAEA (2006), *Fundamental Safety Principles*, IAEA Safety Standards Series No. SF-1, International Atomic Energy Agency, Vienna. www-pub.iaea.org/MTCD/Publications/PDF/Pub1273_web.pdf

IAEA (2011), *Draft IAEA Action Plan on Nuclear Safety*, Report by the Director General, GOV/2011/59-GC(55)/14, International Atomic Energy Agency, Vienna. www.iaea.org/sites/default/files/gc/gc55-14_en.pdf

IAEA (2013), *The Follow-up IAEA International Mission on Remediation of Large Contaminated Areas Off-site the Fukushima Daiichi Nuclear Power Plant*, Preliminary Summary Report, Tokyo and Fukushima Prefecture, Japan, 14-21 October 2013, International Atomic Energy Agency, Vienna. www.iaea.org/sites/default/files/preliminarysummaryreport.pdf

IAEA (2014a), *IAEA International Peer Review Mission on Mid-and-Long-Term Roadmap Towards the Decommissioning of TEPCO's Fukushima Daiichi Nuclear Power Station Units 1-4*, Mission Report, Second Mission, Tokyo and Fukushima Prefecture, Japan, 25 November – 4 December 2013, International Atomic Energy Agency, Vienna. www.iaea.org/sites/default/files/IAEAfinal_report120214.pdf

IAEA (2014b), *6th Review Meeting of the Contracting Parties to the Convention on Nuclear Safety Summary Report*, 24 March-4 April 2014, CNS/6RM/2014/11_Final, International Atomic Energy Agency, Vienna. www.iaea.org/sites/default/files/2014-cns-summary-report-w-annexes-signed.pdf

IAEA (2015), *The Fukushima Daiichi Accident*, Report by the Director General, STI/PUB/1710, International Atomic Energy Agency, Vienna. www.iaea.org/publications/10962/the-fukushima-daiichi-accident

IAEA (2017), *Ensuring Robust National Nuclear Safety Systems – Institutional Strength in Depth*, INSAG-27, A report by the International Nuclear Safety Group, International Atomic Energy Agency, Vienna. www-pub.iaea.org/MTCD/Publications/PDF/P1779_web.pdf

IAEA (2019), *IAEA International Peer Review Mission on Mid-and-Long-Term Roadmap towards the Decommissioning of TEPCO's Fukushima Daiichi Nuclear Power Station*, Mission Report, Fourth Mission, Tokyo and Fukushima Daiichi NPS, Japan, 5-13 November 2018, International Atomic Energy Agency, Vienna. www.iaea.org/sites/default/files/19/01/missionreport-310119.pdf

IAEA (2020), *IAEA Follow-up Review of Progress Made on Management of ALPS Treated Water and the Report of the Subcommittee on Handling of ALPS treated water at TEPCO's Fukushima Daiichi Nuclear Power Station*, Review Report, International Atomic Energy Agency, Vienna. www.iaea.org/sites/default/files/20/04/review-report-020420.pdf

ICRP (2016), "Increase in Disaster-Related Deaths: Risks and Social Impacts of Evacuation", Report by A.M. Hayakawa, Annals of the ICRP, Dec; 45(2_suppl), pp. 123-128, International Commission on Radiological Protection, Sage, London. DOI: 10.1177/0146645316666707.

ICRP (2018), "Ethical Foundations of the System of Radiological Protection", *Annals of the ICRP*; 47(1), pp. 1-65, ICRP Publication 138, International Commission on Radiological Protection, Sage, London. DOI: 10.1177/0146645317746010

ICRP (2020), "Radiological Protection of People and the Environment in the Event of a Large Nuclear Accident", *Annals of the ICRP*; 49(4), pp. 11-135, ICRP Publication 146, International Commission on Radiological Protection, Sage, London. DOI: 10.1177/0146645320952659.

The Investigation Committee on the Accident at Fukushima Nuclear Power Stations of Tokyo Electric Power Company (2011), *Interim Report by the Government Investigation Committee on the Accident at Fukushima Nuclear Power Stations of Tokyo Electric Power Company*, Tokyo. www.cas.go.jp/jp/seisaku/icanps/eng/

The Investigation Committee on the Accident at Fukushima Nuclear Power Stations of Tokyo Electric Power Company (2012), *Final Report by the Government Investigation Committee on the Accident at Fukushima Nuclear Power Stations of Tokyo Electric Power Company*, Tokyo. www.cas.go.jp/jp/seisaku/icanps/eng/

MAFF (2020), *Summary of Monitoring on Fishery Products*, Fisheries Agency of Japan, Ministry of Agriculture, Forestry and Fisheries, Tokyo. www.jfa.maff.go.jp/e/inspection/index.html

METI (2011), *Mid-and-Long-Term Roadmap towards the Decommissioning of Fukushima Daiichi Nuclear Power Station Units 1-4, TEPCO*, Nuclear Emergency Response Headquarters Government and TEPCO's Mid-to-Long Term Countermeasure Meeting, Ministry of Economy, Trade and Industry, Tokyo. www.meti.go.jp/english/earthquake/nuclear/decommissioning/pdf/111221_02.pdf

METI (2019), *Mid-and-Long-Term Roadmap towards the Decommissioning of TEPCO's Fukushima Daiichi Nuclear Power Station* (The 5th Revision), The Inter-Ministerial Council for Contaminated Water and Decommissioning Issues, Ministry of Economy, Trade and Industry, Tokyo. www.meti.go.jp/english/earthquake/nuclear/decommissioning/pdf/20191227_3.pdf

METI (2020a), *The Subcommittee on Handling of the ALPS Treated Water Report*, The Subcommittee on Handling of the ALPS Treated Water, Ministry of Economy, Trade and Industry, Tokyo. www.meti.go.jp/english/earthquake/nuclear/decommissioning/pdf/20200210_alps.pdf

METI (2020b), *Outline of Decommissioning and Contaminated Water Management* (Progress Status Report, September 2020), Secretariat of the Team for Countermeasures for Decommissioning and Contaminated Water Treatment, Ministry of Economy, Trade and Industry, Tokyo. www.meti.go.jp/english/earthquake/nuclear/decommissioning/progress_status.html

The National Diet of Japan (2012), *The Official Report of the Fukushima Nuclear Accident Independent Investigation Commission Executive Summary*, The National Diet of Japan, Tokyo, Japan. https://warp.da.ndl.go.jp/info:ndljp/pid/3856371/naiic.go.jp/en/report

NDF (2020), *Technical Strategic Plan 2020 for the Decommissioning of the Fukushima Daiichi Nuclear Power Station of Tokyo Electric Power Company Holdings, Inc.* (2020 revision), Nuclear Damage Compensation and Decommissioning Facilitation Corporation, Tokyo. www.dd.ndf.go.jp/en/strategic-plan/book/20201214_SP2020eFT.pdf

NEA (2000), "Impact of Short-Term Severe Accident Management Actions in a Long-Term Perspective", NEA/CSNI/R(2000)8, OECD Publishing, Paris. www.oecd-nea.org/upload/docs/application/pdf/2020-01/csni-r2000-8.pdf

NEA (2011a), *Practices and Experience in Stakeholder Involvement for Post-nuclear Emergency Management*, NEA Publication No. 6994, OECD Publishing, Paris. www.oecd-nea.org/jcms/pl_14694/practices-and-experience-in-stakeholder-involvement-for-post-nuclear-emergency-management

NEA (2011b), "Status of National Actions in Response to the TEPCO Fukushima Daiichi Accident_ Technical Note", NEA/SEN/NRA/WGOE(2012)1, OECD Publishing, Paris. www.oecd-nea.org/jcms/pl_19154

NEA (2011c), "NEA Forum on the Fukushima Accident: Insight and Approaches – Forum Proceedings, Paris, France, 8 June 2011", NEA/CNRA/R(2011)12, OECD Publishing, Paris. www.oecd-nea.org/jcms/pl_19078/nea-forum-on-the-fukushima-accident-insight-and-approaches-forum-proceedings-paris-france-8-june-2011

NEA (2011d), *Nuclear Law Bulletin No. 88*. NEA Publication No. 7001, OECD Publishing, Paris. www.oecd-nea.org/jcms/pl_14706/nuclear-law-bulletin-no-88-volume-2011/2

NEA (2012a), *OECD Nuclear Energy Agency (NEA) Activities in Follow-Up to the TEPCO Fukushima Daiichi Nuclear Accident (2012)*, NEA Publication No. 6888, OECD Publishing, Paris. www.oecd-nea.org/jcms/pl_14564/oecd-nuclear-energy-agency-nea-follow-up-to-the-tepco-fukushima-daiichi-nuclear-accident

NEA (2012b), *The Economics of Long-term Operation of Nuclear Power Plants*, NEA Publication No. 7054, OECD Publishing, Paris. www.oecd-nea.org/jcms/pl_14752/the-economics-of-long-term-operation-of-nuclear-power-plants

NEA (2012c), *Japan's Compensation System for Nuclear Damage*, NEA Publication No. 7089, OECD, Paris. www.oecd-nea.org/jcms/pl_14806/japan-s-compensation-system-for-nuclear-damage

NEA (2012d), "Challenges in Long-Term Operation of Nuclear Power Plants - Implications for Regulatory Bodies", NEA/CNRA/R(2012)5, OECD Publishing, Paris. www.oecd-nea.org/jcms/pl_19170/challenges-in-long-term-operation-of-nuclear-power-plants-implications-for-regulatory-bodies

NEA (2012e), "Patterns in Governmental Decisions and Recommendations (GDR) Information Exchange During the Fukushima NPP Accident", NEA/CRPPH(2012)3, OECD Publishing, Paris. www.oecd-nea.org/jcms/pl_19152/patterns-in-governmental-decisions-and-recommendations-gdr-information-exchange-during-the-fukushima-npp-accident

NEA (2012f), *International Structure for Decommissioning Costing (ISDC) of Nuclear Installations,* NEA Publication No. 7088, OECD Publishing, Paris. www.oecd-nea.org/jcms/pl_14804/international-structure-for-decommissioning-costing-isdc-of-nuclear-installations

NEA (2013a), *Stakeholder Confidence in Radioactive Waste Management An Annotated Glossary of Key Terms*, NEA Publication No. 6988, OECD Publishing, Paris. www.oecd-nea.org/jcms/pl_14686

NEA (2013b), *Crisis Communication: Facing the Challenges*, NEA Publication No. 7067, OECD Publishing, Paris. www.oecd-nea.org/jcms/pl_14774/crisis-communication-facing-the-challenges-proceedings

NEA (2013c), *Transition Towards a Sustainable Nuclear Fuel Cycle*, NEA Publication No. 7133, OECD Publishing, Paris. www.oecd-nea.org/jcms/pl_14844/transition-towards-a-sustainable-nuclear-fuel-cycle

NEA (2013d), *The Fukushima Daiichi Nuclear Power Plant Accident: OECD/NEA Nuclear Safety Response and Lessons Learnt*, NEA Publication No. 7161, OECD Publishing, Paris. www.oecd-nea.org/jcms/pl_14866/the-fukushima-daiichi-nuclear-power-plant-accident-oecd/nea-nuclear-safety-response-and-lessons-learnt

NEA (2014a), *The Characteristics of an Effective Nuclear Regulator*, NEA Publication No. 7185, OECD Publishing, Paris. www.oecd-nea.org/jcms/pl_14892/the-characteristics-of-an-effective-nuclear-regulator

NEA (2014b), "Probabilistic Safety Assessment (PSA) of Natural External Hazards Including Earthquakes, Workshop Proceedings", Prague, Czech Republic, 17-20 June 2013, NEA/CSNI/R(2014)9, OECD Publishing, Paris. www.oecd-nea.org/jcms/pl_19518/psa-of-natural-external-hazards-including-earthquakeworkshop-proceedings

NEA (2014c), "Status Report on Hydrogen Management and Related Computer Codes", NEA/CSNI/R(2014)8, OECD Publishing, Paris. www.oecd-nea.org/jcms/pl_19516/status-report-on-hydrogen-management-and-related-computer-codes

NEA (2014d), "Status Report on Filtered Containment Venting", NEA/CSNI/R(2014)7, OECD Publishing, Paris. www.oecd-nea.org/jcms/pl_19514/oecd/nea/csni-status-report-on-filtered-containment-venting

NEA (2014e), "WGOE Report on Fukushima Daiichi NPP Precursor Events", NEA/CNRA/R(2014)1, OECD Publishing, Paris. www.oecd-nea.org/jcms/pl_19395/wgoe-report-on-fukushima-daiichi-npp-precursor-events

NEA (2014f), "12th Workshop on Experience from the Inspection of Licensee's Outage Activities Including Fire Protection Programmes, Event Response Inspections, and the Impact on Inspection Programmes of the Fukushima Daiichi NPP Accident – Workshop Proceedings", Chattanooga, Tennessee, USA, 7-10 April 2014, NEA/CNRA/R(2014)8, OECD Publishing, Paris. www.oecd-nea.org/jcms/pl_19558/12th-workshop-on-experience-from-the-inspection-of-licensee-s-outage-activities-including-fire-protection-programmes-event-response-inspections-and-the-impact-on-inspection-programmes-of-the-fukushima-daiichi-npp-accident-workshop-proceedings-chattanooga-tennessee-usa-7-10-april-2014

NEA (2014g), "Report of the Survey on the Design Review of New Reactor Applications – Instrumentation and Control", NEA/CNRA/R(2014)7, OECD Publishing, Paris. www.oecd-nea.org/jcms/pl_19538/report-on-the-survey-of-the-design-review-of-new-reactor-applications-volume-1-instrumentation-and-controlvolume-1instrumentation-and-control

NEA (2014h), "Supplementary Report on the Regulation of Site Selection and Preparation: CNRA Working Group on the Regulation of New Reactors", NEA/CNRA/R(2014)5, OECD Publishing, Paris. www.oecd-nea.org/jcms/pl_19524/supplementary-report-on-the-regulation-of-site-selection-and-preparation

NEA (2014i), "NEA/CNRA/CSNI Joint Workshop on Challenges and Enhancements to Defence in Depth (DiD) in Light of the Fukushima Daiichi NPP Accident: Workshop Proceedings", NEA/CNRA/R(2014)4, OECD Publishing, Paris. www.oecd-nea.org/jcms/pl_19490/nea/cnra/csni-joint-workshop-on-challenges-and-enhancements-to-defence-in-depth-did-in-lightof-the-fukushima-daiichi-npp-accident

NEA (2014j), "Accident Management Insights After the Fukushima Daiichi NPP Accident: Report of the CNRA Task Group on Accident Management", NEA/CNRA/R(2014)2, OECD Publishing, Paris. www.oecd-nea.org/jcms/pl_19415/accident-management-insightsafter-the-fukushima-daiichi-npp-accidentreport-of-the-cnra-task-group-on-accident-management

NEA (2014k), "Report on Fukushima Daiichi NPP Precursor Events", NEA/CNRA/R(2014)1, OECD Publishing, Paris. www.oecd-nea.org/jcms/pl_19395

NEA (2014m), "Occupational Radiation Protection in Severe Accident Management", NEA/CRPPH/R(2014)5, OECD Publishing, Paris. www.oecd-nea.org/jcms/pl_19578/occupational-radiation-protection-in-severe-accident-management

NEA (2014n), "Framework for the Post-Accident Management of Contaminated Food", NEA/CRPPH/R(2014)4, OECD, Paris. www.oecd-nea.org/jcms/pl_19576/framework-for-the-post-accident-management-of-contaminated-food

NEA (2014o), *Guide for International Peer Reviews of Decommissioning Cost Studies for Nuclear Facilities*, NEA Publication No. 7190, OECD Publishing, Paris. www.oecd-nea.org/jcms/pl_14896/guide-for-international-peer-reviews-of-decommissioning-cost-studies-for-nuclear-facilities

NEA (2015a), *Stakeholder Involvement in Decision Making: A Short Guide to Issues, Approaches and Resources*, NEA Publication No. 7189, OECD Publishing, Paris. www.oecd-nea.org/jcms/pl_14894

NEA (2015b), *Fostering a Durable Relationship Between a Waste Management Facility and its Host Community Adding Value Through Design and Process – 2015 Edition*, NEA Publication No. 7264, OECD Publishing, Paris. www.oecd-nea.org/jcms/pl_14966

NEA (2015c), "Benchmarking of Fast-running Software Tools Used to Model Releases During Nuclear Accidents", NEA/CSNI/R(2015)19, OECD Publishing, Paris. www.oecd-nea.org/jcms/pl_19684

NEA (2015d), "Human Performance under Extreme Conditions with Respect to a Resilient Organisation: Proceedings of a CSNI International Workshop", NEA/CSNI/R(2015)16 , OECD Publishing, Paris. www.oecd-nea.org/jcms/pl_19668

NEA (2015e), "Robustness of Electrical Systems of Nuclear Power Plants in Light of the Fukushima Daiichi Accident: Workshop Proceedings", NEA/CSNI/R(2015)4, OECD Publishing, Paris. www.oecd-nea.org/jcms/pl_19600/robustness-of-electrical-systems-of-npps-in-light-of-the-fukushima-daiichi-accident

NEA (2015f), "Status Report on Spent Fuel Pools under Loss-of-Cooling and Loss-of-Coolant Accident Conditions", NEA/CSNI/R(2015)2, OECD Publishing, Paris. www.oecd-nea.org/jcms/pl_19596

NEA (2015g), "Report of the Survey on the Design Review of New Reactor Applications, Volume 2: Civil Engineering Works and Structures", NEA/CNRA/R(2015)5, OECD Publishing, Paris. www.oecd-nea.org/nsd/docs/2015/cnra-r2015-5.pdf

NEA (2015h), "Nuclear Regulatory Organisations and Communication Strategies", NEA/CNRA/R(2015)2, OECD Publishing, Paris. www.oecd-nea.org/nsd/docs/2015/cnra-r2015-2.pdf

NEA (2015i), "How Can Stakeholder Involvement Be Improved?" (A Flyer of the Forum on Stakeholder Confidence), OECD Publishing, Paris. www.oecd-nea.org/jcms/pl_19640

NEA (2015j), "Challenges and Enhancements to the Safety Culture of the Regulatory Body: A CNRA/CSNI/CRPPH Workshop", NEA/CNRA/R(2015)8, OECD Publishing, Paris. www.oecd-nea.org/jcms/pl_19688/challenges-and-enhancements-to-the-safety-culture-of-the-regulatory-body-cnra/csni/crpph-workshop

NEA (2015k), "Benchmark Study of the Accident at the Fukushima Daiichi Nuclear Power Plant (BSAF Project) – Phase I Summary Report", NEA/CSNI/R(2015)18, OECD Publishing, Paris. www.oecd-nea.org/jcms/pl_19680/benchmark-study-of-the-accident-at-the-fukushima-daiichi-nuclear-power-plant-bsaf-project-phase-i-summary-report

NEA (2015l), *The Practice of Cost Estimation for Decommissioning of Nuclear Facilities,* NEA Publication No. 7237, OECD Publishing, Paris. www.oecd-nea.org/jcms/pl_14934/the-practice-of-cost-estimation-for-decommissioning-of-nuclear-facilities

NEA (2016a), *Implementation of Defence in Depth at Nuclear Power Plants*, NEA Publication No. 7248, OECD Publishing, Paris. www.oecd-nea.org/jcms/pl_14950/implementation-of-defence-in-depth-at-nuclear-power-plants

NEA (2016b), *Five Years after the Fukushima Daiichi Accident: Nuclear Safety Improvements and Lessons Learnt*, NEA Publication No. 7284, OECD Publishing, Paris. www.oecd-nea.org/jcms/pl_14978

NEA (2016c), *Management of Radioactive Waste after a Nuclear Power Plant Accident*, NEA Publication No. 7305, OECD Publishing, Paris. www.oecd-nea.org/jcms/pl_15008

NEA (2016d), "Seismic Input Definition for Nuclear Facilities Current Practices", NEA/CSNI/R(2015)9, OECD Publishing, Paris. www.oecd-nea.org/jcms/pl_19618/seismic-input-definition-for-nuclear-facilities-current-practices

NEA (2016e), "Safety Research Opportunities Post-Fukushima - Initial Report of the Senior Expert Group", NEA/CSNI/R(2016)19, OECD Publishing, Paris. www.oecd-nea.org/jcms/pl_19758

NEA (2016f), "State-of-the-Art Report on Molten-Corium-Concrete interaction and Ex-Vessel Molten-Core Coolability", NEA/CSNI/R(2016)15, OECD Publishing, Paris. www.oecd-nea.org/jcms/pl_19746

NEA (2016g), "International Iodine Workshop – Full Proceedings", NEA/CSNI/R(2016)5, OECD Publishing, Paris. www.oecd-nea.org/jcms/pl_19702

NEA (2016h), *The Safety Culture of an Effective Nuclear Regulatory Body*, NEA Publication No. 7247, OECD Publishing, Paris. www.oecd-nea.org/jcms/pl_14948/the-safety-culture-of-an-effective-nuclear-regulatory-body

NEA (2017a), *Impacts of the Fukushima Daiichi Accident on Nuclear Development Policies*, NEA Publication No. 7212, OECD Publishing, Paris. www.oecd-nea.org/jcms/pl_14922/impacts-of-the-fukushima-daiichi-accident-on-nuclear-development-policies

NEA (2017b), "Phenomena Identification and Ranking Table (PIRT) on Spent Fuel Pools under Loss-of-Cooling and Loss-of-Coolant Accident Conditions: WGFS Report", NEA/CSNI/R(2017)18, OECD Publishing, Paris. www.oecd-nea.org/jcms/pl_19836

NEA (2017c), "Informing Severe Accident Management Guidance and Actions for Nuclear Power Plants through Analytical Simulation", NEA/CSNI/R(2017)16, OECD Publishing, Paris. www.oecd-nea.org/jcms/pl_19820

NEA (2017d), "Workshop Proceedings-Working Group on External Events (WGEV) Understanding the Impact of External Hazards on Nuclear Facilities: Severe Weather and Storm Surge", Paris, France, 24-26 February 2016, NEA/CSNI/R(2017)13, OECD Publishing, Paris. www.oecd-nea.org/jcms/pl_19806

NEA (2017e), "Developments in Fuel Cycle Facilities after the Fukushima Daiichi Nuclear Power Station Accident", Workshop Proceedings, Aomori City, Japan, 15-17 November 2016, NEA/CSNI/R(2017)12, OECD Publishing, Paris. www.oecd-nea.org/jcms/pl_19802/developments-in-fuel-cycle-facilities-fcfs-after-the-fukushima-daiichi-nuclear-power-station-nps-accident

NEA (2017f), "Probabilistic Safety Assessment Insights Relating to the Loss of Electrical Sources", NEA/CSNI/R(2017)5, OECD Publishing, Paris. www.oecd-nea.org/jcms/pl_19776/probabilistic-safety-assessment-insights-relating-to-the-loss-of-electrical-sources

NEA (2017g), "Addressing Uncertainties in Cost Estimates for Decommissioning Nuclear Facilities", NEA Publication No. 7344, OECD Publishing, Paris. www.oecd-nea.org/jcms/pl_15036/addressing-uncertainties-in-cost-estimates-for-decommissioning-nuclear-facilities

NEA (2018a), *Towards an All-Hazards Approach to Emergency Preparedness and Response – Lessons Learnt from Non-Nuclear Events*, NEA Publication No. 7308, OECD Publishing, Paris. www.oecd-nea.org/jcms/pl_15010

NEA (2018b), *State-of-the-Art Report on Light Water Reactor Accident-Tolerant Fuels*, NEA Publication No. 7317, OECD Publishing, Paris. www.oecd-nea.org/jcms/pl_15020

NEA (2018c), *Experience from the Fifth International Nuclear Emergency Exercise (INEX-5)*, NEA Publication No. 7379, OECD Publishing, Paris. www.oecd-nea.org/jcms/pl_15064

NEA (2019d), *Challenges in Nuclear and Radiological Legacy Site Management – Towards a Common Regulatory Framework*, NEA Publication No. 7419, OECD Publishing, Paris. www.oecd-nea.org/jcms/pl_40359/challenges-in-nuclear-and-radiological-legacy-site-management-towards-a-common-regulatory-framework

NEA (2018e), *Country-Specific Safety Culture Forum: Sweden*, NEA Publication No. 7420, OECD Publishing, Paris. www.oecd-nea.org/jcms/pl_15086

NEA (2018f), *Executive Summary of Towards an All-Hazards Approach to Emergency Preparedness and Response*, NEA Publication No. 7436, OECD Publishing, Paris. www.oecd-nea.org/rp/pubs/2018/7436-all-hazards-epr-es.pdf

NEA (2018g), *Proceedings of the Fifth International Nuclear Emergency Exercise (INEX-5) Workshop*, NEA Publication No. 7442, OECD Publishing, Paris. www.oecd-nea.org/jcms/pl_15110

NEA (2018h), "Developments in Fuel Cycle Facilities after the Fukushima Daiichi Nuclear Power Station Accident", Workshop Proceedings Aomori City, Japan 15-17 November 2016, Appendix 3, NEA/CSNI/R(2017)12/ADD1, OECD Publishing, Paris. www.oecd-nea.org/jcms/pl_19840/developments-in-fuel-cycle-facilities-fcfs-after-the-fukushima-daiichi-nuclear-power-station-nps-accident-workshop-proceedings-appendix-3

NEA (2018i), "Examination of Approaches for Screening External Hazards", NEA/CSNI/R(2018)7, OECD Publishing, Paris. www.oecd-nea.org/jcms/pl_19860

NEA (2019a), *Occupational Exposures at Nuclear Power Plants (2016), Twenty-Sixth Annual Report of the ISOE Programme*, 2016, NEA Publication No. 7453, OECD Publishing, Paris. www.oecd-nea.org/jcms/pl_15124

NEA (2019b), *Insights from Leaders in Nuclear Energy: Safety, Performance and Responsibility*, NEA Publication No. 7461, OECD Publishing, Paris. www.oecd-nea.org/jcms/pl_15134/insights-from-leaders-in-nuclear-energy-safety-performance-and-responsibility

NEA (2019c), *Country Specific Safety Culture Forum – Finland*, NEA Publication No. 7488, OECD Publishing, Paris. www.oecd-nea.org/jcms/pl_15146

NEA (2019d), *NEA International Mentoring Workshop in Fukushima, August 2019*, NEA Publication No. 7514, OECD Publishing, Paris. www.oecd-nea.org/jcms/pl_28696/mentoring-a-future-generation-of-female-leaders-in-science-and-engineering-2019

NEA (2019e), "Riverine Flooding: Hazard Assessment and Protection of Nuclear Installations", NEA/CSNI/R(2018)14, OECD Publishing, Paris. www.oecd-nea.org/jcms/pl_37980/riverine-flooding-hazard-assessment-and-protection-of-nuclear-installations

NEA (2019f), "Components and Structures under Severe Accident Loading (COSSAL)", NEA/CSNI/R(2019)2, OECD, Paris. www.oecd-nea.org/jcms/pl_19898

NEA (2019g), "Summary Report of the Joint Symposium on Decommissioning, Reconstruction, Rehabilitation, and Food Safety: Rebuilding Post-Accident Confidence", Paris, France, 26 March 2019, NEA/CRPPH/R(2019)5, OECD, Paris. www.oecd.org/officialdocuments/publicdisplaydocumentpdf/?cote=NEA/CRPPH/R(2019)5&docLanguage=En

NEA (2019h), *Summary of the NEA Workshop on the Application of Remote and Robotic Systems in Nuclear Back-End Activities – Way Forward in System Implementation*, OECD Publishing, Paris. www.oecd-nea.org/rwm/workshops/2019/robsysnba/docs/summary.pdf

NEA (2019i), *Cost Benchmarking for Nuclear Power Plant Decommissioning*, NEA Publication No. 7460, OECD Publishing, Paris. www.oecd-nea.org/jcms/pl_15132/cost-benchmarking-for-nuclear-power-plant-decommissioning

NEA (2020a), *Annual Report 2019*, NEA Publication No. 7517, OECD Publishing, Paris. www.oecd-nea.org/jcms/pl_28563

NEA (2020b), *Occupational Exposures at Nuclear Power Plants (2017)*, Twenty-Seventh Annual Report of the ISOE Programme, 2017, NEA Publication No. 7510, OECD Publishing, Paris. www.oecd-nea.org/rp/pubs/2020/7510-ISOE-2017-annual-report.pdf

NEA (2020c), *Lessons learnt from non-nuclear crises: Making the most of practical experiences gained during past crises or disasters for improving mental health and psychosocial support in radiation emergencies*, OECD Publishing, Paris, www.oecd-nea.org/jcms/pl_37845/egnr-web-events-flyer

NEA (forthcoming a), *Methods for Assessing and Strengthening the Safety Culture of the Regulatory Body*, OECD Publishing, Paris.

NEA (forthcoming b), *Long-Term Management and Actions for a Severe Accident in a Nuclear Power Plant*, OECD Publishing, Paris.

NEA (forthcoming c), "Status of Site-level (Including Multi-Units) PSA Developments", NEA/CSNI/R(2019)16, OECD Publishing, Paris.

NEA (forthcoming d), *Concepts and Terminology for Protecting Nuclear Installations from Flood Hazards*, OECD Publishing, Paris.

NEA (forthcoming e), *Advancing the Robustness of Electrical Power Systems of Nuclear Power Plants*, OECD Publishing, Paris.

NEA (forthcoming f), "CSNI WGAMA Source Term Workshop 2019", OECD Publishing, Paris.

NEA (forthcoming g), "Workshop Summary Report NEA Workshop on Optimisation: Rethinking the Art of Reasonable", Lisbon, Portugal, 13-15 January 2020, OECD Publishing, Paris.

NEA (forthcoming h), "Workshop Summary Report NEA Workshop on "Preparedness for Post-Accident Recovery: Lessons from Experience" co-organised with the Japanese Nuclear Regulation Authority, Tokyo, Japan, 18-19 February 2020, OECD Publishing, Paris.

NEA (forthcoming i), *Towards a Shared Understanding of Radiological Risks: Summary Report of the NEA Stakeholder Involvement Workshop on Risk Communication, Paris*, France, 24-26 September 2019, OECD Publishing, Paris.

NEA (forthcoming j), *Thermodynamic Characterisation of Fuel Debris and Fission Products Based on Scenario Analysis of Severe Accident Progression at Fukushima Daiichi Nuclear Power Station (TCOFF) Project Summary Report*, OECD Publishing, Paris.

NEA (forthcoming k), *Characterisation Methodology for Unconventional and Legacy Waste*, OECD Publishing, Paris.

NEA (forthcoming l), "Dialogue in the Long-term Management of Radioactive Waste", NEA/RWM/R(2020)1, OECD Publishing, Paris.

NEA (forthcoming m), *Fourth International Workshop on the Indemnification of Damage in the Event of a Nuclear Accident*, Lisbon, Portugal, 8-10 October 2019, OECD Publishing, Paris.

NEA (forthcoming n), *BSAF-2 Benchmark Study of the Accident at the Fukushima Daiichi Nuclear Power Plant Phase II Summary Report*, OECD Publishing, Paris.

UNISDR (2015), *Sendai Framework for Disaster Risk Reduction 2015-2030, United Nations Office for Disaster Risk Reduction*, Geneva. www.undrr.org/publication/sendai-framework-disaster-risk-reduction-2015-2030.

UNSCEAR (2014), *Sources, Effects and Risks of Ionizing Radiation*, UNSCEAR 2013 Report, United Nations Scientific Committee on the Effects of Atomic Radiation, New York. www.unscear.org/unscear/en/publications/2013_1.html

UNSCEAR (2015), *Developments since the 2013 UNSCEAR Report on the levels and effects of radiation exposure due to the nuclear accident following the great east-Japan earthquake and tsunami, A 2015 White Paper to guide the Scientific Committee's future programme of work*, United Nations Scientific Committee on the Effects of Atomic Radiation, New York. www.unscear.org/unscear/en/publications/Fukushima_WP2015.html

UNSCEAR (2016), *Developments since the 2013 UNSCEAR Report on the levels and effects of radiation exposure due to the nuclear accident following the great east-Japan earthquake and tsunami, A 2016 White Paper to guide the Scientific Committee's future programme of work*, United Nations Scientific Committee on the Effects of Atomic Radiation, New York. www.unscear.org/unscear/en/publications/Fukushima_WP2016.html

UNSCEAR (2017), *Developments since the 2013 UNSCEAR Report on the levels and effects of radiation exposure due to the nuclear accident following the great east-Japan earthquake and tsunami, A 2017 White Paper to guide the Scientific Committee's future programme of work*, United Nations Scientific Committee on the Effects of Atomic Radiation, New York. www.unscear.org/unscear/en/publications/Fukushima_WP2017.html

UNSCEAR (forthcoming), *Levels and Effects of Radiation Exposure Due to the Accident at the Fukushima Daiichi Nuclear Power Station: Implications of Information Published Since the UNSCEAR 2013 REPORT*, United Nations Scientific Committee on the Effects of Atomic Radiation, New York.

US Department of Energy (2019), Amway, P., Andrews, N., Basu, S., Bunt, R., Butler, J., Ellison, P., Farmer, M., Gabor, J., Gauntt, R., Henry, C., Honda, T., Humrickhouse, P., Klass, K., Kobayashi, T., Kraft, S., Linthicum, R., Luangdilok, W., Lutz, R., Luxat, D., Mizokami, S., Nakayoshi, A., Osborn, D., Paik, C., Plys, M., Rempe, J., Robb, K., Sanders, R., Shearer, K., Wachowiak, R., Washiya, T., Whiteman, P., and Williamson, B., *U.S. Efforts in Support of Examinations at Fukushima Daiichi – 2019 Evaluations*, N. p., 2019. Web. doi:10.2172/1561221, United States. www.osti.gov/biblio/1561221-efforts-support-examinations-fukushima-daiichi-evaluations

USNRC (1994), *Lessons Learned from the Three Mile Island-Unit 2 Advisory Panel*, NUREG/CR-6252, U.S. Nuclear Regulatory Commission, United States. www.nrc.gov/reading-rm/doc-collections/fact-sheets/3mile-isle.html

WANO (2019), *Nuclear Leadership Effectiveness Attributes*, PL 2019-01, WANO Principles, World Association of Nuclear Operators, London, United Kingdom. www.wano.info/resources/nuclear-leadership-effectiveness-attributes

WHO (2020), *A Framework for Mental Health and Psychosocial Support in Radiological and Nuclear Emergencies*, World Health Organization, Geneva, Switzerland. apps.who.int/iris/rest/bitstreams/1318032/retrieve

COVER PHOTO DESCRIPTION

The photo on the cover, taken in April 2019, is of a street planted with cherry trees in the Yonomori district of Tomioka Town. The location is a little over 7 kilometres from the Fukushima Daiichi Nuclear Power Plant. Although access to this area was restricted for a long time after the accident, residents were allowed to visit during the cherry blossom season, when they enjoyed the same full-bloomed cherry blossom scene as before the accident.

On 10 March 2020 the government lifted evacuation orders for a total of about 1.1 kilometres of road around Yonomori Station on the JR Joban Line and railway facilities in a difficult-to-return area of Tomioka Town. This release area, which is adjacent to the street shown in the photo that was also released back in 2017, made the cherry blossom corridor in total 1 kilometre long. The total area released was about seven hectares, but it is limited to the area around the road and railway station building. The aim is for residents to be able to make a full return in the spring of 2023.

In February 2021 Tomioka Town was carrying out environmental rehabilitation work with the government's aid. The project included dismantling deteriorated buildings, restoring roads and reconnecting water and sewage in an area of about 390 hectares in the difficult-to-return area by the spring of 2023. This planned area, a "Specified Reconstruction and Revitalization Base" will ultimately accommodate approximately 1 600 people in 2028.

表紙写真の説明

表紙の写真は2019年4月に撮影された、富岡町夜の森地区の桜並木です。この場所は福島第一原子力発電所から7キロ強です。事故後長期間にわたってこのエリアへの立ち入りは制限されていましたが、住民は桜の開花の季節に訪れることが可能となり、事故前と変わらない満開の桜のシーンを楽しんでいます。

2020年3月10日、政府は、富岡町における帰還困難区域のうちJR常磐線の夜ノ森駅周辺の合計約1.1キロメートルの道路と鉄道施設の避難命令を解除しました。2017年に避難指示が解除された写真の通りと今回の解除エリアとがつながり、約1キロメートルもの桜並木が形成されました。解除された面積は合計約7ヘクタールでしたが、道路や駅舎周辺に限られており、住民が2023年春に帰還できるようにすることを目指しています。

2021年2月現在、富岡町は政府の支援を受けて環境修復工事を実施しています。このプロジェクトには、2023年春までに帰還困難区域の約390ヘクタールの地域で、劣化した建物の解体、道路及び上下水道の復旧を行う工事が含まれています。この計画地域は、「特定復興再生拠点区域」と呼ばれており、2028年に約1600人が居住することを目標としています。

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Fukushima Daiichi Nuclear Power Plant Accident, Ten Years On: Progress, Lessons and Challenges

Much has been learnt in the ten years since the Great Eastern Japan Earthquake and the subsequent accident at the Fukushima Daiichi Nuclear Power Plant, but significant challenges still remain.

This report presents the current situation at the Fukushima Daiichi Nuclear Power Plant and the responses by Japanese authorities and the international community since the accident. It will assist both policymakers and the general public to understand the multi-dimensional issues stemming from the accident. These include disaster recovery, compensation for damages, nuclear safety, nuclear regulation, radiation protection, plant decommissioning, radioactive waste management, psycho-social issues in the community and societal resilience.

Building on two previous reports released by the OECD Nuclear Energy Agency (NEA) in 2013 and 2016, the report examines the plant's future, that of the affected region and population, as well as outlining areas for further improvement and how the international community can help.

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