Five Years after the Fukushima Daiichi Accident

Nuclear Safety Improvements and Lessons Learnt

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Five Years after the Fukushima Daiichi Accident: Nuclear Safety Improvements and Lessons Learnt

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The OECD Nuclear Energy Agency (NEA) was established on 1 February 1958. Current NEA membership consists of 31 countries: Australia, Austria, Belgium, Canada, the Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Korea, Luxembourg, Mexico, the Netherlands, Norway, Poland, Portugal, Russia, the Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States. The European Commission also takes 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 friendly 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 policy analyses in areas such as energy and sustainable development.

Specific areas of competence of the NEA include the safety and regulation of nuclear activities, radioactive waste management, 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. In these and related tasks, the NEA works in close collaboration with the International Atomic Energy Agency in Vienna, with which it has a Co-operation Agreement, as well as with other international organisations in the nuclear field.

Cover photos: Aerial view of the Fukushima Daiichi nuclear power plant in Japan as at 10 February 2016 (Google Earth); A mobile pump at the Takahama nuclear power station (KEPCO, Japan).

Foreword

The Nuclear Energy Agency has been working closely with its member and partner countries to identify lessons learnt and follow-up actions at the national and international levels so as to maintain and enhance the level of safety at nuclear facilities following the Fukushima Daiichi nuclear power plant accident. In 2013, the NEA published a report entitled *The Fukushima Daiichi Nuclear Power Plant Accident: OECD/NEA Nuclear Safety Response and Lessons Learnt* (NEA, 2013c) detailing the key immediate responses of the NEA and its member countries. Since then, much work has been carried out as part of NEA activities to maintain and further develop the scientific, technological and legal bases for the safe use of nuclear energy.

The most important conclusion reached in the 2013 report was that, in the aftermath of the Fukushima accident, nuclear power plants in NEA member countries were safe. Nevertheless, it is the nature of nuclear operations and regulation to learn from all experiences. There were many lessons from the Fukushima experience and NEA countries' nuclear power plants are safer today thanks to a range of actions taken since the accident that respond to the lessons learnt. However, implementation of these lessons and related research activities are long-term actions that will continue to evolve as regulators and the nuclear industry continue to examine regulations and practices in light of the accident. This new NEA report, *Five Years after the Fukushima Daiichi Accident: Nuclear Safety Improvements and Lessons Learnt*, focuses on what has been done by the Agency and its member countries to improve safety since the accident in 2011. It provides a high-level summary and an update on activities performed by member countries and by NEA committees, as well as further lessons learnt and challenges identified for future consideration, including:

- actions taken by regulatory authorities in NEA member countries that have led to the establishment of new requirements resulting in specific nuclear power plant improvements in multiple areas;
- actions to underline the importance of using operating experience and risk insights, in particular through international co-operation;
- activities to improve regulatory frameworks in member countries;
- research activities undertaken to improve the knowledge and understanding of the accident itself, which will be a long-term learning process;
- activities implemented to improve emergency preparedness and radiological protection;
- efforts to understand and characterise the importance of strong nuclear safety cultures;
- actions taken to continue enhancing stakeholder involvement and public communication;
- legal improvements, including those in the area of liability law.

This report has been prepared with the NEA committees involved in nuclear and radiation safety issues – the Committee on Nuclear Regulatory Activities (CNRA), the Committee on the Safety of Nuclear Installations (CSNI), the Committee on Radiation Protection and Public Health (CRPPH) and the Nuclear Law Committee (NLC) – under the leadership of the CNRA. The report focuses on steps taken to ensure nuclear safety now and into the future and is complementary to reports produced by other international organisations, including the International Atomic Energy Agency (IAEA) and the World Association of Nuclear Operators (WANO).

Although enhancing safety is a common objective around the world, NEA member countries have nonetheless addressed this issue using different approaches. Since some national standards or safety requirements are country-specific and relate to the specific circumstances and external hazards in each country, member countries are not necessarily starting from the same point of departure. Some improvements have already been implemented, some are in the process of being completed, and still others are being planned and will be implemented in the coming years. In several countries, governments have also taken action to reinforce the independence of their regulatory bodies.

While all NEA countries have made significant progress since the accident and continue to make further progress towards enhancing safety, it is important to remember that ensuring safety is a process that evolves as we learn through operating experience and research. Much work is still before us to address new lessons, including how to effectively deal with more complex issues such as the human aspects of nuclear safety reflected in safety culture, training and organisational factors. To address these issues, we need to ensure a continuing and consistent effort at national and international levels. The NEA as a whole, and particularly the several NEA committees involved in nuclear and radiation safety issues, will continue to play a key role in assisting and encouraging NEA member countries in the important work of ensuring safety.

The work of the NEA and its member countries described in this report constitutes an important contribution to ensuring the continuing safety of nuclear reactors today and in the future.

William D. Magwood, IV
Director-General
Nuclear Energy Agency

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Executive summary

Since the Fukushima Daiichi nuclear power plant accident, the principal NEA standing technical committees with responsibilities in the areas of regulatory oversight, nuclear safety, radiological protection and public health, and nuclear liability – the Committee on Nuclear Regulatory Activities (CNRA), the Committee on the Safety of Nuclear Installations (CSNI), the Committee on Radiation Protection and Public Health (CRPPH) and the Nuclear Law Committee (NLC) – have been closely co-ordinating their activities in these areas. As part of these efforts, a report entitled *The Fukushima Daiichi Nuclear Power Plant Accident: OECD/NEA Nuclear Safety Response and Lessons Learnt* was published (NEA, 2013c), detailing the immediate response of the NEA and its member countries to the accident. Among the key findings, the 2013 report underlined that member countries had performed focused safety reviews of their operating reactors and had determined that they were safe to continue operations while more comprehensive safety reviews were conducted to identify work needed to further improve safety.

Five Years after the Fukushima Daiichi Accident: Nuclear Safety Improvements and Lessons Learnt provides an update on these activities and lessons learnt, including: *i)* activities undertaken by regulatory authorities in NEA member countries which have led to the establishment of new requirements resulting in specific nuclear power plant improvements in multiple areas; *ii)* activities to improve the regulatory framework in member countries; *iii)* research activities to acquire additional knowledge and understanding of the accident itself; *iv)* activities implemented to improve emergency preparedness and radiological protection; and *v)* legal improvements, including those in the area of liability law. The report focuses on actions taken by the NEA and its member countries, and as such, is complementary to reports produced by other international organisations, including the International Atomic Energy Agency (IAEA) and the World Association of Nuclear Operators (WANO).

TEPCO, Japan.

Recent photo of the Fukushima Daiichi nuclear power plant.

Since the previous report, regulatory authorities in NEA member countries have performed diverse activities that have led to the establishment of new requirements. The potential impact of external hazards has been the focus of such requirements, as has plant improvements related to the diversity of equipment, enhancements in the robustness of safety functions and continuing efforts to improve organisational behaviours. Actions undertaken in these areas have led to: *i)* a re-examination of external hazards; *ii)* an improvement of the robustness of the electrical systems; *iii)* an enhancement of the robustness of the ultimate heat sink (UHS); *iv)* protection of the reactor containment system; *v)* protection of spent fuel in storage pools; *vi)* reinforced capability to rapidly provide diverse equipment and assistance from on-site or off-site emergency preparedness facilities; *vii)* a reinforcement of safety culture, including human and organisational factors in decision making during emergencies; and *viii)* continued safety research. Although the objective of enhancing safety is shared around the world, countries have addressed these issues with different approaches. Since national standards or safety requirements are country-specific and relate to specific threats and hazards in each country, member countries are not necessarily starting from the same point of departure. Some improvements have already been implemented, some are in the process of being completed and still others are being planned and will be implemented at nuclear power plants (NPPs) in the coming years. In several countries, governments have also taken action to reinforce the independence of their regulatory bodies.

Safety is a process that evolves as we learn through research and the evaluation of operating experience. As was the case with the Three Mile Island and Chernobyl accidents, the implementation of lessons learnt from the Fukushima Daiichi accident and the continuation of related research activities are long-term actions that will further develop into the future as regulators and the nuclear industry learn from the accident.

An important need identified by the NEA and its member countries was that of better developing and enhancing the approach taken to the evaluation and inclusion of external hazards in the safety analysis. It was generally concluded that there has traditionally been a more thorough and detailed inclusion and consideration of internal hazards in safety analyses and safety cases. As a consequence, member countries have re-examined the response of their NPPs to external hazards, including those of higher magnitude than have previously been considered, and have used the latest data technology to identify and consider plausible combinations of sequential and consequential events.

In many countries, the focus has remained on the robustness of electrical systems. As a result, NPPs in these countries are in the process of upgrading the capability of the existing direct current power sources as well as installing new, dedicated equipment to ensure redundant and diverse sources of alternating current electrical power, which would be available following a significant event. Measures have included new or improved fixed installations, as well as additional mobile power sources.

Ensuring that heat can be removed from the core in the event of an extreme natural event has led other countries to consider bunkered safety systems, designed to resist extreme natural events. Many countries have now installed or are considering strategic placement of portable equipment that can be quickly positioned and provide emergency cooling. Some countries have enhanced the decay heat removal function by providing an alternate path for cooling water supply, arranging for passive cooling or identifying an alternate heat sink.

The Fukushima Daiichi accident demonstrated that the ability of NPPs to maintain containment integrity could be challenged by severe natural hazards. In response, some NEA member countries have refocused their efforts on upgrading NPP abilities with respect to containment venting and hydrogen mitigation. In other countries, new or improved filtered vents or filtering strategies are being implemented or considered for use during venting to limit containment pressure. Some countries are introducing a different hydrogen mitigation strategy or improving the existing one. The ability to continuously cool the containment during beyond-design-basis events (also called design extension conditions) has been evaluated and modifications are being planned and implemented.

The ability of spent fuel pools (SFPs) to cool and protect spent nuclear fuel was also a challenge during the Fukushima Daiichi accident. Although no damage occurred to any of the SFPs or to the spent fuel at the Fukushima Daiichi nuclear power plant, NEA member countries have taken actions to improve the protection of the SFPs in their countries. For example, protection of SFPs against external events has been reassessed in some countries, and has led to the installation of redundant SFP level and temperature indications, as well as diverse cooling water supplies.

Some countries have required that portable safety equipment be stored in a protected manner at the site, to provide redundancy and diversity of equipment during a significant event. Another approach implemented in countries is to establish off-site equipment storage facilities, which can transport various types of equipment to a facility within hours or days of an event. These facilities can provide a full range of equipment in an emergency, including portable electrical generators, pumps, hoses, ventilation equipment, diesel fuel storage and transport vehicles, as well as fire trucks. The facilities are located far enough away from the existing NPP that a natural disaster at the NPP would not affect the off-site facility.

Several NEA member countries have adopted a broad consideration of safety culture characteristics, including human and organisational factors, which include specific safety culture programmes that focus on attitudes towards safety, organisational capability, decision-making processes and the commitment to learn from experience.

The Fukushima Daiichi accident clearly illustrated the **challenges that operations and emergency response staff can face** when dealing with a major nuclear accident, thus emphasising **the importance of reliable human performance under extreme conditions.**

Following implementation of actions resulting from reviews and self-assessments, member countries have found that, in general, nuclear safety, emergency preparedness and response arrangements have improved. They have also acknowledged that more remains to be done.

National safety frameworks are being further improved with steps taken to establish or reinforce the effective independence of regulatory bodies and to update regulations. International co-operation is also increasing with greater participation in peer reviews and exchanges of information. These actions are reinforcing the global characteristics of nuclear safety, and international collaboration is growing as a result.

While many activities and improvements are in progress, it must be noted that the safety improvements being made at nuclear power plants as a result of the Fukushima Daiichi accident are part of a long-term effort that will continue to evolve as countries continue to share information and learning.

In addition to what has been carried out directly by member countries, this report presents the high-priority follow-on items that NEA committees identified to assist countries in benchmarking and continuously improving their nuclear safety practices.

The CNRA, for example, has considered relevant topics and reached consensus on a variety of reports and documents providing best practices and guidance in the areas of accident management, crisis communication, precursor events, defence in depth (DiD), regulatory effectiveness, safety culture and the regulation of new reactors. Such guidance and best practices are designed for countries with existing, mature regulators and can be used for improving policies and practices, benchmarking and training staff. They can also be useful for new entrant countries in the process of developing and maintaining an effective nuclear safety regulator.

The NEA regulatory guidance booklet on *Implementation of **Defence in Depth** at Nuclear Power Plants: Lessons Learnt from the Fukushima Daiichi Accident* examines and provides advice on the implementation of DiD. A key observation is that the use of the DiD concept remains valid after the Fukushima Daiichi accident. Indeed, lessons learnt from the accident, and the accident's impact on the use of DiD, have reinforced the fundamental importance of DiD in ensuring adequate safety.

In follow-up to the Fukushima Daiichi accident and in agreement with the CNRA, the CSNI decided to launch several high-priority activities. Topics were selected on the basis of high safety significance, where more detailed technical information and common approaches were needed. The approach taken was to attempt to clarify the status of implementation, discuss national requirements, consider the advantages and disadvantages of different options, identify potential room for improvement from an accident management perspective and determine overall strategies going forward. Topics covered include probabilistic safety assessment (PSA) for external events, filtered containment venting, hydrogen management, spent fuel pools, fission product release, human performance, electrical systems and components under seismic load.

The CSNI also launched a series of joint safety research projects in support of accident analysis and management to conduct benchmark studies of the Fukushima Daiichi accident, and to investigate technical phenomena such as hydrogen behaviour, containment response and system thermal-hydraulics under beyond-design-basis accident conditions.

> Research and development efforts to date have already significantly enhanced the understanding of phenomena in relation to the Fukushima Daiichi accident. Many NEA member countries are involved in two key research projects: the **NEA Benchmark Study of the Accident at the Fukushima Daiichi Nuclear Power Plant (BSAF)** and **the NEA Senior Expert Group on Safety Research Opportunities Post-Fukushima (SAREF)**.

The CRPPH, for its part, has been actively involved in the improvement of many aspects of international and national emergency management preparation and implementation. Two reports were published on the post-accident management of food from affected areas, including the presentation of a framework for national and international food management, and an overview of the framework's impact on international food trade. The committee has continued to work on approaches to and lessons from stakeholder involvement, in particular with the International Commission on Radiological Protection (ICRP). Lessons from the Japanese experience that are applicable internationally have been gathered by the CRPPH and will be used to guide further work in this important area. The CRPPH has also developed a detailed report on the state of the art in radiological protection science, and another report on the management of occupational exposure in the event of severe accidents.

The NEA Nuclear Law Committee (NLC) has been examining the Fukushima Daiichi accident from a legal perspective. Its activities have focused on the legal framework established in Japan to compensate victims of nuclear accidents (i.e. the nuclear liability scheme) and its implementation with regard to the victims of the Fukushima Daiichi accident, in order to draw lessons for the benefit of the larger international community. A report was published in 2012 entitled *Japan's Compensation System for Nuclear Damage: As Related to the TEPCO Fukushima Daiichi Nuclear Accident,* and an update of this report is under preparation.

Conclusions from the report

Continuing enhancement of safety

Since the publication of *The Fukushima Daiichi Nuclear Power Plant Accident: OECD/NEA Nuclear Safety Response and Lessons Learnt* (NEA, 2013c), member countries have continued to seek lessons from the accident at the Fukushima Daiichi NPP. The report examined prompt actions and analyses at national levels, as well as international engagement to ensure safety. NEA member countries have continued to take appropriate actions to maintain and enhance the level of safety at their nuclear facilities, and thus nuclear power plants are safer now because of actions taken since the accident.

Ensuring safety is a continual process, which evolves as we learn through operating experience and research. Safety is the prime responsibility of the operator, with the regulator's goal to ensure that operators continuously improve and make NPPs safer. The continued operation of nuclear power plants requires that their robustness to extreme situations be reinforced beyond-design-basis safety margins, and many of these improvements have been implemented or are in the process of being implemented. While an external event (an earthquake-induced tsunami) caused the Fukushima Daiichi accident, the actions that have been taken around the world to make NPPs safer are applicable to any type of event, man-induced or naturally occurring.

Effective implementation of safety improvements

While NEA member countries have been able to discuss the same lessons learnt from the Fukushima Daiichi accident and the outcomes sought are very similar, there are nonetheless different avenues being taken to achieve the goal of enhancing safety, and preventing and mitigating potential accidents.

Unique natural conditions exist in member countries, in particular with regard to potentially extreme natural events; different national regulatory requirements, for example, for the prevention and mitigation of severe accidents; various approaches to and applications of periodic safety reviews in order to continuously improve safety; and different types and generations of NPPs. Since national standards or safety requirements, as well as those safety measures actually implemented, are country-specific and reflect operating experience from the particular country or regulatory practices within the country, member countries are not necessarily starting from the same point of departure. Differences in the priorities and implementation of schedules for safety improvements exist among member countries.

Using operating experience and risk insights

Lessons learnt concerning operating experience have been disseminated internationally, particularly in relation to the main initiators and conditions that have been observed during the Fukushima Daiichi accident. The accident did not reveal any unknown initiators, sequences or consequences. However, the combination and the severity of initiating events had never occurred before, and the evolution of the accident in three different units simultaneously was also new.

The accident at the Fukushima Daiichi site demonstrated that while existing operating experience feedback systems provide a good tool to provide lessons learnt and help prevent the recurrence of events, operating experience combined with risk insights can provide an even greater source of potential improvement as demonstrated in the course of real events.

The timely implementation of NPP operating experience is a continuous challenge for both regulators and operators. The challenge is to identify precursor events and the subsequent lessons learnt, and then to implement the related actions to enhance plant safety and prevent recurrence.

> The **NEA Working Group on Operating Experience** has found that more efforts are needed to ensure timely and full implementation of lessons learnt from precursor events. It has also found that combining the use of risk insights with operating experience may drive plant changes that would effectively reduce risk.

Strengthening regulatory frameworks

National safety frameworks have been and are being further strengthened to enhance governmental frameworks and update regulations, including through reinforcing the independence of regulatory bodies. The principle of regulatory independence, in particular the effective separation between the functions of the regulatory body and those of any other body or organisation concerned with the promotion or use of nuclear energy, is fundamental and requires vigilance to ensure it is maintained.

Some member countries have reviewed, and other member countries are in the process of reviewing, their regulatory frameworks and are making changes as appropriate to update their legislation so as to reflect lessons learnt from the Fukushima Daiichi accident. One example is the emphasis on ensuring that a clear and comprehensive legal framework exists to allow the operator of a nuclear installation – and its government, if necessary – to quickly react and adapt to the specific circumstances of an event in order to ensure timely and financially adequate compensation to victims.

Much has been done by member countries in benchmarking and continuously improving their nuclear safety frameworks and regulations: this has included activities on accident management, crisis communication, precursor events, defence in depth, regulatory effectiveness, safety culture and regulation of new reactors. International co-operation is also increasing with greater participation in benchmarking of effective regulatory practices and exchanges of information.

A long-term learning process supported by safety research

As was the case with the Three Mile Island and Chernobyl accidents, implementation of lessons learnt from the Fukushima Daiichi accident and the continuation of related research activities are long-term actions that will evolve into the future as regulators and the nuclear industry continue to learn from the accident.

While near-term, higher priority lessons learnt are currently being addressed, our knowledge will expand as the Fukushima Daiichi units are decommissioned. Efforts such as the NEA Senior Expert Group on Safety Research Opportunities Post-Fukushima (SAREF) and the NEA Benchmark Study of the Accident at the Fukushima Daiichi Nuclear Power Station (BSAF) have already provided invaluable insights concerning severe accident progression and the current status of reactors in all three units that experienced core melt. Research continues into accident progression, recovery and the human factors involved in severe accident response. Important information is emerging from post-accident recovery efforts at the Fukushima Daiichi nuclear power plant.

The human element as an essential aspect of safety

Human and organisational factors and safety culture are essential to all aspects of nuclear safety, from design, construction and operation to the response to potential events or accidents. Both licensees and regulatory bodies identified these as relevant issues to be addressed in the post-Fukushima Daiichi accident assessment. The human element has a considerable impact on all levels of the defence-in-depth concept.

Work carried out by the NEA and its member countries on both the characteristics of an effective nuclear regulator and on regulatory safety culture have been recommended for benchmarking, peer review, and for training and development of regulatory staff.

Several NEA member countries have initiated a broad consideration of safety culture characteristics, including human and organisational factors. These initiatives include specific safety culture programmes that focus on attitudes towards safety, organisational capability, decision-making processes and the commitment to learn from experience. Going forward, the NEA and its member countries recognise that nuclear safety will benefit from continuing work in areas such as safety culture, and human and organisational factors.

Although the **prime responsibility for the safety of a nuclear installation** is with the licensee or plant operator, the regulatory body itself has an important responsibility in ensuring the safety of nuclear installations. The NEA guidance booklet on *The Safety Culture of an Effective Nuclear Regulatory Body* identifies five principles that support the safety culture of an effective nuclear regulatory body. These principles concern leadership for safety, individual responsibility and accountability, co-operation and open communication, a holistic approach, and continuous improvement, learning and self-assessment.

Emergency management and the long-term commitment of resources

The accident at the Fukushima Daiichi site demonstrated the challenges involved when managing the consequences of a large-scale accident. As time progressed, radiological and social consequences became increasingly evident, while decisional responsibilities were shifting from central government to regional and local governments, and to affected individuals. Approaches to address the complexity generated by such long-lasting circumstances needs to be considered and included in national planning.

Moreover, the resources needed to manage an emergency on the scale of the accident at the Fukushima Daiichi nuclear power plant have proven to be considerable. Non-accident countries, even those not directly affected, expended significant resources on understanding the rapidly evolving situation so as to support recommendations on how to best protect expatriate populations in Japan, to address issues of people and cargo arriving from Japan and to manage food emanating from Japan. The Japanese government was challenged by the need to expend significant resources to address the accident situation, and simultaneously dedicate resources to formally and informally address questions from other countries and from international organisations. Emergency management planning should thus take into account the Japanese experience in terms of the training and resources required to be appropriately prepared to manage the collection and flow of information.

Enhancing stakeholder involvement and public communication

Involvement of stakeholders (local authorities, industry, non-governmental organisations, government officials and the public) in decision making is appropriate and advisable to enhance the credibility, legitimacy, sustainability and final quality of regulatory and off-site emergency management decisions. In addition, proactive outreach to stakeholders in regular communications (i.e. in non-accident situations) is highly desirable to improve their understanding in times of crisis.

Some member countries have further developed their policies on transparency, openness and involvement of stakeholders in the regulatory process, providing a window into the regulatory decision-making process. Different country-specific practices and regulatory requirements reflect more general practices within each individual country.

Experience during the Fukushima Daiichi NPP accident highlighted the need to reconsider approaches to information sharing and assessment, both domestically and internationally. The experience reaffirmed that regulators and governments should be effectively communicating with their stakeholders to ensure that all aspects of safety in relation to nuclear facilities are understood. To achieve this goal, regulators need to continue improving their communication strategies, as well as the implementation of such strategies.

International co-operation as a key factor in continuous safety enhancement

International co-operation provides a forum for regulators to work together to share and analyse data and experiences, gain consensus and develop approaches that can be applied within each country's regulatory process. International co-operation also provides a platform for peer regulators to encourage vigilance in ensuring NPP safety and avoiding the complacency that contributed to the accident at Fukushima Daiichi. Regulatory authorities from NEA member countries are working together internationally to share information and actions taken in order to improve their regulatory frameworks and NPP safety. The NEA provides an effective forum for co-operation on both medium- and longer-term issues in its specific task groups, working parties and expert groups, as well as through joint international safety research projects.

Introduction

The accident that occurred on 11 March 2011 at the Fukushima Daiichi nuclear power plant, following a massive earthquake and tsunami, was one of the most severe accidents ever experienced at a nuclear power plant and has impacted the use of nuclear energy all over the world. Addressing the accident, both in terms of its immediate consequences and the implementation of corrective actions from lessons learnt to prevent a recurrence, became a priority for regulators and for the nuclear industry in all countries with nuclear power plants.

This report, *Five Years after the Fukushima Daiichi Accident: Nuclear Safety Improvements and Lessons Learnt,* discusses actions taken and those in progress in NEA member countries. Such actions further enhance and improve safety, and include research activities undertaken to learn more from the accident. Improving safety is a process that continues as our understanding evolves through the evaluation and analysis of operating experience and research activities.

The report has been written for a wide array of potentially interested stakeholders. Nuclear professionals from the international community will find it useful as an update to activities completed, in progress and planned in future years. It is also directed at government officials, local authorities, industry, non-governmental organisations and members of the public that are interested in following the safety improvements being implemented since the accident. It is in a spirit of openness and transparency that NEA member countries share this information, the corrective actions and research activities taken and underway to continue making nuclear power plants safer.

The first report published by the NEA on this subject, *The Fukushima Daiichi Nuclear Power Plant Accident: OECD/NEA Nuclear Safety Response and Lessons Learnt* (NEA, 2013c), focused on detailing the immediate response of the NEA and its member countries to the accident. Among other findings, the report found that member countries had performed focused safety reviews of their operating reactors and determined that they were safe to continue operation while more comprehensive safety reviews were conducted.

Both of these NEA reports on the Fukushima Daiichi accident focus on actions taken by NEA member countries and as such are complementary to reports produced by other international organisations, including the International Atomic Energy Agency (IAEA) and the World Association of Nuclear Operators (WANO).

Since the Fukushima Daiichi accident, NEA member countries have continued to look at what lessons they can learn, and to take appropriate action to maintain and enhance the level of safety at their own nuclear facilities, to improve on-site and off-site emergency preparedness responses, and to share those lessons and actions with other countries. Member countries' reports on their safety reviews, actions taken and actions planned have been provided and presented at various fora since the Fukushima Daiichi accident (IAEA, 2014a; ENSREG, 2013). These reports have included details on reviews and measures identified to further enhance the resilience of nuclear facilities.

The reports detail, for example:

- actions undertaken by regulatory authorities in NEA member countries that have led to the establishment of new requirements resulting in specific nuclear power plant improvements in multiple areas;
- activities taken by NEA committees such as initiatives to improve regulatory frameworks in member countries, research activities undertaken to continue improving the knowledge and understanding of the accident itself, activities to improve emergency preparedness and radiological protection, as well as those concerning legal improvements in relation to liability law.

While the present report focuses on actions taken since the Fukushima Daiichi accident and reports on their status, it also looks forward, and provides information on ongoing and future activities that NEA member countries are undertaking to continue learning from the accident so as to further enhance safety.

Member country responses and safety enhancements

General observations about developments since the 2013 report

Regulatory authorities in NEA member countries have performed a number of common activities that have led to the establishment of new requirements, resulting in specific plant improvements in multiple areas. Common activities have included a focus on the potential impact of external hazards, on plant improvements, for example in relation to the diversity of equipment, as well as enhancements in the robustness of safety functions and in continuing efforts with respect to organisational behaviours. More specifically, these areas include: *i)* a re-examination of external hazards; *ii)* an improvement of the robustness of the electrical systems; *iii)* an enhancement of the robustness of the ultimate heat sink (UHS); *iv)* protection of the reactor containment system; *v)* protection of spent fuel in storage pools; *vi)* reinforced capability to rapidly provide diverse equipment and assistance from on-site or off-site emergency preparedness facilities; *vii)* a reinforcement of safety culture, including human and organisational factors in decision making during emergencies; and *viii)* continued safety research. Some of these improvements have already been implemented, some are in the process of being completed, and still others are planned and will be implemented at nuclear power plants (NPPs) in the coming years. In addition, governments in several countries have taken action to reinforce the independence of their regulatory bodies.

See Annex I for links to reports on plant improvements and enhancements being planned, undertaken or completed by member countries.

External hazards

In response to the Fukushima Daiichi accident, NEA member countries have re-examined NPP responses to external events of higher magnitude than those previously considered. The focus was on the need to re-evaluate, using the latest data and technology, the hazards posed by external events, such as earthquakes, floods and extreme weather conditions, and to ensure the adequacy of associated design-basis assumptions and define margins. Plausible combinations of sequential events (e.g. earthquake and resultant tsunami, hurricane and flooding) as well as consequential events, such as an earthquake that causes fires or a pipe rupture with a loss-of-coolant accident, have also been included in the assessments.

Severe external hazards can be of long duration and result in devastation and isolation of the site, unavailability of numerous safety systems, simultaneous accidents at several units on the same site as well as their spent fuel pools (SFPs), and potentially radioactive releases. Therefore, member countries have required their licensees to implement the necessary measures to prevent accidents and limit their consequences in case of an event caused by a rare, extreme natural hazard.

In NEA member countries, licensees have been requested to examine the margin available at each NPP over the current design-basis external events and also examine its capacity to respond to extreme natural events (such as earthquakes, flooding and other external hazards, including tornadoes or hurricanes) that are beyond the current design basis. These types of natural hazards can cause a prolonged loss of electrical power and/or a loss of cooling to the reactors and containment.

Licensees have conducted, or are conducting, external hazard re-evaluations using the most up-to-date geologic, hydrological and meteorological information. For example, flooding analyses have been done using probable maximum precipitation levels, conservative assumptions involving the potential blockage of site drainage systems, and coincident storm surge from the available UHS. Other examples include seismic analyses that have been conducted using the latest geologic information, enhanced by geo-spatial technology that was not available when many of the NPPs were designed and constructed. Many licensees are in the process of performing level 1 and 2 probabilistic safety assessments (PSAs) to assess seismic risks, flooding, high winds or a combination of hazards. In some member countries, seismic and flooding PSAs in particular are proving to be a challenge in terms of the state of the art, as well as gaining general acceptance to use new and innovative techniques for classifying very low frequency but potentially very high-consequence events.

In response to the ongoing reassessment of external hazards, licensees in NEA member countries have begun developing and implementing enhancements to mitigate consequences of high-consequence, low-frequency events that can be caused by external hazards. Even though methodologies varied among member countries, there were many common elements among NEA countries in terms of the implementation of design upgrades and improvements in regulatory requirements to existing NPPs.

Examples of safety enhancements

Examples of safety enhancements implemented as a result of the external hazard reassessments at many existing NPPs include:

- Reinforcing and extending permanent flood protective measures (e.g. tsunami/flooding walls at susceptible NPPs).
- Installing and using monitoring systems or early warning systems for adverse meteorological conditions (such as tornadoes), flooding and tsunami warnings and earthquakes.
- Implementing automatic plant trips for seismic or tsunami hazards.
- Using reinforcements to increase the protection of essential equipment and the on-site emergency response organisation from harsh environmental conditions.
- Conducting hazard-specific PSAs (e.g. seismic PSAs) to better understand the risks associated with the hazard reassessments.
- Increasing the robustness of the emergency or alternative power supply in case the external grid is affected for a long period.
- Ensuring that if an external event impacts the UHS, an alternative UHS strategy is available and is capable of resisting external events.
- Implementing the newest technology to conduct external hazard reassessments. These techniques are planned for use in future periodic safety reviews or as considered in modification of existing requirements or regulatory programmes.

Accident management

It is important to distinguish between on-site accident management for severe accidents and off-site emergency preparedness and response since these usually involve different organisations and different approaches. Off-site aspects are further discussed in the section on emergency preparedness, planning and off-site response.

One of the lessons learnt from the Fukushima Daiichi NPP accident is that it is necessary to provide accident management measures for conditions more complex and/or more severe than those postulated as design-basis accidents. Another significant lesson learnt concerns the importance of accident management, taking into account that a single event could affect multiple units at a site and that plans should be made accordingly.

The selection of equipment to prevent failure(s) and to mitigate consequences in the NPPs of member countries has generally been based on a consideration of reasonably foreseeable events. Where these events have the potential to lead to a large release of radioactive material, the plant design basis requires suitable protection to prevent damage to barriers to the radioactive release, or at least to preserve one barrier. Since the accident at Fukushima Daiichi, many countries have been and are carefully considering what should be taken into account in scope and what if anything is out of scope. A number of countries have adopted an approach which consists of assuming extensive damage to the equipment intended to mitigate design-basis faults and provide diverse protection through the installation of additional systems and/or mobile equipment. Another approach is to consider that the initiating event affects multiple units at the site such that enough equipment is needed to protect more than one unit simultaneously. This equipment is intended to be part of a defence-in-depth (DiD) approach that accepts the possibility of errors in the original design process and accounts for uncertainties. Most countries require a minimum level of protection against severe accidents as a basic regulatory requirement and some require that further conceivable measures be examined to determine whether they could reasonably make a useful contribution to safety. Historically, research and development (R&D) in severe accidents has involved extensive international collaboration, and severe accident management guidelines (SAMGs) are often developed based on broad consensus on commendable practices.

Many member countries now generally consider that their accident management measures need to be based on an appropriate analysis and the application of at least a level 2 PSA. These analyses could be enhanced by R&D, for example in the area of core retention where it has been recommended that a state-of-the-art report be developed at the international level, for example by the NEA. Member countries have noted the advantage of harmonising the approach to severe accident analysis through exchange of information and experience.

Member countries have been and are looking at how best to evaluate events that are extremely unlikely to occur. In some member countries, the concept of the "practical elimination" of early or large releases (i.e. radioactive releases requiring off-site emergency and protective measures, but in a time frame too early to allow implementation of protective measures, too large to be limited in area or time and large enough that it would require long-term evacuation of people) have been introduced for new reactor designs (e.g. IAEA, 2015). Practical elimination is included in both the IAEA Safety Requirements for new reactor designs (IAEA, 2012) and in the Western European Nuclear Regulators Association (WENRA) Safety Reference Levels (WENRA, 2014). More detail is provided for new reactor designs in the chapter on NEA developments later in this report. The Fukushima Daiichi accident has led to enhanced consideration of this concept among operating plants. Because the implementation of the practical elimination concept is most effective through design features, it can be applied more easily to new reactors. There are therefore likely to be fewer practical opportunities for enhanced safety through practical elimination for operating reactors. Nevertheless, most member countries consider that the concept of practical elimination for operating reactors should not be claimed solely on compliance with a probabilistic cut-off value. In other words, even if the probability of an accident sequence is very low, any additional design features, operational measures or accident management procedures to lower the risk further or eliminate it when the consequences could be high, should be implemented to the extent practicable.

Member countries have given careful consideration to provisions of adequate severe accident management (SAM) hardware that will survive external hazards. Examples include equipment qualification against extreme external hazards (e.g. engineering substantiation and/or qualification against high pressures, temperatures, radiation levels), or storage in a protected, safe location. Other SAM strategies have included assessments of the long-term durability of the nuclear industry's emergency response capability against the effects of severe accidents, and ensuring that improvements have been implemented to address the long-term requirements, including taking account of staff welfare. Consideration has also been given to the critical functions of communications, management of personnel in potentially hazardous areas and plant parameter indications that can be replicated by providing back-up equipment which can be deployed and operational within the required timescales. A flexibility of approach has been shown through the provision of mobile back-up equipment in combination with hardened on-site structures to ensure a degree of separation and independence.

Some member countries have performed stress tests that resulted in a focus on the aspects of an emergency response in extreme conditions that needs to be addressed during emergency preparedness work. Work has also been undertaken by member countries regarding the development of long-term severe accident exercises along with reviews of source terms and dose uptakes. Regulators have also reviewed and evaluated their own emergency preparedness and response programmes, including their links with other authorities and organisations at the national level. The progress made has been assisted by the lessons learnt from national, bilateral and multi-lateral emergency exercises, as well as evaluations of accident management at the Fukushima Daiichi NPP.

Examples of safety enhancements

The provision of the following accident management equipment, infrastructure and instrumentation are examples of safety enhancements that have already been implemented or are being considered in member countries:

- To prevent fuel melt during accidents, making available systems/equipment for cooling the reactor and the spent fuel pools that are independent of normal/emergency power supplies and heat sink (e.g. diesel- or turbine-driven pumps with alternate water sources).
- The availability of systems/equipment, which can withstand the harsh conditions of the accident, to mitigate the consequences of a severe reactor accident, including those needed to cool the corium and the containment, to manage combustible gases like hydrogen (e.g. passive autocatalytic recombiners) and control containment pressure.
- Design cooling water supplies with suitable diversity to provide the required level of resilience and redundancy. Dedicated water sources have been identified and prioritised that can supply an alternate source of cooling water if the UHS is unavailable.
- Provision of a reliable means of depressurising the reactor.
- In-vessel-retention measures are being considered or applied in more countries.
- The use of a filtered vent or filtering strategies instead of an unfiltered system if containment venting is used to limit the containment pressure.
- Having resilient severe accident instrumentation that enables well-timed operator actions, surveying the effectiveness of the actions and monitoring the progress of the accident.
- Improvements and training in SAMGs, as well as extensive damage mitigating guidelines (EDMGs), incorporating lessons learnt from the Fukushima Daiichi accident.
- Provision of portable power supplies for essential systems, and sufficient battery capacity to support severe accident instrumentation and other essential control systems in an extended period of station blackout:
  - For direct current (DC) power systems, some countries have added the capacity to extend the time that DC power will remain available before recharging becomes necessary. Another common practice is to extend the availability of DC power through the establishment of detailed procedures for shedding non-essential loads to maximise power to essential equipment and instrumentation.
  - For alternating current power systems, some countries have additional emergency diesel generators to provide enhanced electrical supplies. In many countries, portable generators have also been procured and placed in special storage areas designed to resist external hazards (e.g. flooding, earthquakes) to provide enhanced electrical capabilities with flexibility for installation as needed. In addition, many countries have improved connection capabilities for mobile and emergency power supplies.

- Heavy equipment, including earth movers being made available for site damage repair.
- Availability of a secondary location if the main control room is lost, to enable monitoring and control of the plant.
- The provision of personal protective equipment, dosimeters and portable shielding to allow site operations to continue in harsh conditions.
- The employment of satellite, microwave phones and other diverse communication systems for voice and data.
- Provision for transmission of a limited set of plant parameters to different emergency organisations.
- Provision of emergency lighting in key areas of the plant as required for emergency response.
- Ensuring the availability of mobile equipment when needed, having well-defined responsibilities and routines for managing the equipment (e.g. storage, maintenance, testing, transfer and training).
- A strategy for pre-emptive deployment of mobile equipment in the event of an anticipated hazard. Modifications have been made to system piping that will allow the quick connection of portable pumps using flexible hoses to permit alternative core cooling to be quickly implemented in an extreme event.
- The accident has brought additional attention to SFPs and therefore their protection against external events has been reassessed in many countries. This has led to the installation of redundant SFP water level and water temperature indications, and diverse cooling water supplies. In addition, physically separated and redundant lines for supplying cooling water to SFPs from outside the building have been implemented in some countries.
- Another innovation implemented in some countries is the establishment of off-site equipment storage facilities. These facilities can provide a wide range of equipment in an emergency, including portable equipment such as electrical generators, pumps, hoses, ventilation equipment, diesel fuel storage and transport vehicles, and fire trucks. The facilities are located far enough away from the existing NPPs that a natural disaster at the NPP should not affect the off-site facility.

Radiological protection

Member countries have been giving consideration to enhancing the provision and arrangements for radiological protection of operators and all other staff involved in severe accident management and emergency responses, both on-site and off-site. Regulators have been, where appropriate, working closely with other agencies to address capability gaps in radiological protection arrangements in response to severe radiation accidents. One example is the attempt to improve the radiological protection of responders through the national adoption of consistent and harmonised arrangements for setting and implementing emergency exposure criteria across all the response services that would be involved in dealing with a severe accident, both on-site and off-site.

Reference levels for protective actions – for the urgent, intermediate and long-term phases – are being reviewed and revised as appropriate by some member countries, and in an increased number of cases, harmonised between neighbouring countries. In general, this means being reviewed and benchmarked (and updated as appropriate) against the most recent international recommendations (i.e. ICRP 103, 109 and 111) (ICRP, 2009a, 2009b, 2007) and criteria (i.e. IAEA GSR Part 3, BSS; GSR Part 7, Emergency Response) (IAEA, 2014b) and lessons learnt from the Fukushima Daiichi accident. This includes member countries reviewing the radiological protection criteria used as an accident transitions from the immediate response and urgent phase through the intermediate and then long-term phases.

Experiences gained by member countries during their supervision of emergency preparedness at nuclear facilities, as well as experience gained from the Fukushima Daiichi accident, have led to reviews of emergency arrangements and planning. More specifically, clearer and more stringent demands are being put in place regarding radiological protection of personnel and the communications infrastructure at nuclear facilities. In general, this includes the need for detailed plans to obtain protective equipment in the event of a long-term situation.

Some of the technical and organisational provisions for hardening on-site and off-site safety measures have required the operator to ensure the availability of active dosimetry equipment, radiological protection measurement instrumentation, and the personal and collective protective equipment. Furthermore, the verification of the feasibility of planned human actions should take into account the radiological protection of the persons involved. Operators should ensure that it is possible to monitor and manage the facilities after a severe accident's radioactive releases, while also ensuring the radiological protection of all workers and emergency responders involved.

Some member countries are requiring modifications at nuclear facilities within their jurisdiction to ensure that, in the event of release of dangerous substances or an opening of the venting system, operation and monitoring of all facilities on-site are guaranteed until a long-term safe state is reached. As part of this effort, dose estimates have been made for different scenarios and for those involved under the response conditions during emergency management.

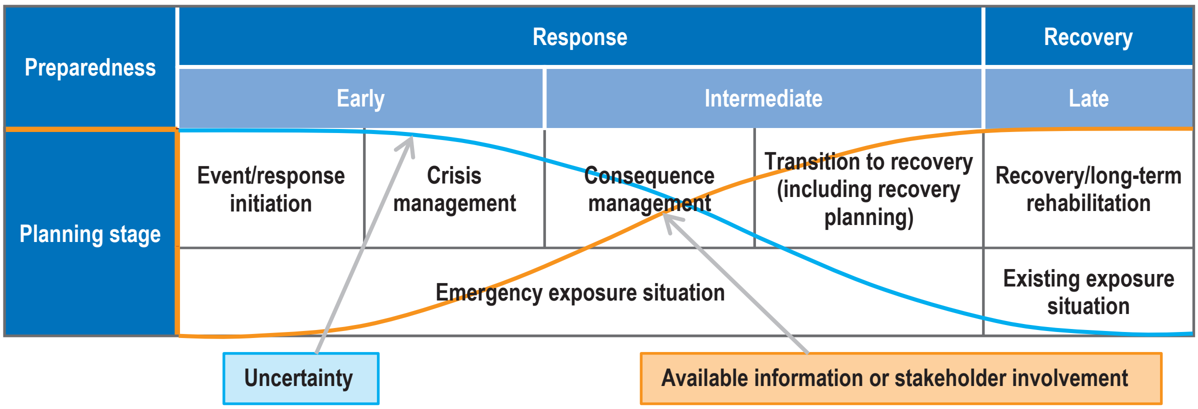
Many member countries have amended their radiological protection and emergency plans to include a simultaneous emergency at multiple units. The plans, which were originally structured to cope with a radiological emergency at one unit, have been restructured considering simultaneous emergencies at multiple units. In addition, the accident at Fukushima Daiichi NPP presented challenges with respect to dose assessment and source-term estimation capability because of the multi-unit nature of the release. The presence of releases from multiple units and the potential for releases from SFPs has highlighted the need for the ability to project doses from releases at multiple units. Some member countries are examining their source-term and dose assessment tools and upgrading their capability to conduct multi-source assessments. Issues also arose in terms of the sizing of emergency planning zones, the management of populations in potentially affected areas, and the ability to effectively and efficiently address international questions and information requests. These issues are being addressed nationally, and include international discussions to help ensure continuity.

For radiological protection of plant staff on-site, many licensees have improved the habitability and the size of their emergency response facilities including the Technical Support Centre and the Operations Support Centre. Some member countries have required that these facilities be hardened to protect workers in the event of a beyond-design-basis event.

Examples of safety enhancements

- Adoption of consistent and harmonised arrangements for setting and implementing emergency exposure criteria across all the response services involved, both on-site and off-site.
- Review of reference levels for protective actions, for both the urgent and intermediate phases, and as appropriate, revision and harmonisation with neighbouring countries, taking into consideration accepted international criteria and lessons learnt from the Fukushima Daiichi accident.
- Ensuring the availability of active dosimetry equipment, radiological protection measurement instrumentation and personal protective equipment.
- Review and upgrading of dose and source-term assessment tools.
- Use of alternative measures for environmental radiation monitoring, such as monitoring vehicles.

Timeline of emergency situations



Emergency preparedness, planning and off-site response

In the event of an accident in a nuclear installation, such as an NPP in a member country, the emergency response is usually based on both an on-site emergency plan that is the responsibility of the licensee, and on an off-site emergency plan that is the responsibility of the local, regional and/or national authorities. In most member states the off-site plan (or plans) will start with the involvement of local or regional authorities and local emergency response services, and it will then extend as necessary to involve national government and national emergency response organisations. The prime objective of the off-site actions in these plans is to optimise the protection of the population at large, the environment (including the food chain) and society more generally. These extended off-site plans at the regional and national levels usually involve the integration and co-ordination of many different organisations.

Issues such as sheltering, evacuation and relocation, controlling the movement of people, and banning food are central to these off-site plans at local, regional and national levels. Often these off-site plans, their execution and the decision making involved, require the co-ordination of many different agencies, different parts of government and the integration of the different interests that are inherent in such multi-lateral decision making.

Member countries consider that it is necessary to balance the consequences of any countermeasures taken against the benefits of any protective actions. In the case of relevant long-term protective actions (relocation, foodstuffs and water control), some member countries consider that the applicable national criteria needs to be reviewed and developed in further detail, considering the lessons learnt from the Fukushima Daiichi accident and the most recent developments in these areas.

Member countries have developed reference levels for their protection strategies, and have been reviewing and as necessary revising them against the most recent international criteria and good practices. Issues that have been given consideration and continue to evolve, both within member countries and internationally, include the radiological criteria that may be appropriate for evacuation in urban areas where the consequences of the countermeasure may be severe and may involve large numbers of people, challenging the capacity of local, regional or national infrastructures.

These off-site plans are often designed to be flexible and extendable so as to enable them to deal with a variety of scenarios, as well as the unpredictability inherent in severe accidents and their consequences. In some member countries, these plans have been integrated in those developed for responding to non-nuclear accidents and events.

During the regular testing of these plans through emergency exercises and their regulatory evaluation, there has been increased focus on exercising over longer timescales that begin to address consequence management issues and the multi-agency integrated decision making shown necessary by the accident. This testing by member countries of their extended off-site response plans and organisation through the conducting of emergency exercises with simulated off-site consequences has included national, bilateral and international initiatives, for example the International Nuclear Emergency Exercise (INEX) series co-ordinated by the NEA.

The Fukushima Daiichi accident has led to increased bilateral and regional co-operation between countries to harmonise and co-ordinate protective measures between neighbouring countries. The accident also highlighted the need to reconsider approaches to information sharing and assessment, to making and co-ordinating protection decisions across borders and to foreign nationals in the accident country. Member countries are working with the NEA and IAEA on mechanisms to develop more co-ordinated decisions and recommendations, to facilitate the protection of public safety and to build public confidence in governmental decisions.

Further, there has been general acknowledgement of the importance of communication internationally, particularly of decisions regarding protective measures taken by the accident country or by other countries with respect to their foreign nationals in the accident country. There is also a need to develop a commonly accepted framework for managing trade in food and non-food goods from the accident country, and member countries, as well as the International Commission on Radiological Protection (ICRP), the NEA, the IAEA and the Heads of the European Radiological Protection Competent Authorities (HERCA)/WENRA, are actively pursuing ways of achieving this.

In some countries, the range of accidents included in their contingency planning has been redefined to more closely reflect an accident's potential impact rather than its likelihood. This has led to some reviews and revisions of detailed emergency planning zones near nuclear power plants in some member countries.

Some member countries have secured additional radiological protection supplies for protecting residents near a nuclear power plant, such as increasing the inventory of potassium iodide (KI) tablets to supply a larger area of local residents living around the plants. To effectively respond to a sudden increase in patients due to a radiological disaster, medical facilities, equipment and supplies for the hospitals designated for radiological emergency medical services have also increased in number.

The importance of stakeholder involvement in emergency planning and emergency management has for some time been highlighted by the work of the NEA and recognised nationally and internationally. This was strongly reinforced by the Fukushima Daiichi accident. Governments and international organisations have turned significant attention to reviewing, and if needed, improving their policies, regulations and practices to further emphasise stakeholder input in decisional processes.

Examples of safety enhancements

- Review and development of national countermeasure criteria, considering the lessons learnt from the Fukushima Daiichi accident and the most recent developments.
- Regular testing of plans, which has resulted in an increased focus on exercising longer timescales, consequence management and the multi-agency integrated decision making shown necessary by the accident.
- Refining the range of accidents included in contingency planning, including multi-unit and sequential events.
- Review and development, as needed, of resources to address international communications of accident assessments and protection recommendations.
- Review and development, as needed, of approaches to stakeholder involvement in emergency preparedness and management decision-making processes.
- Strengthening international co-operation and cross-border co-ordination (e.g. HERCA, HERCA-WENRA approach).

Post-accident recovery

The transition from the acute crisis phase to the consequence management phase and then to the post-accident recovery and rehabilitation phases are issues that member countries have been considering for some time. The accident at Fukushima Daiichi NPP and the short-, medium- and long-term activities that have been revealed to be necessary at the site have brought focus to member country deliberations at both the national and international levels, including on how to best define the different phases and approaches (and philosophies) to be adopted in order to optimise protection.

As with the immediate off-site emergency response, reference levels for long-term protection of the public in the recovery phase have been developed by member countries; these involve such things as the consideration of the effects of exposure levels on a long-term post-accident basis to such things as contaminated land, water and food, as well as inherent socio-economic factors to be taken into account. Criteria have and are being reviewed by member countries at national and international levels against the most recent international criteria and good practices. Because of the importance of stakeholder involvement in the determination of such criteria, pre-accident reference levels for ending urgent countermeasures and for longer-term countermeasures are increasingly viewed as starting points for stakeholder discussions. Member countries are also giving consideration to issues such as cross-border countermeasure co-ordination and consistency, and to long-term framework approaches to the national and international trade management of food and goods from affected areas.

Radiation monitoring is crucial for all phases of an accident situation, in terms of management planning, as well as implementation and public acceptance. During the crisis and consequence management period, field teams are dispatched to take real-time radiation readings off-site. Member countries are examining innovations, providing field teams with the ability and equipment to deliver real-time monitoring in order to help validate dose projections, quantify actual dose, and provide confidence to the public and stakeholders that the conditions around the site are being accurately characterised. This characterisation is crucial for determining recovery strategies and acceptable levels to allow inhabitant re-entry when the facility returns to a safe and stable state, significant radioactive release ceases and no further threat of release exists. During the recovery period, the Fukushima Daiichi accident demonstrated the importance of stakeholder radiation measurements to assist residents in better understanding their circumstances, and of the need for national accommodation and support of such measurements to help to rebuild post-accident public confidence.

Some member countries have given consideration to the conceptual preparation of post-accident approaches to specific issues, such as the management of large volumes of on-site contaminated water. The initial approach in some countries has involved installing centrally located storage tanks that could be deployed as necessary, together with appropriate pumping equipment. Longer-term water treatment has also been considered together with the use of suitable water treatment chemicals. However, the shelf life of such chemicals would mean that procurement would be required rather than having centrally held stocks, although some small-scale storage could be available on-site. In most studies, the approach will be to leave water where it accumulates if secure, and only pump to specific storage areas if necessary. Some member countries have ongoing development work on how to deal with large volumes of contaminated water, while others have carried out detailed evaluations of geotechnical containment on the sites.

Approaches to off-site residential and municipal decontamination are also under consideration in some member countries. In the recovery phase, the optimisation of protection, and decisions regarding acceptable and sustainable protection options, tend to shift gradually from central government authorities to the municipal and individual levels. In terms of local decontamination work, this level of decision can have a profound effect on the volume of decontamination materials (e.g. removed soil, building rubble, felled trees) that are produced. Because such volumes of slightly contaminated material can be extremely large, consideration is being given to how large-scale decontamination issues should be addressed in recovery preparation programmes.

The events in Japan have also highlighted the importance of the human element, on workers during response to an emergency, and the continued impact on those members of the public affected by the event. With regard to those that respond to the emergency, much work is being considered to assist plant staff and emergency responders in terms of crew relief, as well as protection and accommodations for physical wellbeing. For the public affected by the event, some member countries are evaluating innovative solutions with regard to post-accident stress counsellors and other social services.

While longer-term recovery actions are under serious consideration by member countries, the priority continues to be with more immediate short and intermediate actions in accident prevention and mitigation. It is expected that longer-term actions involving post-accident recovery and clean-up will continue for quite some time and will benefit from the continuing lessons learnt from the Fukushima Daiichi accident recovery.

Examples of safety enhancements

- Consideration, review and development of the criteria involved in the transition from the acute accident phase to the longer-term accident and consequence management phase, and then to the recovery phase.
- Examination of innovations in providing field teams with the ability and equipment to provide real-time monitoring so as to help validate dose projections, quantify actual dose and provide confidence in the characterisation of conditions around the site.
- Recognition of the importance of the human element, on workers during response to an emergency, and the continued impact on those members of the public affected by the event.
- Assessment and implementation of opportunities to deal with large volumes of contaminated water.

TEPCO, Japan.

Fuel removal from unit 4.

Regulatory infrastructure

NEA member countries have reinforced the fundamental principle that there needs to be an effective separation between the functions of the regulatory body and the functions of organisations concerned with the promotion or use of nuclear energy. Associated with this fundamental principle is the need to provide the regulatory body with the necessary human and financial resources to fulfil its mission and support its independence. Member countries have worked at the international level with, *inter alia*, the IAEA, the NEA, the European Union (EU) and the European Nuclear Safety Regulators Group (ENSREG) to develop guidance and good practices for both independence and transparency.

As well as independence, technical capability, competence and qualification are seen by member countries as important and necessary aspects of an effective nuclear safety regulatory infrastructure. Core technical competency and experience are seen as the basis of an effective regulatory body where competence is the foundation of many of the other characteristics of an effective regulator such as independence, transparency, credibility and trust. It is now generally recognised by member countries that the regulatory organisation's technical competency is a necessary and fundamental condition but not sufficient in itself. Other complementary competencies need to be built upon it. Relevant competencies include knowledge of organisational and human factors, legal competence and core regulatory competence. The competency and skills for effectively exercising legal enforcement are also key elements for the decisions of the regulatory body so that these decisions have the intended impact on the level of safety.

Through their membership in the NEA Committee on Nuclear Regulatory Activities (CNRA), member countries have developed and produced a series of regulatory guidance reports known as "green booklets". These reports are prepared and reviewed by senior regulators from member countries and provide a valuable resource on key contemporary nuclear regulatory issues. Since the 2011 accident, the CNRA has considered what additional guidance may be appropriate and has commissioned and approved three new green booklets – on *The Characteristics of an Effective Nuclear Regulator* (NEA, 2014l), on *Implementation of Defence in Depth at Nuclear Power Plants: Lessons Learnt from the Fukushima Daiichi Accident* (NEA, 2016a), and on *The Safety Culture of an Effective Nuclear Regulatory Body* (NEA, 2016b).

Many member countries have further developed their policies on transparency, openness and involvement of the public in the regulatory process. Some countries have established national information systems providing online data on the current radiological situation around their nuclear power plants, as well as increasingly making publicly available their peer review results, annual reports, their regulatory decisions, and the rational and basis for these decisions.

Some member countries have reviewed and updated their legislation and regulatory guides to reflect lessons learnt from Fukushima Daiichi. Other member countries are in the process of reviewing their regulatory frameworks and making changes as appropriate. And still other regulators have required changes to facility licensees to incorporate specific lessons learnt from the Fukushima Daiichi accident.

Safety culture and organisational factors were identified by member countries as relevant issues meriting particular attention, which could to be addressed in the post-Fukushima Daiichi accident reassessment by both licensees and regulatory bodies. This issue was seen by member countries as being particularly important given that major accidents in the nuclear and other high hazard industries most frequently arise from organisational and human factors. Some have adopted a systematic consideration of safety culture characteristics in inspection and oversight processes. Other regulatory bodies and licensees have in place specific safety culture programmes that focus on attitudes to safety, organisational capability, the decision-making processes and commitments to learn from experience. These include periodic internal and external safety culture assessments.

Examples of safety enhancements

- Reinforcing the fundamental principle of regulatory independence – in particular by effective separation between the functions of the regulatory body and those of any other body or organisation concerned with the promotion or use of nuclear energy.
- Emphasising that core technical competencies and experience are the foundation of an effective regulator.
- Further development by regulatory bodies of their policies on transparency, openness and involvement of the public in their regulatory process.
- Adoption of a systematic consideration of safety culture characteristics and organisational factors in inspection and oversight processes.
- Updated regulations and regulatory guides.
- Increased international co-operation and experience exchange.

Safety research

Member countries have continued to be involved in nuclear safety research and assessment and to initiate new research in the light of the accident at Fukushima Daiichi NPP. Many member countries have also been involved in the sharing of information on research activities related to severe accidents, as well as research activities undertaken to address the Fukushima Daiichi accident and lessons learnt. Some member countries have in particular been pursuing research to:

- Further understand the specific accident behaviour at the Fukushima Daiichi NPP – both in terms of the physical/scientific events and the human, organisational and cultural factors involved.
- Further explore severe accident behaviours – both to learn from the accident at the Fukushima Daiichi NPP and also to explore further possible severe accident scenarios with other reactor and SFP designs (usually with a focus on the designs specific to their country).
- Develop an understanding and evaluation of external hazards in safety analyses including those of higher magnitude than have previously been considered, and plausible combinations of sequential and consequential events.

Some of this research has been targeted to confirm what was previously known or assumed, and other research will target new areas.

Research work has been stimulated within some member countries on human, organisational and cultural factors, in particular under extreme conditions (environmental, physical and psychological, with a very high political and public concern) of severe accidents and are exploring new issues and areas that were revealed by the accident. These topics were seen by some member countries as particularly important given that major accidents in the nuclear and other high hazard industries most frequently originate from organisational and human factors. Some countries have adopted a systematic consideration of safety culture characteristics and some have put in place specific safety culture programmes that focus on attitudes to safety, organisational capability and decision-making processes under severe accident conditions.

Other examples where member countries are pursuing new or further research as a consequence of the accident include:

- Electrical systems of NPPs and their robustness in severe accident conditions and environments.
- System behaviour in severe conditions.
- Extreme external events (tsunami, seismic events, severe weather, flooding, etc.) including their modelling, prediction and inclusion in PSA.
- Modelling fission product releases from severe accidents to better predict dispersion of radioactive material.
- Mitigation of fission product release, including filtered venting.
- Mitigation of spent fuel pool accident consequences.
- Loss of safety functions.
- Enhancements to containment systems, electrical systems, instrumentation and control, cooling systems and ultimate heat sink.
- Hydrogen control and mitigation, including venting techniques, effectiveness of equipment, (such as hydrogen igniters and passive autocatalytic recombiners) as well as research into scavenging hydrogen pockets in the upper reaches of containment structures.
- Accident progression mitigation including in-vessel retention limits and the ability to cool ex-vessel corium.
- Behaviour of containment designs (other than boiling water reactor [BWR] Mark I containments) during severe accidents, such as BWR Mark II and III containments, pressurised water reactor (PWR) ice condenser containments and PWR large dry containments.
- In-vessel retention capabilities are being studied in many countries with mid-size reactors (approximately 1 000 MWe).

- Reliable human performance under extreme conditions. This activity is described in more detail in the section on human performance in extreme conditions on page 48 of this report, which discusses the CSNI Working Group on Human and Organisational Factors (WGHOF) workshop entitled "Human Performance under Extreme Conditions with Respect to a Resilient Organisation".

Many member countries are also involved in the NEA Benchmark Study of the Accident at the Fukushima Daiichi Nuclear Power Plant (BSAF) and the NEA Senior Expert Group on Safety Research Opportunities Post-Fukushima (SAREF). BSAF was established to improve severe accident codes and analyse accident progression, as well as to better understand the current reactor core status at Fukushima Daiichi NPP. SAREF was established to identify follow-on research opportunities for addressing safety research gaps and advancing safety knowledge related to the Fukushima Daiichi nuclear accident, which will also support safe and prompt decommissioning efforts in Japan. More details on these issues are provided in the following chapter on NEA developments.

Annex I provides links to further examples of safety research work being planned, undertaken or completed by NEA member countries.

NEA developments

Nuclear regulation

Accident management

The NEA Task Group on Accident Management (TGAM) was established by the Committee on Nuclear Regulatory Activities (CNRA) in June 2012 to assess member country needs and challenges in light of the Fukushima Daiichi NPP accident, from a regulatory point of view. The objectives of the TGAM include identifying measures that should be considered to enhance the regulations and regulatory guidance for operators' accident management activities. Emphasis should be placed on identifying commendable regulatory practices that support enhanced on-site accident management response and decision making by the operators.

Membership in the task group includes representatives of the regulatory authorities or their technical support organisations from Belgium, Canada, Finland, France, Germany, Japan, Korea, the Netherlands, Russia, Slovenia, Spain, the United Kingdom and the United States. The European Commission and the CSNI Working Group on Human and Organisational Factors (WGHOF) also participate in the group.

Topics considered by the task group include:

- enhancements of on-site accident management procedures based on lessons learnt from the Fukushima Daiichi NPP accident;
- decision making and guiding principles in emergency situations;
- guidance for instrumentation, equipment and supplies for addressing long-term aspects of accident management;
- guidance and implementation when taking extreme measures for accident management.

In 2012-2013, the group further defined the scope of work and a report outline, developed a survey to support report preparation, analysed survey responses and finalised the report on commendable practices for on-site accident management. The final report on "Accident Management Insights after the Fukushima Daiichi NPP Accident" (NEA, 2014a) was then published.

This report focused on the experiences and practices existing or being proposed in NEA member countries, as well as on new findings from post-Fukushima Daiichi studies addressing accident management issues such as procedures and guidelines, equipment, infrastructure and instrumentation, and human and organisational resources. Other factors covered were accidents involving spent fuel pools, multi-unit aspects of accident management, the interface between on-site and off-site organisations and resources, and degradation of the surrounding infrastructure.

The report is related mainly to light water reactors, because most facilities in NEA member countries are based on that technology. The report not only covers reactors in operation, but it also covers reactors that are permanently shut down and still contain fuel, as well as reactors in the design phase or under construction and the spent fuel pool(s).

An important goal was to achieve the right balance and prioritisation between activities focused on prevention and mitigation. The TGAM considered this balance to be the prevention of severe accidents as fully as reasonably possible, and at the same time, to be ready to minimise the consequences of a severe accident, should one occur. The preventive arrangements of accident management aim to prevent significant fuel degradation or damage in the reactor core as well as in the spent fuel pool(s), or to terminate the progress of fuel degradation or damage once it has started. The mitigation arrangements aim to ensure as efficiently as possible the integrity of the containment and the spent fuel pool building, if one exists, in order to minimise radioactive releases into the environment.

A short summary of commendable practices identified in this report are provided below.

Procedures and guidelines

Emergency operating procedures (EOPs) and severe accident management guidelines (SAMGs) should include all operating modes, cover accidents occurring in the spent fuel pool, long-term event aspects and multi-unit accidents. Integrated accident management (IAM) procedures and guidelines should take full advantage of existing plant capabilities (fixed or mobile), if necessary going beyond the originally intended functions of some systems and using some temporary or ad hoc systems to achieve the goal of enhancing plant safety for beyond-design-basis accidents. SAMGs should take into account additional factors, including significantly damaged infrastructure, the disruption of plant level, corporate-level and national-level communication, long-duration accidents, and accidents affecting multiple units and nearby industrial facilities at the same time. EOPs and SAMGs should be comprehensively verified and validated taking account of the potentially long duration of the accident, the degradation of the plant and the surrounding site conditions. The transition between different sets of procedures and guidelines should be clearly specified and justified with regard to the design of the plant as well as interactions between the different organisations (on-site and off-site) that have been established.

Equipment, infrastructure and instrumentation

Systems, equipment and instrumentation should be designed to prevent the escalation of an event into a severe accident and to mitigate the consequences of a severe accident. Systems and equipment include those needed to cool the core and the spent fuel pool, maintain containment integrity, manage combustible gases (such as hydrogen) and provide for filtered containment venting. In addition, instrumentation should be included that enables well-timed operator actions to be performed, surveying the effectiveness of the actions and monitoring the progress of an accident. Systems, equipment and instrumentation should withstand the harsh conditions of the accident (e.g. very high temperatures, high radiation levels) and may be required to remain operable for a considerable period of time (several months or more). Consideration should be given to both fixed and mobile equipment. If the main control room (MCR) is lost, a secondary location should be provided to monitor and control the plant state or accident progression – either a centralised control station or a distributed one making use of local measurements and controls. Whatever the arrangement, the reason for the loss of the MCR (fire, smoke, high radiation, physical damage, man-made hazard, etc.) should not endanger the use of the secondary control location(s). In beyond-design-basis accidents, systems and equipment for cooling the reactor core and the fuel pools should be independent of normal/emergency power supplies and heat sink (e.g. diesel- or turbine-driven pumps with alternate water sources). Sufficient battery capacity or portable power supplies need to support severe accident instrumentation and other essential systems and equipment during an extended period of station blackout. Personal protective equipment and portable shielding should be available to allow site operations to continue in harsh conditions. The responders should be provided with emergency lighting in key areas of the plant as required for emergency response. To ensure the availability of the mobile equipment when needed, responsibilities and routines for managing the equipment (e.g. storage, maintenance, testing, transfer and training) should be well defined. A strategy for pre-emptive deployment of mobile equipment in the event of an anticipated hazard should also be considered.

Human and organisational resources

Staffing needs should be evaluated to ensure that an adequate number of personnel are available to respond to a major event, taking into account long duration and multi-unit accidents. Approaches that include analysing training needs are valuable in identifying gaps with regard to the implementation of the IAM plan. The systems approach to training is also useful to develop the appropriate training for each class of emergency responder based upon the individual's role in the IAM response. An appropriate level of training for off-site responders, such as fire brigades, medical personnel and subcontractors should also be included. Using plant reference simulators to the extent possible in conducting training for beyond-design-basis accidents, and desktop computer or tabletop exercises when limits of simulation are reached, is also seen as a good practice. Also, a combination of periodic drills and exercises to test the full range of emergency response capabilities including enhancing realism by including out-of-hours drills, reduced availability of responders, long duration and multi-unit accident scenarios should be considered and included. Necessary co-ordination with other response organisations as part of drill/exercise scenarios, to include local, state and national government counterparts, news media and neighbouring countries should be in place. Other good practices include strengthening infrastructure to enhance the readiness of initial and sustained responses, ensuring diverse means of communication for personnel recall and event command and control, as well as hardened or alternate command and control centres. Another good practice is ensuring the evaluation and availability of necessary resources (food, water, shelter, sanitation and medical care), instrumentation, radiological protection equipment for responders, monitoring devices and shielding to support a sustained response.

Crisis and emergency communications

After the Fukushima Daiichi nuclear power plant accident, the CNRA Working Group on Public Communication of Nuclear Regulatory Organisations (WGPC) addressed the international dimension of the communicative response to crises. The group dedicated a specific activity to the follow-up of the crisis communication of nuclear regulatory organisations (NROs) during the accident from an international perspective and took into account lessons learnt. It drafted a "Road Map for Crisis Communication of Nuclear Regulatory Organisations – National Aspects" (NEA, 2011) and issued the proceedings of its workshop held on 9-10 May 2012 in Madrid, *Crisis Communication: Facing the Challenges* (NEA, 2013b), as well as a report entitled "Crisis Communication of Nuclear Regulatory Organisations: Towards Global Thinking" (NEA, 2012a). The latter report highlighted that national nuclear crisis communication should be thought of in a more global context, as opposed to a national context, that a long-term perspective is necessary for building trust with the public and that a balanced approach needs to be maintained between emotions and logic. As one of the follow-up actions identified in the report, the roadmap has been extended and is now accessible as a tool for WGPC members. It will be updated on a regular basis.

Another recommendation from the report was to increase interactions with all stakeholders. In this context, the WGPC organised a first pilot workshop in April 2014 in Paris, bringing together NRO communication specialists and a wide range of European stakeholders including the media, communication experts, representatives of local information committees and non-governmental organisations. As a result of its success, a second workshop was held in April 2015 in Washington DC, gathering similar stakeholders from North America. A third workshop is planned in Tokyo in April 2016 with stakeholders from Asian countries, namely Japan, India, Korea and China. Findings from the first workshops include the need for NROs to continue to build trust and credibility with the public and to continually reinforce the message that the NRO staff is separate from the industry. There is a need to establish a positive relationship between NROs and stakeholders based on openness, educational approaches (such as training opportunities, workshops or webinars for journalists), timely responsiveness to inquiries and proactive communication. The media needs accurate, timely and clear information from NROs. Responsive public affairs offices populated with communication officers who develop a personal and confident relationship with journalists and make active efforts to keep reporters "in the loop" is crucial. In case of an abnormal situation, the media do not expect an emotional response from NROs but a prompt and correct assessment of the seriousness of an event.

Enhancing the general public's knowledge of nuclear issues and its safety culture is a difficult issue because NROs have to find a good balance between denial and panic, and to give reliable and objective information. This is a long-term commitment, to be conducted both in routine and in emergency situations.

As shown during the Fukushima Daiichi nuclear power plant accident, there is a strong need to provide clear messages that can be understood by the public and delivered in a timely manner. Furthermore, national regulators have to ensure the consistency of these messages. As a result of globalisation and new information technologies, including social media, today's information is instantly disseminated throughout the world. Social media can contribute and help NROs inform, educate and provide accurate information to a large public audience. Social media can also be used to help build an NROs reputation as a credible, transparent and independent organisation. The WGPC developed guidance on this issue entitled "Nuclear Regulatory Organisations, the Internet and Social Media: The What, How and Why of their Use as Communication Tools" (NEA, 2014n). This report outlines the most popular social media tools available today, provides tips and techniques that have worked for nuclear regulators around the world, and provides case studies and links to help regulators create, maintain or improve their social media usage. The report also highlights the need for each NRO to review and analyse its strengths and weaknesses and determine which platforms are best to serve its needs, taking into consideration budgeting and staffing restraints. It is also important to note that social media platforms should be engaged to improve communication and used as an integral part of an overall communication strategy.

Indeed, the Fukushima Daiichi nuclear power plant accident reaffirmed that NROs should be constantly communicating with their target audiences to ensure that all aspects of safety and security of nuclear facilities are understood. Regular communication with stakeholders and target audiences helps reduce the risk of misunderstanding fed by fear and rumour. Simple, factual details that put a situation in context is often more effective than scientific explanations that may be difficult to understand. To ensure the transmission of such details, NROs need to develop and implement a day-to-day communications strategy. To better structure communications strategies, the WGPC report "Nuclear Regulatory Organisations and Communication Strategies" (NEA, 2015f) provides information and suggestions to all NROs, regardless of the level of communications maturity, describing various communication concepts and approaches and listing applicable case studies to enable them to manage expectations, ensure consistent messaging, improve productivity and measure outcomes.

The North American workshop and other feedback has led the WGPC to focus future efforts on public meetings. It is important for NROs to continuously develop strategies and tools to plan for and conduct public meetings, to guide their participation in public meetings and to monitor the effectiveness of their efforts.

Review of precursor events

In response to the Fukushima Daiichi accident, the CNRA requested the Working Group on Operating Experience (WGOE) to examine and evaluate various accident initiators and precursors and possible lessons learnt from this assessment. In response, the WGOE, with support from the CSNI Working Group on Risk Assessment (WGRISK), considered these issues and produced a report on precursor events to the Fukushima Daiichi NPP accident (NEA, 2014g). Two questions were asked in this context:

- Could the Fukushima Daiichi NPP accident have been prevented?
- Can future potential severe accidents be prevented?

The WGOE addressed several aspects of this problem. First, whether precursors to the Fukushima Daiichi NPP accident existed in the operating experience feedback system; second, if precursor events had occurred, the reasons why these precursors did not evolve into a severe accident; third, whether lessons learnt from these precursor events were adequately considered by member countries; and finally, if the operating experience feedback system needs improvement, based on the previous analysis.

The WGOE considered precursor events identified through a search and analysis of the incident reporting system (IRS) database and also precursor events based on risk significance. Both methods were used to identify areas where further work may be needed. The WGOE found that based on its review of operating experience, more efforts are needed to ensure timely and full implementation of lessons learnt from precursor events. It also found that combining the use of risk insights with operating experience may drive plant changes that could effectively reduce risk.

In order to conduct this review, the WGOE analysed the Fukushima Daiichi NPP accident sequence, evaluated the IRS coding criteria and found that nearly all aspects of the Fukushima Daiichi NPP accident could be sufficiently described in the key words of the IRS system. The WGOE analyses found that there are related precursor events in the IRS database. It also found that operating experience lessons learnt had been disseminated internationally in relation to the main initiators and conditions that had been observed during the Fukushima Daiichi NPP accident. The accident did not show unknown initiators, sequences or consequences. However, the combination and the severity of initiating events had not occurred before and the evolution of the accident in three different units simultaneously was also new. Currently, there are no major changes to the IRS database because of the Fukushima Daiichi NPP accident, but updates might be necessary once a full understanding of the accident is available.

The WGOE report also contains a short description and evaluation of selected precursors that are related to the Fukushima Daiichi NPP accident. The main question answered in this section was "what barriers stopped these precursor events before they evolved into accidents?" The effective barriers were analysed and discussed. These barriers were specific to the events' sequences, to the severity of the events and the design of the NPPs affected. The WGOE determined that there was no single effective barrier that prevented escalation of the event into an accident. Rather, it was a combination of systems, design features and in some instances, operator actions that created barriers which prevent an escalation. The WGOE determined that there is no simple solution to prevent future accidents using only barrier analyses.

The WGOE addressed the question of whether operating experience feedback can be effectively used to identify plant vulnerabilities and minimise potential for severe core damage accidents. Based on several of the precursor events, national and international in-depth evaluations were undertaken. The vulnerability of NPPs due to external and internal flooding has clearly been addressed, as well as the dependency on the function of electrical systems. But the combination of rare events – such as flooding, station blackout or loss of instrumentation and control – were not found in the IRS system. In addition, the severity of reported events is not comparable to the Fukushima Daiichi NPP accident. Such single rare events, such as the Fukushima Daiichi event, have resulted in important lessons learnt that have been reported worldwide to the responsible institutions.

Major events lead to intensive national and international work to analyse the causes and to derive lessons from such events. For some of them, the final lessons learnt are derived only after several years of analysis. The number of significant lessons learnt is very large. The challenge is the assessment of these lessons and the priority setting for their timely implementation at each NPP.

In addition to the IRS-based investigation, the WGRISK was asked to identify important precursor events based on risk significance. These precursors have also been analysed in terms of the initiators, the effective barriers to escalation and the major lessons learnt. Among the precursors, initiating events included earthquakes, loss of ultimate heat sink, and loss of off-site power, all of which were directly related to the Fukushima Daiichi NPP accident. The two other precursor events selected by WGRISK were related to a loss-of-coolant accident. In addition to the major events and initiators directly related to the Fukushima Daiichi NPP accident, there are other important initiators or event sequences that could result in core melt accidents. Therefore, the focus of plant improvements should also consider the risk significance in addition to operating experience feedback.

The question related to effective barriers in significant events can be answered by examining the different event sequences and specific NPP designs. There is no generic lesson to be learnt from these events that has not already been addressed in the national and international operating experience networks.

The WGOE also considered potential improvements for the international systems concerning operating experience, noting that significant efforts have been made, both nationally and internationally, to derive specific and generic recommendations for further safety improvement to NPPs. The challenge is the assessment of the applicability to specific NPPs and the prioritisation of the proposed actions. Also, the lessons learnt related to human and organisational factors as well as safety culture issues represent additional challenges. While the implementation of lessons learnt is mainly a task for the utilities, the regulatory bodies should also be aware of the applicability of the lessons learnt disseminated by international systems.

The WGOE, through the analysis of the IRS database, has provided insights on important single events and derived generic lessons to be learnt from individual events or event groups for more than 30 years. The responsibility of the WGOE ends with the dissemination of its results. Implementation is clearly the task of the national regulatory authorities and NPP owners.

When considering whether it is possible to prevent future potential severe accidents, the WGOE concluded that operating experience feedback is an important tool to prevent events but there exist other approaches to maintain or improve the required level of safety of NPPs. Lessons learnt from the evaluation of operating experience are helpful in the prevention of future accidents, if implemented in a timely manner. The challenge for utilities and regulators is to prioritise the numerous lessons learnt according to individual plant designs and conditions.

The conclusions of WGOE work on Fukushima Daiichi NPP precursor events show that:

- Existing operating experience feedback systems provide a good tool to provide lessons learnt to help prevent recurrence of events.
- Operating experience combined with risk insights can provide a very good source of potential improvement as demonstrated in the course of real events.
- Significant lessons learnt have been revealed from operational events and these have improved overall plant safety when implemented. The Barsebäck and Forsmark-1 events, for example, produced significant lessons learnt even though these events did not lead to core melt. The events that resulted in core damage, including those at Three Mile Island, Chernobyl and Fukushima Daiichi, have led to international advances in the analysis of operational data beyond the continuous work of the WGOE.

The implementation of NPP operating experience is a continuous challenge for both regulators and NPP operators. The challenge is to identify precursor events and subsequent lessons learnt, and then to implement the related actions so as to enhance plant safety and prevent recurrence. Preliminary approaches have already been published by the CNRA in its series of NEA regulatory guidance booklets (“green booklets”). For example, the *Regulatory Challenges in Using Nuclear Operating Experience* (NEA, 2006) provides valuable recommendations to improve the use of operating experience.

Defence in depth

Defence in depth (DiD) is a concept that has been used for many years, along with other tools, to optimise nuclear safety in reactor design, assessment and regulation. The March 2011 Fukushima Daiichi NPP accident gave unique insight into nuclear safety issues, including the DiD concept.

In June 2013, the NEA organised a Joint CSNI/CNRA Workshop on Challenges and Enhancements to DiD in Light of the TEPCO Fukushima Daiichi NPP accident (NEA, 2014c). It was noted that further work would be beneficial, especially with regard to implementation of DiD, to enhance nuclear safety worldwide. Accordingly, a CNRA senior-level task group (STG) was set up to produce a regulatory guidance booklet to assist member countries in the use of DiD, taking account of lessons from the Fukushima Daiichi NPP accident.

This regulatory guidance booklet, *Implementation of Defence in Depth at Nuclear Power Plants: Lessons Learnt from the Fukushima Daiichi Accident* (NEA, 2016a), builds on the work of the NEA Joint CSNI/CNRA Workshop, of the International Atomic Energy Agency (IAEA), the Western European Nuclear Regulators Association (WENRA) and of other members of the STG-DiD. It uses as its basis the International Nuclear Safety Advisory Group’s *Defence in Depth in Nuclear Safety* study (IAEA, 1996).

The booklet provides insights into the implementation of DiD by regulators and emergency management authorities after the Fukushima Daiichi accident, aiming to enhance global harmonisation by providing guidance on:

- the background to the DiD concept;
- the need for independent effectiveness among the safety provisions for the various DiD levels, to the extent practicable;
- the need for greater attention to reinforce prevention and mitigation at the various levels;
- the vital importance of ensuring that common cause and common mode failures, especially external events acting in combination, do not lead to breaches of safety provisions at several DiD levels, taking note of the particular attention that human and organisational factors demand;
- the concept of "practical elimination" of significant radioactive releases;
- implementation of DiD for new and existing reactors, multi-unit sites and other nuclear facilities;
- the implementation of DiD through regulatory activities (based on a survey among CNRA members);
- the protection measures in the DiD concept of level 5 (off-site emergency arrangements).

The use of the DiD concept remains valid after the Fukushima Daiichi accident. Indeed, lessons learnt from the accident and its impact on the use of DiD has reinforced its fundamental importance in ensuring adequate safety. This is illustrated by the recent Vienna Declaration on Nuclear Safety adopted by the contracting parties of the Convention on Nuclear Safety.

This regulatory guidance booklet also identifies areas where further work may be beneficial, including:

- the impact of human and organisational factors on DiD;
- improvements on the use of the DiD concept for multi-unit sites, fuel cycle facilities, 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.

Effective nuclear regulator

In December 2012, the NEA decided that a regulatory guidance booklet on *The Characteristics of an Effective Nuclear Regulator* would be a timely and appropriate addition to this series of green booklets on key contemporary nuclear regulatory issues.

An early observation in this area was that both national and international organisations agree that the fundamental objective of all nuclear safety regulatory bodies – the regulator's prime purpose – is to ensure that nuclear licensees operate their facilities at all times in a safe manner. The CNRA concluded that in order to effectively achieve this objective, the nuclear safety regulator must possess specific characteristics that will allow it "to do the right thing well and efficiently". It considered that effective organisations are those that have good leadership and are able to transform strategic direction into operational programmes. Effectiveness is about how well the organisation is achieving its fundamental purpose – in the case of a nuclear safety regulator, ensuring that licensees operate their facilities and discharge their obligations in a safe manner.

This CNRA report describes the characteristics of an effective nuclear safety regulator in terms of roles and responsibilities, principles and attributes, using the following definitions:

- Principles – Fundamental and accepted rules for the basis of conduct from which all actions are derived.
- Attributes – Qualities that identify or describe an organisation that results from the actions of the organisation.

Each of the characteristics identified is considered a necessary feature of an effective nuclear safety regulator; however, no one characteristic is sufficient on its own. The combination of these characteristics, including the roles and responsibilities, the principles and the attributes, contribute to the effectiveness of a nuclear regulatory body.

The report concluded that an effective nuclear 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 the government that sponsors 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 continuous self-improvement and learning culture, including the willingness to subject itself to independent peer reviews.

A regulator with the above characteristics should be effective in ensuring that nuclear facilities are operated at all times in a safe manner, in accordance with international safety principles and with full respect of the environment.

The NEA considers *The Characteristics of an Effective Nuclear Regulator* (NEA, 2014l) a unique resource for countries with existing, mature regulators that can be used for benchmarking as well as training and developing staff. It should also be useful for new entrant countries in the process of developing and maintaining an effective nuclear safety regulator.

The safety culture of the regulatory body

When discussing, reviewing and approving the regulatory guidance report on *The Characteristics of an Effective Nuclear Regulator*, the CNRA noted that "safety focus and safety culture" is one of the most important characteristics discussed in the report, as one of the four fundamental principles identified. It was therefore decided that it would be a timely and appropriate moment to develop a green booklet on *The Safety Culture of an Effective Nuclear Regulatory Body* (NEA, 2016b).

Although the prime responsibility for the safety of a nuclear installation is with the licensee or plant operator, the regulatory body itself has an important responsibility in assuring safety of nuclear installations. The regulatory body, along with many other stakeholders, is embedded in a wide system, based on broad societal values and norms. By directly and indirectly interacting with each other, all participants of this system mutually influence their respective safety cultures. By nature of its role, one of the stakeholders who most deeply influence the licensees' safety culture is the regulatory body. With its regulatory strategy, the way it carries out its daily oversight work, the type of relationship it cultivates with the licensees, the values it conveys and the importance it gives to safety, in short, with its own safety culture, the regulatory body profoundly impacts the licensee's safety culture and its sense of responsibility for safety. Hence, the regulatory body needs to be conscious of its own safety culture's impact on safety culture of the organisations it regulates and oversees in order not to hamper those organisations' willingness and efforts to take on their primary responsibility for safety. For this reason, it is paramount that the regulatory body not only consider safety culture as a matter of oversight, but also as a matter of self-reflection. It should actively scrutinise how its own safety culture impacts the licensees' safety culture. It should also reflect on its role within the wider system and on how its own culture is the result of its interactions with licensees and all other stakeholders.

Although *Safety Culture* (IAEA, 1991) was originally written for operators, the concepts apply equally well to regulatory bodies despite the differing roles. Safety culture is defined in the IAEA safety glossary (IAEA, 2007) as follows: "Safety culture is that assembly of characteristics and attitudes in organisations and individuals which establishes that, as an overriding priority, protection and safety issues receive the attention warranted by their significance."

The report identifies and describes five principles and their associated attributes that underpin and support safety culture of an effective nuclear safety regulator. Each of the characteristics – the principles and the attributes – discussed in this report is a necessary feature of the safety culture of an effective nuclear regulatory body, but no one characteristic is sufficient on its own. It is the combination of these characteristics that leads to a healthy safety culture within a nuclear regulatory body.

The five principles which are adopted in the report are:

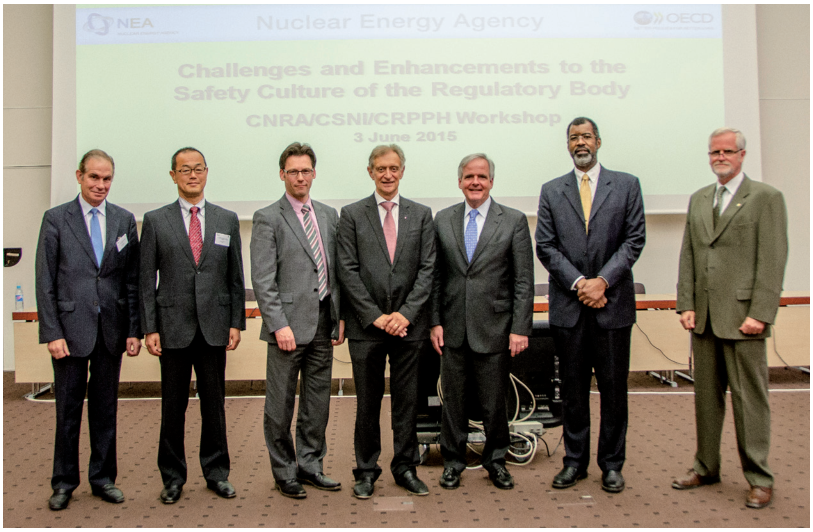
- Leadership for safety is to be demonstrated at all levels in the regulatory body.
- All staff of the regulatory body have individual responsibility and accountability for exhibiting behaviours that set the standard for safety.
- The culture of the regulatory body promotes safety and facilitates co-operation and open communication.
- Implementing a holistic approach to safety is ensured by working in a systematic manner.
- Continuous improvement, learning and self-assessment are encouraged at all levels in the organisation.

A regulatory body that applies these principles and the associated attributes described in the report should have a continuously developing and constantly improving safety culture which makes a significant contribution to the ability of a nuclear regulatory body to be effective. The safety culture of an organisation can also build an atmosphere where many positives are seen, helping to build pride in belonging and commitment to the organisation from all those involved.

The report concludes that a regulatory body with a healthy safety culture maintains its focus on safety and makes safety its first priority. When the staff of a regulatory body demonstrate positive behaviours at all levels, it positively influences the behaviour of licensees and enhances the confidence of all stakeholders. The report also concludes that the following factors support healthy safety cultures within a regulatory body:

- Excellence in leadership for safety at all levels of the organisation to demonstrate the importance of prioritising safety above all else.
- Strong sense of personal accountability so that everyone takes personal ownership of their actions and decisions with respect to safety.
- Formal direction on safety culture (i.e. a clear corporate policy on safety culture in the form of statements, guidance or a code of conduct).
- Staff who are aligned and engaged: a healthy safety culture is supported by staff who know what they are doing.
- Open and transparent communication, internally and externally.
- Informed, balanced accountability that encourages open and honest reporting and respects safety information.
- A comprehensive and systemic approach to the regulatory environment which is a complex and interdependent system that requires a holistic approach to its management.
- A clear and appropriate regulatory framework.
- Continuous improvement and learning: an open, adaptable and learning attitude in technical, regulatory and organisational areas helps avoid complacency by continuously challenging existing conditions and activities.
- Self-assessment: assessment of the safety culture of the regulatory body supports continuous improvement. At the same time, more work is needed in the development of assessment methodologies and appropriate performance indicators.
- Benchmarking to ensure consistency with peers, share experiences and support a global safety approach.

The above safety culture characteristics make a significant contribution to the ability of a nuclear regulatory body to be effective. Safety culture cannot survive solely on goodwill and good attitude. It needs to be nourished by adequate resources, competence and support programmes such as management systems.



At the Joint CNRA/CSNI workshop on Challenges and Enhancements to the Safety Culture of the Regulatory Body, Paris, 2015.

New reactors

In July 2014, the Working Group on the Regulation of New Reactors (WGRNR) issued a supplemental report to the "Report on the Survey on Regulation of Site Selection and Preparation" (NEA, 2010) to address siting issues reconsidered as a result of the Fukushima Daiichi nuclear power plant accident. The "Supplementary Report on the Regulation of Site Selection and Preparation" (NEA, 2014k) assessed the impacts of accidents at multi-unit sites, site seismicity, security and other specific design features of NPPs in relation to the plants' fixed site parameters. The report also examined the need for public consultation during siting, and regulatory approaches for new reactor siting, including changes or enhancements to the current processes.

The supplemental report also includes high-level summaries describing how external hazards, human-induced hazards, combinations of internal and external hazards, survivability of local infrastructure and emergency preparedness arrangements and feasibility at the siting stage are assessed through the siting process. It showed that the overarching requirements for site evaluation, selection and preparation were already well defined. Changes to the regulatory framework resulting from the Fukushima Daiichi nuclear power plant accident were generally needed to clarify requirements or to provide guidance on how requirements should be met.

The report noted that some NEA member countries are developing or revising siting requirements for new reactors. Design basis natural hazards and human-induced hazards, combinations of hazards and design extension conditions are being addressed as well as margin assessments and potential cliff-edge effects. Some member countries are re-evaluating seismic and flooding hazards at operating reactor sites to determine if regulatory requirements for structures, systems and components important to safety should be updated. Some member countries are reviewing the adequacy of countermeasures against hazards internal to the station, such as fire or flooding, and are enhancing the ability of on-site and off-site power sources to deal with station blackout. In time, when the accident progression is better understood and as other developments occur on the international scene (such as the revision of the IAEA Safety Standards series); it is possible that national approaches may undergo some refinement. It may therefore be worth revisiting this survey in a few years' time.

In parallel to this effort, the WGRNR completed a study of recent regulatory activities at member countries involving licensing, resources and skills needed to perform design reviews, assessments of construction oversight and the training needed to support these activities. Over the last years, member countries have shared their updated views on licensing in the light of experience gleaned from the Fukushima Daiichi nuclear power plant accident and have issued these first volumes of the "Report of the Survey on the Design Review of New Reactor Applications" about instrumentation and control (NEA, 2014h) and about civil engineering works and structures (NEA, 2015b). Similarities were observed among the regulatory organisations that responded to the survey in the design information provided by an applicant. In addition to the regulations and guidance documents, member countries commonly refer to country-specific building codes as well as internationally recognised consensus standards to provide the technical basis of regulatory authorisation. Design review strategies most commonly used to confirm that the regulatory requirements have been met include document review and independent verification of analyses performed by the applicant. Confirmatory analyses are commonly performed in this technical area.

New reactor designs

The Multinational Design Evaluation Programme (MDEP) was established in 2006 as a multinational initiative to develop innovative approaches to leverage the resources and knowledge of the national regulatory authorities that are currently or will be tasked with the review of new reactor power plant designs. The nuclear regulatory authorities of 15 countries take part in MDEP, which is structured under five design-specific working groups (DSWGs) and three generic issue-specific working groups.

Following the Fukushima Daiichi accident, the MDEP Policy Group gave direction to the Steering Technical Committee (STC) to undertake an evaluation of the reactor designs that are being reviewed by member regulators so as to address lessons learnt from the accident. All five DSWGs have completed at least the initial phase of their assessment of the impact of a Fukushima-Daiichi-type incident on their reactor designs.

The EPR working group has completed its evaluation and published its finding in a Common Position paper approved by all member regulators in the working group. The paper identifies common approaches for potential safety improvements of EPR plants to address lessons learnt from the accident. In addition to the main body of the core position, the paper also includes five appendices that address specific technical areas of concern. These are: long-term loss of electrical power (LTLEP), reliability and qualification of severe accident management instrumentation, pressure management of containment during severe accidents, long-term cooling of the fuel pools, and management of primary circuit residual heat removal and sub-criticality.

The working group findings concluded that the EPR reactor design appropriately accounts for external and internal events, making the likelihood of an LTLEP extremely low. It proposed an approach to use a combination of permanently installed and mobile means as an acceptable way to address LTLEP. In terms of instrumentation, the members of the group noted that all EPR designs include measures to prevent and mitigate the consequences of severe accidents. Licensees and applicants have made commitments to meet the regulators' expectations, stipulating that the severe accident instrumentation and controls necessary to stay on the mitigation path, including support systems, should be appropriately designed, qualified and protected for severe accident conditions.

Regarding the management of containment pressure in the event of extended loss of alternating current power and loss of ultimate heat sink, the EPR licensees and applicants have provided measures to manage the pressure within the containment. The different solutions proposed are deemed as safety improvements to address severe accident situations, combined with long-term loss of electrical power. National regulators nevertheless emphasised that they are currently considering their licensees' and applicants' solutions and have yet to finalise their respective positions. Concerning the long-term cooling of the fuel pools, regulators concluded that the EPR reactor provides an acceptable response to their expectations for the design of spent fuel pools and their associated systems.

The other four MDEP DSWGs (AP1000, APR1400, VVER, and ABWR) have submitted draft common position papers to the STC for review and further direction. The final goal of MDEP is to issue one common position paper with input from each DSWG that will address the major elements of the Fukushima Daiichi accident lessons learnt.

Nuclear safety

The CSNI has undertaken a certain number of activities to address lessons learnt from the events at Fukushima Daiichi. CSNI membership comprises representatives from safety research organisations – primarily technical scientific support organisations (TSOs) and research units of regulatory bodies – with the goal of maintaining and advancing the scientific and technical knowledge base for the safety of nuclear installations. With input from the CNRA, the CSNI identified eight high-priority areas requiring follow-up by its working groups.

Probabilistic safety assessment for external events

The Fukushima Daiichi accident focused discussions on the significance of external hazards and their treatment in safety analyses. In addition, stress tests conducted by some NEA member countries have shown vulnerabilities and the potential for cliff-edge effects in plant responses to external hazards. In order to address these issues and provide relevant conclusions and recommendations to the CSNI and CNRA, WGRISK directed, in co-operation with the CSNI Working Group on Integrity and Ageing of Components and Structures (WGIAGE), a workshop entitled "International Workshop on Probabilistic Safety Assessment (PSA)[1] of Natural External Hazards Including Earthquakes", hosted by the Nuclear Research Institute Rez (ÚJV Rez) on 17-19 June 2013 in Prague, Czech Republic. The outcomes from the workshop are summarised in the report entitled "PSA of Natural External Hazards Including Earthquake Workshop proceedings" (NEA, 2014e).

The focus of the workshop, which built upon previous WGRISK and WGIAGE activities, was on improving external events PSA for nuclear power plants, in all modes of operation. The workshop scope was generally limited to external, natural hazards, including those hazards where the distinction between natural and man-made sources is not well defined (e.g. external floods caused by dam failures). The participation was open to experts from regulatory authorities and their technical support organisations, research organisations, utilities, nuclear power plant (NPP) designers and vendors, industry associations and observers from NEA member countries. Some general conclusions from the workshop are:

- The lessons learnt from the Fukushima Daiichi accident emphasised the importance of assessing risks associated with external hazards, including combinations of those hazards, and their impacts. It is important that such an analysis cover not only individual plant units, but also the site as a whole, including all dependent effects and impacts.
- While systematic approaches for addressing external hazards in PSA currently exist and there is a well-developed state-of-practice (e.g. with respect to external flooding, seismic events and high winds), additional work is needed. More realistic evaluations are needed to provide more accurate information.
- Some methods and guides are available for seismic hazard determination, identification of external hazards, screening[2] of external events for detailed consequence analysis, including several lists of screening criteria. However, additional development is also needed in the area of consensus standards and guides.
- The major areas for improvement of external hazard studies include: scope of the PSA for external events in terms of plant operation regimes (e.g. full power, low power and shutdown operational states), combining external hazards impacts (e.g. high winds and flooding), multi-unit impacts and screening procedures for site specific hazards.

1. In this report, the terms PSA and probabilistic risk analysis (PRA) are used interchangeably.
2. In this context, the term "screening" refers to a systematic process that distinguishes items that should be included or excluded from an analysis based on defined criteria.

- The following are significant technical/methodological challenges for external hazard PSA: fragility analysis of non-seismic external hazards, correlation effects and consequent damage scenarios, human reliability analysis (HRA) for external events, PSA mission times for long-term external event scenarios, and the effects of climate change on the hazard frequencies and magnitudes.

Filtered containment venting

Following the Fukushima Daiichi accident, the CSNI Working Group on Analysis and Management of Accidents (WGAMA) updated the status report on filtered containment venting systems (FCVS). The "Status Report on Filtered Containment Venting" (NEA, 2014i) was compiled in consultation with all stakeholders in the nuclear field (end users, safety authorities, technical safety organisations, research institutes, FCVS designers and utilities).

This updated status report provides a comprehensive description of safety requirements associated with FCVS and of the status of their implementation as provided by the various contributing countries. The different level of detail describing the accident management situation in different countries in relation to FCVS reflects in part the reality of the different levels of the current regulatory and/or technological appraisal of FCVS internationally. Further, the safety requirements differ in various countries, being more or less prescriptive, with FCVS not necessarily explicitly mandated or not considered as the primary measure to prevent containment over-pressurisation.

A description of FCV strategies for emergency operating procedures (EOPs) and severe accident management (SAM) domains is also provided in the report. FCVS are considered to be an additional system to protect the containment integrity (maintain the containment function until stable conditions are reached, no matter how severe the accident). FCVS are typically used in severe accidents as part of the overall applied SAM strategy for pressurised water reactors (PWRs) and boiling water reactors (BWRs), while they are also used in design-basis accidents for some pressurised heavy water reactor (CANDUs). Operation of FCVS have also been considered in some countries and for some reactor designs for accident management other than countering the long-term over-pressurisation of the containment, e.g. for BWRs in the case of loss of heat sink to remove decay heat or to reduce the hydrogen inventory in the containment.

The report presents the well-known existing filtration technologies (e.g. scrubbers, deep-bed filtration and different sorption systems), with any focus on a particular technology or product simply a reflection of the fact that a system is currently available and information has been provided by the corresponding designer. Other systems are being developed and will be commercialised.

It was also considered valuable to provide FCVS general design requirements and specific design aspects, and to recommend state-of-the-art qualification of filter technologies for reliable function and performance of FCVS. Such information can be used as a guide for their implementation.

Deterministic consequence analyses show a large reduction of radiological impacts when comparing effective filtered releases against unfiltered releases. Generally, all contributing countries recognised through this work the potential benefits of FCVS for emergency response, reduction of the extent of land contamination and health effects and increased social acceptability of nuclear power plant installations. FCVS should, however, be considered in conjunction with other SAM strategies, e.g. no large benefit is expected for containment by-pass scenarios which have to be managed by other SAM strategies. However, FCVS may not be appropriate for all circumstances, for example containments with pressure-suppression systems and SAM strategies applying a corium in-vessel retention strategy.

FCVS implemented before the Fukushima Daiichi accident were mainly designed to manage long-term pressure build-up in the containment; new FCVS may perhaps be designed to deal with more challenging conditions (management of early phases of an accident, cycling or long-term use in severe accident conditions). The robustness (including a design withstanding several external events), the safe use and the reliability of FCVS for such conditions should be further assessed either to improve existing systems or to propose upgraded design requirements for future systems.

Hydrogen management

As a follow-up to the Fukushima Daiichi accident, the WGAMA undertook an activity in 2012 to generate a status report on hydrogen generation, transport and mitigation under severe accident conditions. The drafting committee consisted of participants from Belgium, Canada, the Czech Republic, Finland, France, Germany, Italy, Japan, Korea, the Netherlands, Poland, Sweden, Switzerland, Spain and the United States.

The resulting "Status Report on Hydrogen Management and Related Computer Codes" (NEA, 2014j), provides a general understanding of hydrogen behaviour and control in severe accidents. A description of the various reactor designs (PWR, BWR, VVERs, pressurised heavy water reactors [PHWRs], etc.) is provided as context for the containment design features in relation to hydrogen management measures. The report also provides a detailed description of national requirements on hydrogen management and hydrogen mitigation measures inside containment and other areas (e.g. annulus space, secondary buildings and the spent fuel pool). Discussions are followed on hydrogen analysis approaches, application of safety systems (e.g. spray, containment ventilation, local air cooler, suppression pool, and latch systems), hydrogen measurement strategies as well as lessons learnt from the Fukushima Daiichi nuclear power accident. And finally, the report provides an overview of various codes that are being used for hydrogen risk assessment, and the code capabilities and validation status for modelling hydrogen-related phenomena (e.g. generation, distribution, combustion and mitigation).

Hydrogen mitigation strategies vary from country to country and depend primarily on the design of the containments. For NPPs with large dry containments, such as PWR, PHWR, and VVER-1000, a combination of a large free containment volume, the use of passive autocatalytic recombiners (PARs), and/or glow plug igniters is commonly used, whereas for NPPs with small containments, such as BWR Mark I, nitrogen inerting in the whole containment is typically applied.

In response to the Fukushima Daiichi accident, some countries now require the installation of hydrogen mitigation systems, particularly PARs, inside the containment if there was no mitigation concept required in the past. For the NPPs, where the hydrogen mitigation systems are currently designed for design-basis accidents only, the existing systems are being evaluated and considered for enhancement under severe accident conditions.

The Fukushima Daiichi accident revealed that hydrogen transport from the inerted BWR containment to the surrounding reactor buildings should be investigated. Most countries have not yet adopted specific national requirements for hydrogen mitigation measures outside the containment (e.g. annulus, reactor or secondary building) or the spent fuel pool areas. Due to the Fukushima Daiichi accident, some countries have started to study severe accident conditions within such areas and to consider hydrogen management outside of the primary containment (i.e. reactor building) and at the spent fuel pool area.

In some member countries, the requirements for operation of the engineering systems (e.g. spray, containment ventilation, local air cooler, suppression pool, latch systems) are defined based on their primary purpose (e.g. heat removal or depressurisation). It is expected that these requirements will be defined/updated to take into account their effect on hydrogen behaviour. In addition, some NPPs have installed hydrogen measurement systems, and this activity is currently under consideration by other member countries, but the implementation details vary (e.g. number and location of samples, actions defined in SAMG).

Regarding the analytical techniques to assess the hydrogen behaviour in a post-accident containment, most of the NEA member countries are using lumped parameter codes (e.g. integral or system codes with mechanistic models) for full plant long-term severe accident analysis combined with 3D-like or 3D codes for detailed short-term and/or local hydrogen analysis (e.g. hydrogen distribution, combustion and mitigation).

Of the codes assessed, only the integral or system codes are capable of calculating hydrogen generation in the reactor core and/or from molten-core-concrete interaction (MCCI) in the cavity. Most codes have capabilities to model hydrogen distribution, combustion, mitigation systems and engineered safety features. In addition, some member countries have developed more complex models with computational fluid dynamics (CFD) codes for better assessing hydrogen combustion, recombination and key phenomena such as condensation or evaporation, which can affect hydrogen distribution in the containment.

Code validation performed for hydrogen-related phenomena such as generation, distribution, combustion and mitigation vary largely among member countries. Some have performed extensive validations using their own experimental data and/or by participating in international benchmarks, but some heavily rely on code developers. None of the codes are fully validated for the entire list of hydrogen generation, distribution, combustion and mitigation phenomena due to a lack of experimental data to validate desired application range. Engineering judgement and a large degree of experience in code application is therefore needed in order to obtain realistic results.

Research and development efforts to date have already significantly enhanced the understanding of the phenomena governing the distribution of hydrogen gas mixtures and their potential combustion. Research will continue to improve the understanding of severe accident conditions and consequences to equipment and components inside containment. The purpose is to reduce uncertainties and provide insights to refine the SAMGs. Further efforts are still needed to close research gaps, enhance code capability and reduce code uncertainty.

In conclusion, the report provides a basis for reviewing SAM strategies for hydrogen management. It is recommended that assessment of the SAM strategies or guidelines, as well as advantages and drawbacks of the various hydrogen mitigation approaches implemented by different countries, be pursued as a follow-up activity.

TEPCO, Japan.

Fukushima Daiichi units' 3 and 4 damage after hydrogen explosion.

Spent fuel pools under loss-of-coolant accident (LOCA) conditions

Following the 2011 accident at the Fukushima Daiichi Nuclear Power Station, the CSNI Working Group on Fuel Safety (WGFS) collaborated with WGAMA to prepare a status report on spent fuel pools (SFPs) under loss-of-cooling accident conditions. The report entitled “Status Report on Spent Fuel Pools under Loss-of-Cooling and Loss-of-Coolant Accident Conditions” (NEA, 2015d) concluded that:

- All SFPs are large robust monolithic structures. The cooling systems have built in redundancies and are connected to emergency back-up power to maintain their function. The possibility of loss-of-cooling and loss-of-coolant accidents are accounted for in the basic design of SFPs. The large water mass provides significant thermal inertia, generally slowing transients. Following the Fukushima Daiichi accident, additional measures have been undertaken to improve SFP safety even further in many member countries.
- Although numerous events (mostly inoperable cooling pumps or coolant flow diversion) have occurred in the past, none have led to fuel uncovery or fuel damage. Operational experience shows that reliable SFP instrumentation, accident management procedures and training are needed to respond to events efficiently and effectively.

- Fuel-degradation and fission-product-release phenomenology are well known from severe accident studies, however expected SFP-accident conditions differ from these and SFP source-term estimation is a challenge. The relevant experiment database related to SFP loss-of-cooling and loss-of-coolant accidents consists largely of a number of integral light water reactor (LWR) LOCA tests. Some integral tests dedicated specifically to SFP accidents are planned; these experiments are important and should be supported.
- Currently available computational tools are intended primarily for the analyses of reactor accidents, and more specific modelling tools for SFPs are needed. Thermal-hydraulic system codes and severe accident codes are usually limited to 1 or 2D applications, but SFP accidents are expected to be significantly influenced by 3D effects due to heterogeneous fuel arrangement and boundary conditions. CFD tools can address problems at local scale in 3D but SFPs involve a large simulation domain imposing simplified modelling.

Human performance in extreme conditions (with respect to a resilient organisation)

The Fukushima Daiichi accident illustrated the challenges in supporting reliable human performance under extreme conditions. Acknowledging that further work is needed to be better prepared for human and organisational factor (HOF) challenges of the extreme conditions that may be present in severe accidents, the CSNI's Working Group on Human and Organisational Factors (WGHOF) hosted, with the Swiss Federal Nuclear Safety Inspectorate (ENSI), a workshop entitled "Human Performance under Extreme Conditions with Respect to a Resilient Organisation". The workshop took place in Brugg, Switzerland in February 2014. A total of 34 experts participated from 14 countries, the IAEA and OECD/Halden. Experts were from nuclear authorities, research centres, technical support organisations, training simulator centres, utilities and non-nuclear fields (aircraft accident investigation, firefighting, military, design of resilient organisations). The proceedings are summarised in "Human Performance under Extreme Conditions with Respect to a Resilient Organisation" (NEA, 2015a).

From the discussions at the workshop, it was clear that the accident at Fukushima Daiichi has illustrated the challenges that operations and emergency response staff can face in dealing with a major nuclear incident. In addition to the complexities of understanding what is happening in the reactor and taking appropriate actions, people were exposed to a harsh environment (e.g. loss of power, radiation, lack of tools, fatigue) and demanding psychological factors (e.g. shock, disbelief, uncertainty and fear related to personal and family situations).

Moreover, the Fukushima Daiichi accident had fundamental implications for our understanding of accident management. The traditional approach to such accidents is to seek improvements in reliability that should prevent recurrence and provide staff with measures (procedures and equipment) that can be applied. The difficulty with this approach is that the increased complexity can lead to unanticipated situations that render the pre-planned responses inapplicable and ineffective. One of the fundamental conclusions from the workshop was that in addition to reliability, the focus should be on increasing resilience through improving flexibility. In addition, the workshop identified the following good practices in the areas of human capabilities, organisation and infrastructure.

Human capabilities:

- Ensure pre-planned responses for the very early stages of a severe accident – e.g. preparatory activities, mobilisation of resources and information gathering, which allows personnel to get over shock, gain some understanding of the situation and start on a successful note.
- Use realistic exercises to test and develop response capability. These are particularly important in testing lines of communication, decision making, improvising and replanning capabilities, leadership and team behaviour.
- Recognise that stress will be a reality and ensure that there are mechanisms for addressing stressors (such as uncertainty in family situations), and that staff rotation plans are in place.
- Establish an observer role – a person responsible for watching team dynamics and fatigue. Such a role is important in helping make changes before stress and fatigue have an adverse impact. Train personnel that will be in leadership roles in the requisite interpersonal and communications skills.

Organisation:

- Ensure that accident management teams are provided with clear lines of communication and clear authorities for distributed decision making in advance of any incident.
- Establish an emergency management process that involves regular "stop-points" to review the current situation and determine if the plan of action needs to be revised (watching for anomalies).
- Identify reserve capacity (people and equipment) that can be used to provide necessary flexibility to respond to the unexpected.

Infrastructure:

- Provide the redundant infrastructure and equipment (including transportation equipment) necessary for resilient emergency response, and ensure that the infrastructure and equipment is adequately sheltered.
- Pre-establish inventory of systems and components that may have an alternate use during emergencies (e.g. electrical systems, water-supply systems, including fire pumps).
- Ensure that consideration is given to events that unfold over an extended time. Include transitions between response teams and basic living requirements.
- Involve off-site emergency response capability in exercises to ensure lines of communication are effective and the overall emergency response will be co-ordinated.

Robustness of electrical systems

The Fukushima Daiichi accident renewed discussions about the significance of electrical power hazards and their treatment in safety analyses. In order to address these issues and provide relevant conclusions and recommendations to the CSNI and CNRA, the Task Group on Robustness of Electrical Systems of NPPs in Light of the Fukushima Daiichi Accident (ROBELSYS) was established in 2012. The ROBELSYS Task Group organised an international workshop to focus on actions taken by various organisations to enhance the robustness of electrical systems, especially protection against extreme external hazards. The workshop was held in Paris in April 2014, with 105 participants representing industry and government organisations from 25 countries, as well as international organisations. The results are summarised in "Workshop Proceedings: Robustness of Electrical Systems of NPPs in Light of the Fukushima Daiichi Accident" (NEA, 2015c).

The ROBELSYS workshop resulted in recommendations to establish a more permanent international working group, the need for new specific international standards regarding system and component requirements for beyond-design-basis external events, diversity in the on-site electrical power systems, relaxation of electric power protection features used in emergency situations, and qualification of existing and portable components to cope with alternating current station blackout.

The following issues were highlighted by the participants as topics of concern that needed further development:

- enhancement of the robustness of electrical systems;
- enhancement of the analysis and simulation of electrical systems transients in general and in particular of asymmetric three-phase electrical faults (one/two-open-phase issue);
- addressing safety challenges from the use of power and software-based electronics in electrical systems.

Metallic component margins under high seismic loads

One of the concerns identified from the Fukushima Daiichi accident was the potential for "cliff-edge" effects whereby once a safety limit is exceeded there is no residual margin, and there can be a failure with serious consequences. This was the case for Fukushima Daiichi where the flooding limit was exceeded and led to impairment of the electrical power systems. Recognising that an earthquake could exceed the seismic design limit for a nuclear plant, the CSNI's WGIAGE initiated a project (Metallic component margins under high seismic loads [MECOS]) to look at the seismic margins for metallic components (e.g. piping systems). The main objectives of the MECOS project were to quantify the existing margins in seismic analysis of safety class components for high seismic loads and assess the existing design practices within a benchmark activity.

The first phase of MECOS work included a survey on the existing seismic regulations and design analysis methods in the member countries. The survey showed that all respondents have a minimum seismic demand in their specified standards (either national or adopted from other jurisdictions), and that most countries are using a combination of analysis and physical testing to demonstrate systems and components are seismically acceptable.

In the first phase of MECOS, the existing database of experiments on response of piping systems to seismic loads was assessed, at which time it was determined that:

- all the experiments carried out around the world conclude unanimously that there are large margins in the design of piping systems;
- however, the failure mode addressed by the design criteria (plastic instability) is not the one observed in the experimental campaigns (fatigue-ratcheting).

As a result, the conclusion from the first phase of MECOS is that the Fukushima Daiichi accident has not raised any new issues in seismic regulations and in design of components and structures, and properly designed piping systems will have large seismic margins.

External events – initial focus on severe weather events

A lesson learnt from the accident at Fukushima Daiichi was that external events can pose a significant risk to nuclear plant safety by leading to impairment of multiple reactor systems. At Fukushima Daiichi, the tsunami overwhelmed most of the systems providing power to the reactors, and thereby challenged the operators' ability to maintain adequate core and containment cooling. Over the years, the CSNI has focused work on the technical basis for safety of nuclear installations exposed to a full range of internal hazards and to external seismic hazards. In light of the Fukushima Daiichi accident, the committee expanded its efforts to include international collaboration on other external hazards. Accordingly, in December 2014, a working group (Working Group on External Events – WGEV) was established to improve the understanding and treatment of external hazards with the goal of supporting the continued safety performance of nuclear installations and improving the effectiveness of regulatory practices in NEA member countries.

The newly established working group has identified weather and flooding-related hazards as an immediate priority for many member countries. These include coastal storms, severe local storms, riverine flooding, extreme temperatures, tsunami and dam failures. In particular, severe weather events, with a focus on high winds and flooding, was identified as the scope for a focused task based on the primary interest expressed during round table discussions. In the summer of 2014, as part of the preliminary activities to establish a working group, a survey was conducted of CSNI members to identify current regulatory practices, research activities and knowledge gaps for severe weather hazards. Following an initial assessment of the survey results in February 2015, a workshop is being planned, tentatively for February 2016, to engage relevant experts in identifying practices and activities to address the knowledge gaps. The working group has also started to identify possible activities for other weather and flooding-related hazards, and to develop a list of other external hazards of common interest.

TEPCO, Japan.

Tsunami at Fukushima Daini.

Safety research

Safety research opportunities post-Fukushima Daiichi

Recognising that improving the understanding of the accident progression in the various Fukushima Daiichi reactors is important to safety research and to decommissioning the reactors, the CSNI established a Senior Expert Group on Safety Research Opportunities Post-Fukushima (SAREF) in June 2013. The objective of the group is to propose a process for identifying opportunities for addressing safety research gaps and advancing safety knowledge related to the Fukushima Daiichi nuclear accident. The group is mandated to produce a report in 2016 with specific recommendations.

SAREF is working on a process for addressing research opportunities through identification of examinations that can be conducted on the damaged reactors, prioritising these research opportunities, and assessing their feasibility and the associated challenges in terms of cost, schedule, dose, etc. Research opportunities identified include:

- severe accident progression (e.g. in-vessel phenomena, primary system failure, primary vessel failure, molten-core-concrete interaction, pool scrubbing, containment failure and venting, fission product behaviour, and hydrogen distribution and combustion);
- system, structure or component (SSC) behaviour and condition (e.g. salt water and concrete debris effects, cables and sealing, instrumentation, pump seals, reactor core isolation cooling system, relief valves and piping, and isolation condenser);
- recovery phase (long-term accident management and recovery, and debris and waste management).

Research opportunities that are of sufficient priority in addressing safety gaps and supporting safe and timely decommissioning have been selected for action, including in-plant investigations and specific inspection activities.


TEPCO, Japan.

SAREF members at the Fukushima Daiichi site.

Joint projects post-Fukushima Daiichi

Benchmark Study of the Accident at the Fukushima Daiichi Nuclear Power Station

In 2012, the CSNI initiated a joint project to conduct a benchmark study of the accident progression for the Fukushima Daiichi NPS units 1-3, titled, "Benchmark Study of the Accident at the Fukushima Daiichi Nuclear Power Station (BSAF)". A total of 17 organisations from 8 countries (France, Germany, Japan, Korea, Russia, Spain, Switzerland and the United States) joined the project. The objective of the first phase of the project is to focus on the first six days of the accident to:

- analyse accident progression and current status inside reactor pressure vessels (RPVs) and primary containment vessels (PCVs) of Fukushima Daiichi units 1-3;
- improve methods and models of severe accident codes;
- provide Japan with useful information for decommissioning activities at Fukushima Daiichi.

The BSAF phase I results focused on integral debris weights in the three main regions of importance (i.e. core region, lower head and primary containment vessel) and provided the debris composition (UO_2, Zr, ZrO_2, stainless steel, oxidised stainless steel and B_4C).

Regarding the progression of the accident in the three units and the expected current plant status, several common understandings were reached:

- For unit 1, consensus was reached that the RPV failed and a large amount of molten core material was relocated into the pedestal, and there was MCCI between the relocated core material and the concrete pedestal.
- The majority of calculations predict for unit 2 that from around 20% to 70% of the initial core inventory melted and relocated into the lower head with complete retention of the fuel inside the RPV. However, it also possible that almost the entire core relocated into the pedestal with consequent MCCI onset.
- Two plausible scenarios were identified as a result of the uncertainties still existing for unit 3. The first scenario predicts that the RPV remained intact and melt was retained in the lower head, so that MCCI did not begin. In this scenario, it is possible that from 40% to 60% of the initial mass inventory melted. The second scenario predicts RPV breach and core debris transfer to the pedestal with onset of MCCI and gas generation. In this scenario, the flammable gas generation is considerably larger compared to the in-vessel case.

Phase 1 of the BSAF has yielded information on the predicted state of each unit's degraded core in the reactor pressure vessel and in the containment. Despite the uncertainties in code calculations, the results offer some comparative and qualitative information to assist in recovery efforts (robotic inspection and planning for defueling) currently in progress. For example, based on code calculations, it is highly likely that the vessel in unit 2 was not breached, whereas the vessel in unit 1 most likely was breached. Hence recovery efforts (e.g. where to start inspection) can be prioritised for these units. Another example is that according to code calculations, the entire core inventory appeared to have been relocated from the vessel in unit 1. During an inspection, one could then expect to see the debris likely covering most of the floor area. Again, confirmation or even negation of these findings is viewed as a positive outcome of the BSAF. Other significant information provided by code calculations includes the range of core composition whereby the debris final state can be determined. During recovery efforts, debris samples collected from different co-ordinates within the containment, as well as within the reactor vessel, can be chemically and metallurgically analysed as needed. The results of such analyses will either lend credibility to code calculations or provide needed information to further investigate areas where code improvements may be warranted. This too is viewed as a positive outcome of the BSAF.

Institute of Applied Energy, Japan.

BSAF meeting.

Advanced Thermal-hydraulic Test Loop for Accident Simulation

Following the Fukushima Daiichi accident, the Advanced Thermal-hydraulic Test Loop for Accident Simulation (ATLAS) project was proposed by the Korea Atomic Energy Research Institute (KAERI) to study design-basis and beyond-design-basis accidents in the ATLAS facility. The CSNI agreed to establish the project centred on the ATLAS experimental capabilities to validate code predictive capability and the accuracy of modelling.

The ATLAS project is based around a thermal-hydraulic integral effect test facility for advanced LWRs located in Korea. It was commissioned in 2006 and has been carrying out beyond-design-basis accident tests since 2012.

The ATLAS project investigates safety issues with tests that simulate:

- prolonged station blackout (SBO), including asymmetric, secondary active or passive cooling;
- small break loss-of-coolant accidents (SBLOCAs) during SBO, including reactor coolant pump (RCP) seal failure and steam generator tube rupture (SGTR);
- total loss of feed water (TLOFW), including anticipated transient without scram (ATWS) and additional multiple failure;
- medium break loss-of-coolant accidents (MBLOCAs), including risk-informed break size definition.

In addition, the experimental programme was devised to allow for an open test, which would be defined in consultation with project members and which could cover the above issues or other safety-relevant issues. This experimental programme, along with associated analytical activities, will allow members – both NEA and non-NEA member countries – to share knowledge that will help maintain or improve the technical competence of thermal-hydraulics for nuclear reactor safety evaluations.

The initial experimental programme was agreed in 2014-2015, and included the selection of a benchmark test. In October 2014, the operating agent, KAERI, performed the first experimental test in the test programme. This test involved simulating a multi-hour, prolonged SBO followed by the delayed introduction of passive water cooling. The test examined the effect on the flows around the coolant loop and the simulated reactor core. A second test simulating SBO with a small break loss-of-coolant accident has been completed and the partners have begun to receive the data from these later tests to allow further analytical work. The remaining tests to investigate other aspects of SBO, TLOFW and MBLOCAs have either been conducted in 2015 or will be completed in 2016.

Transient Tests Under Postulated Accident Scenarios

The Primary Coolant Loop Test Facility (PKL-2) project, which ran from July 2007 to December 2011, consisted of eight experiments carried out in the PrimärKreislauf (PKL) thermal-hydraulic facility, which is operated by Areva NP in Erlangen, Germany, together with side experiments conducted in the PMK facility in Budapest, Hungary, and in the ROCOM facility in Rosendorf, Germany. The experiments investigated safety issues relevant to current PWRs as well as for new PWR design concepts, and focused on complex heat transfer mechanisms in the steam generators and boron precipitation processes under postulated accident situations.

As there were still a number of open issues that would benefit from testing in the PKL facility, the CSNI authorised a follow-up project PKL phase 3, which began in April 2012. The PKL-3 tests investigate safety issues relevant for current PWR plants as well as for new PWR design concepts by means of transient tests under postulated accident scenarios and systematic parameter studies of thermal-hydraulic phenomena.

Good progress has been made on the test matrix for PKL-3. The first tests addressed current safety issues related to beyond-design-basis accident transients with significant core heat-up, i.e. SBO scenarios or LOCAs in connection with failure of safety systems. Without adequate accident management procedures, the postulated course of events would lead to a severe accident scenario with core damage. The tests have looked at the efficiency of accident management measures initiated late in the transient. In addition, the tests have been used to assess the performance of core exit temperature (CET) measurements which could be used as a criterion for the initiation of accident management measures involving emergency operating procedures and/or severe accident management measures.

Another area which has been investigated is events in cold shutdown (i.e. failure of residual heat removal [RHRS]), looking at the ability of countermeasures to suppress steam formation in the core, limit core inventory loss and heat-up, and allow for reactivation of RHRS. Findings from the former PKL and PKL-2 projects on thermal-hydraulic phenomena (e.g. pressure evolution following failure of RHRS or boron dilution) will be compared to the transient tests conducted with an open reactor coolant system (RCS).

Further tests cover subjects that had been begun during previous phases of the PKL project. In particular, they are extending already existing data bases on cool down procedures under asymmetric natural circulation, and on boron precipitation in the core following large-break LOCAs. In addition, some counterpart testing with other OECD projects (e.g. ATLAS and ROSA-2) is being proposed.

Hydrogen Mitigation Experiments for Reactor Safety

In light of the hydrogen release and explosions at Fukushima Daiichi units 1, 2 and 3, the CSNI authorised the Hydrogen Mitigation Experiments for Reactor Safety (HYMERES) project, which began in January 2013 and will run to December 2016. The objective of the project is to improve the understanding of the hydrogen risk phenomenology in containment in order to enhance its modelling in support of safety assessments that will be performed on current and new nuclear power plants. The project is supported by safety organisations and industry in Canada, China, the Czech Republic, Finland, France, Germany, India, Japan, Korea, Russia, Spain, Sweden and Switzerland. The knowledge gained from the HYMERES project will contribute to the improvement of SAM measures for mitigating hydrogen risks.

With respect to previous projects related to hydrogen risk, the HYMERES project introduces three new elements. First, it addresses realistic flow conditions to provide crucial information for the evaluation of the basic computational and modelling requirements (mesh size, turbulent models, etc.) needed to analyse hydrogen movement in an actual nuclear plant. Second, the project studies different combinations of “safety elements”, e.g. the thermal effects created by two passive autocatalytic recombiners (PARs), spray and cooler, spray and opening hatches operating simultaneously. In general, previous investigations have focused on the activation of one safety component (spray, cooler, PAR) and showed their benefits and drawbacks. Third, it examines system behaviour for selected cases for different reactor types. In certain reactors (e.g. various BWR, PWR or PHWRs designs), the hydrogen concentration build-up in the containment depends on the responses of different components in the system. Consequently, investigations for relevant safety system behaviour related to BWRs, PWRs or PHWRs is covered in the HYMERES project. To date, tests have been completed on the interaction of hydrogen jets with flow obstructions, on the effects of sprays and a cooler and on thermal stratification in a water pool.

Radiological protection

Since the 2013 NEA report on the Fukushima Daiichi NPP accident, the Committee on Radiation Protection and Public Health (CRPPH) has continued to assist the Japanese government, bringing international experience where requested, and learning from national and international responses to the accident. The committee’s focus since 2012 has been on the following areas: international aspects of off-site emergency management, post-accident management of food, post-accident stakeholder involvement, radiological protection science and management of occupational exposure in severe accidents.

International communication aspects of off-site emergency management

Experience during the Fukushima Daiichi NPP accident highlighted the need to reconsider approaches to information sharing and assessment, to making and co-ordinating protection decisions with regard to foreign nationals in the accident country, and to resource management for the accident country’s provision of information to foreign competent authorities and to international organisations.

During the early phase of the accident, verified plant and environmental status information was extremely limited. While some informal discussions were held among the competent national authorities of some NEA member countries, and some verified information was shared on the IAEA Unified System for Information Exchanger (USIE) system, there were no pre-established pathways for informal conversations to share information, experience or thoughts regarding accident assessment or governmental recommendations. Pre-established processes and structures to informally share such information are being studied by NEA member countries to more broadly share understanding of the quickly evolving, prevailing circumstances.

The early phase of the accident also involved many governments making recommendations to their embassies and foreign nationals in Japan with regard to protective actions to follow. Again, while some informal discussions on the nature of the accident's progression, and of national protective action recommendations, did take place among some NEA member countries, there were no pre-established agreements that national recommendations could be co-ordinated, and no mechanisms for such co-ordination to be undertaken. Member countries are working with the NEA and IAEA on mechanisms to develop more co-ordinated decisions and recommendations, or at least a better understanding of their rationale, to facilitate building or rebuilding public confidence in governmental decisions.

These issues illustrate the extremely high level of foreign government interest that a nuclear emergency situation in any country can generate. The number of formal and informal international inquiries challenged the capabilities of Japanese authorities and technical organisations to quickly respond, and in English. While the focus of responsibilities of Japanese experts certainly remained on addressing Japanese safety issues, the need for foreign governments to address their own protection questions and issues demonstrated that the consideration of international needs should be more significantly addressed in national emergency plans. Member countries are working to more directly include this aspect in emergency plans.

Finally, member countries are revisiting their emergency and crisis management plans. In particular, some member countries are revisiting the flexibility of their pre-identified emergency planning zones, the rationale for evacuation and planning for special evacuations (e.g. hospitals, prisons, etc.), and their criteria for lifting evacuation orders.

Stakeholder involvement in recovery

The role of members of the affected public in recovery from a significant radiological contamination event has been clearly demonstrated by the Fukushima Daiichi NPP accident. Individuals quickly begin to actively collect their own radiological information, both personal dose data and environmental dose-rate data, using detector systems purchased independently, or provided by local officials or local/university experts. Such independently collected information tends to be more detailed than "official" survey information, and more specifically addresses stakeholder focus areas. However, it tends to replace governmental survey data, which may be distrusted. It is also not necessarily easily understood in the context of overall risks, and it tends to be collected in a somewhat isolated fashion, such that comparison and experience exchange is difficult. NEA member countries have been reviewing their preparations for recovery in the context of supplying instrumentation, training in its use and explanation of its meaning. Significant resources are necessary for effective actions.

As part of planning for this preparation, NEA member countries are investigating the shift of decision making from central authorities to local municipalities and individuals as an accident situation stabilises and moves to recovery. In particular, this shift in decision making will require governmental infrastructures (e.g. regular whole-body counting, health check-ups, instrument calibration, and continuing informational meetings) to adjust from making central decisions to supporting local decisions.

One of the most important decisions that individuals from affected areas will make is whether or not to remain in the area. Experience from the Fukushima Daiichi NPP accident suggests that this will apply equally to those from an area that was contaminated either heavily or lightly. Such individual decisions are difficult to make, and although they will most likely be informed by "an understanding of the radiological situation", they will be driven by broader social and economic factors. NEA member countries are considering this experience in terms of making preparations for performing and presenting detailed assessments of post-accident radiological circumstances, but are also focusing on approaches to rebuilding social and economic structures (e.g. schools, stores, hospitals, jobs, groceries, doctors, sports) after significant contamination events. Those choosing to stay in contaminated areas will need to feel that their "new normality" is in fact "normal". How to effectively support this social transition is a topic under discussion.

Post-accident management of food

The management of food from areas affected by the Fukushima Daiichi NPP accident presented local, regional, national and international challenges, and to one extent or another, these were felt by all NEA member country governments. Nationally, the Japanese government selected initial food and water criteria that were lower than values recommended internationally by Codex Alimentarius (Codex, 2006), and then in time it lowered these numbers. This challenged importing countries in terms of what values to use for acceptation, and what management controls (e.g. radiological measurement of incoming food items) should be used to release imported foods from Japan for their national markets.

The CRPPH formed a group to address these issues, and developed a comprehensive framework for post-accident food management, addressing the protection of those living in contaminated areas, those living in non-contaminated areas in the rest of the country, criteria for exporting food from the accident country, and criteria for importing food from the accident country. The CRPPH framework uses the same numerical criteria for all four of these protection circumstances. The numerical values of the protection criteria are based on the specific circumstances of the accident under consideration, and on the protection of those most at risk, i.e. those living in contaminated areas. The International Commission on Radiological Protection (ICRP) is revising its recovery recommendations (ICRP, 2009b) based on experience from the Fukushima Daiichi accident, and modelled on the CRPPH framework. The IAEA is producing a review of all of its standards for contamination in food, and is also referring to the CRPPH framework. Some NEA member countries are reviewing their recovery policies and planning with this in mind.

Radiological protection science

Radiological accidents can result in some individuals receiving extreme or even life-threatening doses. Such exposures are very unlikely, and it is extremely improbably that such high exposures would be received by more than a few workers or emergency response workers. However, radiological accidents can result in exposures to workers and to members of the public, during releases and long afterwards as a result of deposition.

The Fukushima Daiichi NPP accident confirmed, like the Chernobyl accident, that for a given group of individuals (e.g. those living in the same town), their individual annual doses will form a log-normal distribution. The high-end of the distribution will involve only a very few individuals, even in a large exposed population, and the peak of the distribution, as well as the vast majority of exposed individuals, will generally be in the 1 to 10 mSv in a year range.[3] While radiological protection science can with some certainty say that radiological risks exist above approximately 50 mSv of exposure, at levels below this, science cannot say if there is or is not a risk, and it cannot say what level of risk there might be if there is one.

In almost any large-scale radiological emergency, and certainly in the case of the Fukushima Daiichi NPP accident, the vast majority of individuals would receive low exposures in this scientifically unsure range. For this reason, it is important to explain to these individuals, in plain language, what we know and do not know about radiological risk, and to address their concerns as best possible with state-of-the-art scientific knowledge.

3. Note that most such populations will be in areas where long-term habitation is allowed, suggesting that virtually all levels are less than 20 mSv in a year.

In 1998 and in 2007, the CRPPH issued two reports summarising the state of the art in radiological protection science (NEA, 1998, 2007). It was agreed in 2013 that new and emerging epidemiological and radio-biological studies made it worthwhile to update the 2007 report. This report was finalised in 2015 and published in 2016. It includes a public and policy overview that states:

> While scientific evidence suggests that low doses of radiation may cause cancer, there is no clear scientific proof that this is true. To be cautious, regulatory authorities around the world assume that any dose, no matter how small, is a potential risk. It is important therefore to prevent unnecessary exposure, and particularly exposure caused by activities bringing little or no benefit. Most scientists believe that this assumption – as it is an assumption and not a fact – does not under or overestimate radiation risks, and regulations thus require that doses are kept as low as reasonably achievable (ALARA).

Management of occupational exposure in severe accidents

Safety and radiological protection are the most important factors for a safe response to a severe accident at an NPP. Experience of past accident responses has shown that comprehensive occupational radiological protection measures should be adopted in on-site emergency preparedness plans so as to ensure radiation exposures to emergency workers/responders are maintained ALARA. The Information System on Occupational Exposure (ISOE), recognising the importance of this topic, developed a state-of-the-art report (NEA, 2014d) identifying best radiological protection management practices for proper radiological protection job coverage during a response to a severe accident. The following major issues were identified:

- On-site emergency response plans should address emergency worker/responder staffing, command and control, emergency facility design, emergency response procedures, enhanced radiological controls, including dose reference levels and instrumentation, on-site decision making, emergency worker/responder training and communications.
- Severe accident management training is imperative for all emergency workers/responders.
- Effective implementation of worker radiological protection during a severe accident may be significantly impacted by the plant's facility configuration and access controls. Properly designed and operated habitability controls are essential.
- State-of-the-art radiation detection equipment must be properly used to effectively detect external and internal exposure of emergency workers/responders in order to maintain their radiation exposures ALARA.
- Radioactive releases must be monitored and managed on-site, using robust monitoring equipment and engineering controls, to appropriately protect emergency workers/responders.
- Remote radiological monitoring, high-dose-rate detection equipment, and robotic/remote equipment are imperative when responding to a severe accident at a nuclear power plant.

Nuclear law

As indicated in this report, NEA member countries have undertaken actions with regard to nuclear safety, the organisation and function of nuclear regulatory bodies and radiological protection in the aftermath of the Fukushima Daiichi accident. However, the accident also made evident the importance for countries to be prepared to deal with the legal implications of a nuclear accident. The Fukushima Daiichi NPP accident affected the lives of tens of thousands of displaced citizens, resulted in very large economic loss and caused considerable environmental damage in the surrounding area. As of 21 August 2015, the operator of the Fukushima Daiichi NPP, Tokyo Electric Power Company (TEPCO), has had to manage some 2 452 000 applications for compensation and has paid out approximately JPY 5.2 trillion,[4] an amount which is expected to increase over time.

4. Approximately EUR 38 billion or USD 43 billion according to the applicable currency exchange rate as of 27 August 2015.

The Fukushima Daiichi NPP accident fully demonstrated that a clear and comprehensive legal framework is necessary to allow the operator of a nuclear installation and, if necessary, its government, to quickly react and adapt to the specific circumstances of an event in order to ensure timely and financially adequate compensation to victims.

Since the beginning of the nuclear industry, special regimes governing liability for nuclear damage suffered by third parties have been put in place, both at the international level through international conventions and at the national level through domestic legislation. These regimes have been largely adhered to by nuclear power generating countries, especially at the national level, but they have also been adopted by many non-nuclear power generating nations in an effort to ensure timely and adequate compensation of victims of nuclear accidents. These countries take the position that ordinary tort law is not well suited to deal with exceptional risks related to nuclear installations and have opted for regimes that are founded upon a series of basic principles.

At the international level, the relevant conventions are:

- the 1960 *Paris Convention on Third Party Liability in the Field of Nuclear Energy* ("Paris Convention") and the 1963 *Brussel Convention Supplementary to the Paris Convention* ("Brussels Supplementary Convention"), both of which were amended in 1964, 1982 and 2004 (the 2004 amendments have not yet entered into force);
- the 1963 *Vienna Convention on Civil Liability for Nuclear Damage* ("Vienna Convention"), which was amended by the 1997 *Protocol to Amend the Vienna Convention* ("1997 Vienna Protocol") (IAEA, 1963);
- the 1997 Convention on Supplementary Compensation for Nuclear Damage ("CSC") (IAEA, 1997).

The common basic principles underlying each convention are:

- *Strict liability*: The operator of a nuclear installation is strictly liable for any damage suffered by third parties resulting from a nuclear incident occurring at its installation or during the course of transport of nuclear substances to and from that installation; in other words, the operator is held liable regardless of fault, negligence or intention to harm.
- *Exclusive liability (or legal channelling)*: The operator of a nuclear installation is exclusively liable for any damage suffered by third parties resulting from a nuclear incident occurring at its installation or during the course of transport of nuclear substances to and from that installation. No person other than the operator may be held liable for such damage; all liability is "channelled" directly to that operator.
- *Limitation of liability in amount*: Unlike ordinary tort law rules under which there is no limit to the compensation amounts payable, the international conventions originally provided for a maximum amount of liability to be borne by the operator of a nuclear installation. However, the most recent instruments instead provide for a minimum liability amount, allowing states to adopt unlimited liability at their option. Several states, such as Germany, Japan and Switzerland, have adopted unlimited liability regimes.
- *Compulsory financial security*: The operator of a nuclear installation must financially secure its liability in order to ensure that, in case of a nuclear incident, funds will actually be available to pay the victims' claims for compensation. In most cases, the security is provided by the private insurance market, although it may take other forms approved by the state where the nuclear installation is situated.
- *Limitation of liability in time*: Claims for damage to property must normally be instituted within ten years from the date of the accident. As health-related illnesses caused by the emission of ionising radiation may not be perceptible until many years after the nuclear incident occurs, the legal period during which an action may be brought is a matter of great importance for the victims. The Paris Convention as amended in 2004 and the 1997 Vienna Protocol have extended this period from 10 to 30 years for loss of life and personal injury to the benefit of the victims of an accident.

- *Jurisdiction and applicable law*: Only the courts of the state in whose territory the incident has occurred will have jurisdiction. They will apply the relevant international convention and their own national law or national legislation to claims arising out of a nuclear incident. The law or legislation shall be applied to all matters both substantive and procedural, without any discrimination based on nationality, domicile or residence. Judgements rendered by the competent courts are to be enforceable in any state party to the same convention as the state whose courts have jurisdiction.

Although Japan was not a party to any of the international nuclear liability conventions at the time of the accident, its national legislation, the Act on Compensation for Nuclear Damage, conforms to the basic principles of these conventions.

Since the occurrence of the accident, the Japanese Delegation to the OECD has been providing briefings to each meeting of the NEA Nuclear Law Committee (NLC) on the progress and implementation of new legislative innovations to address the magnitude of the compensation claims. The committee has been examining both the legal framework and the actual implementation of Japan's compensation scheme in order to draw lessons for the benefit of the international community, holding dedicated sessions on the matter until 2013.

In order to provide useful insights to other national authorities and their experts on potential improvements to their own national legislative regimes, the Japanese government, in co-operation with the NEA, prepared a publication entitled *Japan's Compensation System for Nuclear Damage: As Related to the TEPCO Fukushima Daiichi Nuclear Accident* (NEA, 2012b). This publication gathers in one volume 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 NPP accident. It also includes several commentaries by Japanese experts who were actively and closely involved in the actual carrying out of that scheme.

The briefings provided to NLC members revealed that the existing Japanese legislation on nuclear third party liability, coupled with the innovative mechanisms adopted to supplement that legislation, had indeed fulfilled the purpose of allowing the nuclear operator, TEPCO, to compensate victims of the accident in a timely and adequate manner. In particular:

- The fact that TEPCO is strictly and exclusively liable under Japanese legislation means that victims need only to establish a causal link between the nuclear accident and the damage suffered, rendering their compensation much easier than under the application of ordinary tort law rules.
- The requirement under Japanese legislation that TEPCO maintain financial security to ensure the availability of funds allowed victims to start receiving compensation very shortly after the accident, even though the amounts paid out soon reached far more than the legally required financial security amount (JPY 120 billion[5]).
- A country such as Japan that provides for unlimited liability must be prepared to respond to the possibility that the liable operator may not have the financial capacity to compensate all victims. The Japanese Act on Compensation for Nuclear Damage had already envisaged that possibility by stipulating that where the damage amounts exceed the required financial security, and where the government deems it necessary, the government shall provide, with the prior approval of the National Diet, such aid as may be necessary to allow the operator to fully compensate all victims. In the case of the Fukushima Daiichi NPP accident, the government did just that, primarily by setting up, with 11 Japanese nuclear operators[6], the Nuclear Damage Compensation and Decommissioning Facilitation Corporation (the "Corporation") described below.

5. Approximately EUR 900 million or USD 1 billion according to the applicable currency exchange rate as of 27 August 2015.
6. Consisting of ten electric power generating companies and a nuclear fuel recycling company.

- The government holds 50% of the Corporation's shareholding and the nuclear operators hold the other 50%. The Corporation's purpose is to provide financial support to such nuclear operators in case they face nuclear damage compensation obligations beyond their required financial security amount. Such financial support is provided either through the Corporation's reserves, which are funded by compulsory annual contributions paid by the nuclear operators holding a stake in the Corporation, or, if the reserves are insufficient, through government bonds granted to the Corporation. In the latter case, the Corporation will be obliged to reimburse the government bonds, normally by means of compulsory annual contributions, and additional specific annual contributions, paid by the concerned operator to the Corporation. However, in order to benefit from any additional financial support, the nuclear operator making the request must prepare, in co-ordination with the Corporation, a special business plan which demonstrates both business rationalisation and management accountability.
- To facilitate the compensation procedure and minimise potential disputes over entitlements and amounts, both the nuclear operator and the victims have received guidance on the types of damage that may be compensated and the corresponding amounts for a given type of damage. Pursuant to the Japanese Act on Compensation for Nuclear Damage, a committee of experts known as the Dispute Reconciliation Committee for Nuclear Damage Compensation has issued several sets of "Guidelines" beginning as early as April 2011 and extending up to December 2014, to define the types of nuclear damage and to assess the appropriate compensation for a given type of damage. Even though such guidelines are not legally binding upon either TEPCO or the victims, compensation has been paid out according to their terms in a generally uncontested manner.
- The Dispute Reconciliation Committee for Nuclear Damage Compensation has also established a mediation procedure, which aims to provide prompt and smooth dispute resolution between victims and TEPCO outside of court. As of 21 August 2015, 0.7% of the disputes regarding compensation (17 317 cases) have been submitted to the mediation process, and 70% of the cases have been successfully settled.

Since the Fukushima Daiichi accident, the international community has moved towards encouraging broad adherence to the international nuclear liability conventions with the goal of achieving a global nuclear liability regime.[7] Broader adherence would lead to greater harmonisation of national nuclear liability and compensation schemes, and thus promote 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 which may be affected by a nuclear accident falling within the scope of that regime (NEA, 2014f). This would, in turn, provide greater certainty both to nuclear industry investors and suppliers as well as to the general public regarding which country's courts have exclusive jurisdiction to hear nuclear damage claims, which country's laws shall apply to the adjudication of such claims and in which countries judgements for compensation may be enforced. In addition, depending on the applicable convention, increased compensation funds may become available to victims through the operation of a supplementary international fund, such as is provided for under the Brussels Supplementary Convention or the CSC.

7. The General Conference of the IAEA endorsed in September 2011 an Action Plan on Nuclear Safety ("IAEA Action Plan") to strengthen the global nuclear safety framework (IAEA document GOV/2011/59-GC(55)/14 available at www.iaea.org/About/Policy/GC/GC55/Documents/gc55-14.pdf; see also *Nuclear Law Bulletin*, No. 88, www.oecd-nea.org/law/nlb/). The IAEA Action Plan calls upon member states "to work towards establishing a global nuclear liability regime that addresses the concerns of all states that might be affected by a nuclear accident with a view to providing appropriate compensation for nuclear damage", and "to give due consideration to the possibility of joining the international nuclear liability instruments as a step towards achieving such a global regime". As directed by the plan, the IAEA International Expert Group on Nuclear Liability (INLEX) made recommendations in June 2012 to facilitate the achievement of such a global regime (available at ola.iaea.org/ola/documents/ActionPlan.pdf). In addition, the Joint Statement on Liability for Nuclear Damage signed by France and the United States in August 2013 (available in English and French in the *Nuclear Law Bulletin*, No. 92, www.oecd-nea.org/law/nlb/), the G20 Leaders' Declaration of September 2013 (available at www.g20.org/English/Documents/PastPresidency/201512/P020151225709417239707.pdf), and the Franco-Russian Nuclear Power Declaration signed in November 2013 encourage multilateral co-operation towards achieving a global nuclear liability regime (available in English and French in the *Nuclear Law Bulletin*, No. 92, www.oecd-nea.org/law/nlb/).

Given the importance of the matter, the NEA Steering Committee held a policy debate on "Progress Towards a Global Nuclear Liability Regime" during its April 2014 meeting (NEA, 2014f). At the conclusion of the debate, the Steering Committee stressed the importance of achieving greater globalisation and harmonisation of nuclear liability regimes in order to ensure adequate and timely compensation of damage to persons and property resulting from a nuclear accident, and to promote consistent treatment of potential victims and operators worldwide.

In particular, the Steering Committee noted the benefits of adhering to one or other of the international nuclear liability regimes, and more particularly to the enhanced regimes such as the Paris Convention as amended in 2004, the 1997 Vienna Protocol and the CSC. It encouraged NEA member countries with nuclear power programmes and other consenting countries to adhere to one of the enhanced nuclear liability regimes and to adopt consistent legislation, if they have not already done so. It also encouraged already existing Paris Convention or Vienna Convention member countries to join the efforts to establish a more global nuclear liability regime by adhering to the Joint Protocol Relating to the Application of the Vienna Convention and the Paris Convention, and/or to the CSC, if they have not already done so. The Steering Committee noted the importance of ensuring an adequate legal framework to make the necessary funds available to compensate victims in case of a nuclear accident, while ensuring that the operator assumes the primary financial responsibility for compensation. Finally, the Steering Committee invited NEA member countries to continue drawing lessons from the Japanese experience in order to improve their own nuclear liability legislation and to ensure that they are prepared to manage the practical aspects of claims processing and administration.

Since the Fukushima Daiichi accident in 2011, several countries have adhered to one or other of the international nuclear liability conventions, among them Japan, which joined the CSC on 15 January 2015. To date, 24 out of the 31 NEA member countries have adhered to one of these conventions. Australia, Austria, Iceland, Ireland, Luxembourg and Korea currently remain non-Convention countries; Canada signed the CSC on 3 December 2013, and is expected to ratify it in the very near future.

Conclusions

Continuing enhancement of safety

Since the publication of *The Fukushima Daiichi Nuclear Power Plant Accident: OECD/NEA Nuclear Safety Response and Lessons Learnt* (NEA, 2013c), member countries have continued to seek lessons from the accident at the Fukushima Daiichi nuclear power plant (NPP). The report examined prompt actions and analyses at national levels, as well as international engagement to ensure safety. NEA member countries have continued to take appropriate actions to maintain and enhance the level of safety at their nuclear facilities, and thus nuclear power plants are safer now because of actions taken since the accident.

Ensuring safety is a continual process, which evolves as we learn through operating experience and research. Safety is the prime responsibility of the operator, with the regulator's goal to ensure that operators continuously improve and make NPPs safer. The continued operation of nuclear power plants requires that their robustness to extreme situations be reinforced beyond-design-basis safety margins, and many of these improvements have been implemented or are in the process of being implemented. While an external event (an earthquake-induced tsunami) caused the Fukushima Daiichi accident, the actions that have been taken around the world to make NPPs safer are applicable to any type of event, man-induced or naturally occurring.

Effective implementation of safety improvements

While NEA member countries have been able to discuss the same lessons learnt from the Fukushima Daiichi accident and the outcomes sought are very similar, there are nonetheless different avenues being taken to achieve the goal of enhancing safety, and preventing and mitigating potential accidents.

Unique natural conditions exist in member countries, in particular with regard to potentially extreme natural events; different national regulatory requirements, for example, for the prevention and mitigation of severe accidents; various approaches to and applications of periodic safety reviews in order to continuously improve safety; and different types and generations of NPPs. Since national standards or safety requirements, as well as the actually implemented safety measures, are country-specific and reflect operating experience from the particular country or regulatory practices within the country, member countries are not necessarily starting from the same point of departure. Differences in the priorities and implementation of schedules for safety improvements exist among member countries.

Using operating experience and risk insights

Lessons learnt concerning operating experience have been disseminated internationally, particularly in relation to the main initiators and conditions that have been observed during the Fukushima Daiichi accident. The accident did not reveal any unknown initiators, sequences or consequences. However, the combination and the severity of initiating events had never occurred before, and the evolution of the accident in three different units simultaneously was also new.

The accident at the Fukushima Daiichi site demonstrated that while existing operating experience feedback systems provide a good tool to provide lessons learnt and help prevent the recurrence of events, operating experience combined with risk insights can provide an even greater source of potential improvement as demonstrated in the course of real events.

The timely implementation of NPP operating experience is a continuous challenge for both regulators and operators. The challenge is to identify precursor events and the subsequent lessons learnt, and then to implement the related actions to enhance plant safety and prevent recurrence.

Strengthening regulatory frameworks

National safety frameworks have been and are being further strengthened to enhance governmental frameworks and update regulations, including through reinforcing the independence of regulatory bodies. The principle of regulatory independence, in particular the effective separation between the functions of the regulatory body and those of any other body or organisation concerned with the promotion or use of nuclear energy, is fundamental and requires vigilance to ensure it is maintained.

Some member countries have reviewed, and other member countries are in the process of reviewing, their regulatory frameworks and are making changes as appropriate to update their legislation so as to reflect lessons learnt from the Fukushima Daiichi accident. One example is the emphasis on ensuring that a clear and comprehensive legal framework exists to allow the operator of a nuclear installation – and its government, if necessary – to quickly react and adapt to the specific circumstances of an event in order to ensure timely and financially adequate compensation to victims.

Much has been done by member countries in benchmarking and continuously improving their nuclear safety frameworks and regulations: this has included activities on accident management, crisis communication, precursor events, defence in depth, regulatory effectiveness, safety culture and regulation of new reactors. International co-operation is also increasing with greater participation in benchmarking of effective regulatory practices and exchanges of information.

A long-term learning process supported by safety research

As was the case with the Three Mile Island and Chernobyl accidents, implementation of lessons learnt from the Fukushima Daiichi accident and the continuation of related research activities are long-term actions that will evolve into the future as regulators and the nuclear industry continue to learn from the accident.

While near-term, higher priority lessons learnt are currently being addressed, our knowledge will expand as the Fukushima Daiichi units are decommissioned. Efforts such as the NEA Senior Expert Group on Safety Research Opportunities Post-Fukushima (SAREF) and the NEA Benchmark Study of the Accident at the Fukushima Daiichi Nuclear Power Station (BSAF) have already provided invaluable insights concerning severe accident progression and the current status of reactors in all three units that experienced core melt. Research continues into accident progression, recovery and the human factors involved in severe accident response. Important information is emerging from post-accident recovery efforts at the Fukushima Daiichi nuclear power plant.

The human element as an essential aspect of safety

Human and organisational factors and safety culture are essential to all aspects of nuclear safety, from design, construction and operation to the response to potential events or accidents. Both licensees and regulatory bodies identified these as relevant issues to be addressed in the post-Fukushima Daiichi accident assessment. The human element has a considerable impact on all levels of the defence-in-depth concept.

Work carried out by the NEA and its member countries on both the characteristics of an effective nuclear regulator and on regulatory safety culture have been recommended for benchmarking, peer review, and for training and development of regulatory staff.

Several NEA member countries have initiated a broad consideration of safety culture characteristics, including human and organisational factors. These initiatives include specific safety culture programmes that focus on attitudes towards safety, organisational capability, decision-making processes and the commitment to learn from experience. Going forward, the NEA and its member countries recognise that nuclear safety will benefit from continuing work in areas such as safety culture, and human and organisational factors.

Emergency management and the long-term commitment of resources

The accident at the Fukushima Daiichi site demonstrated the challenges involved when managing the consequences of a large-scale accident. As time progressed, radiological and social consequences became increasingly evident, while decisional responsibilities were shifting from central government to regional and local governments, and to affected individuals. Approaches to address the complexity generated by such long-lasting circumstances needs to be considered and included in national planning.

Moreover, the resources needed to manage an emergency on the scale of the accident at the Fukushima Daiichi nuclear power plant have proven to be considerable. Non-accident countries, even those not directly affected, expended significant resources on understanding the rapidly evolving situation so as to support recommendations on how to best protect expatriate populations in Japan, to address issues of people and cargo arriving from Japan and to manage food emanating from Japan. The Japanese government was challenged by the need to expend significant resources to address the accident situation, and simultaneously dedicate resources to formally and informally address questions from other countries and from international organisations. Emergency management planning should thus take into account the Japanese experience in terms of the training and resources required to be appropriately prepared to manage the collection and flow of information.

Enhancing stakeholder involvement and public communication

Involvement of stakeholders (local authorities, industry, non-governmental organisations, government officials and the public) in decision making is appropriate and advisable to enhance the credibility, legitimacy, sustainability and final quality of regulatory and off-site emergency management decisions. In addition, proactive outreach to stakeholders in regular communications (i.e. in non-accident situations) is highly desirable to improve their understanding in times of crisis.

Some member countries have further developed their policies on transparency, openness and involvement of stakeholders in the regulatory process, providing a window into the regulatory decision-making process. Different country-specific practices and regulatory requirements reflect more general practices within each individual country.

Experience during the Fukushima Daiichi NPP accident highlighted the need to reconsider approaches to information sharing and assessment, both domestically and internationally. The experience reaffirmed that regulators and governments should be effectively communicating with their stakeholders to ensure that all aspects of safety in relation to nuclear facilities are understood. To achieve this goal, regulators need to continue improving their communication strategies, as well as the implementation of such strategies.

International co-operation as a key factor in continuous safety enhancement

International co-operation provides a forum for regulators to work together to share and analyse data and experiences, gain consensus and develop approaches that can be applied within each country's regulatory process. International co-operation also provides a platform for peer regulators to encourage vigilance in ensuring NPP safety and avoiding the complacency that contributed to the accident at Fukushima Daiichi. Regulatory authorities from NEA member countries are working together internationally to share information and actions taken in order to improve their regulatory frameworks and NPP safety. The NEA provides an effective forum for co-operation on both medium and longer-term issues in its specific task groups, working parties and expert groups, as well as through joint international safety research projects.

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Annex I

Links provided by countries regarding safety improvements and safety research

NEA countries	National website links for safety improvements and research activities
Belgium	www.fanc.fgov.be/fr/page/nucleaire-stress-tests/1838.aspx www.fanc.fgov.be/nl/page/stress-tests-nucleaires/1838.aspx
Canada	www.cnsc-ccsn.gc.ca/eng/resources/fukushima/index.cfm www.cnl.ca/en/home/resources/fukushima.aspx
Czech Republic	www.sujb.cz/aktualne/detail/clanek/fukusimska-havarie-rok-pote/ http://otazky-fukusima.cvrez.cz/
Finland	www.stuk.fi/stuk-valvoo/ydinturvallisuus/fukushima-selvitykset www.stuk.fi/documents/12547/256417/national-action-plan_stress-tests_Finland_dec2014.pdf/1b780e73-d0ee-4890-a625-275e97584895 www.vtt.fi/inf/pdf/technology/2015/T213.pdf (several projects, see e.g. pages 376-386) http://safir2018.vtt.fi/ (several projects)
France	www.french-nuclear-safety.fr/Inspections/European-stress-tests www.irsn.fr/EN/publications/thematic-safety/fukushima/Pages/overview.aspx
Germany	www.bmub.bund.de/en/topics/nuclear-safety-radiological-protection/nuclear-safety/response-to-fukushima/ www.grs.de/en/fukushima
Hungary	www.oah.hu/web/v3/HAEAportal.nsf/D016E68896B8A0DCC1257DC4004ED0E7/$FILE/National%20Action%20Plan%20reviewed.pdf www.oah.hu/web/v3/HAEAportal.nsf/web?openagent&menu=04&submenu=4_3
Japan	www.nsr.go.jp/english/regulatory/index.html
Korea	www.kins.re.kr/en

Mexico	www.cnsns.gob.mx/seguridad_nuclear/Documentos/NationalReport-Mexico2012.pdf
Netherlands	http://english.autoriteitnvs.nl/topics/fukushima
Russia	http://en.gosnadzor.ru/international/Post-Fukushima/
Slovak Republic	www.ujd.gov.sk/ujd/www1.nsf/$All/9C6092082174BCDFC1257CB300475068
Slovenia	www.ursjv.gov.si/si/info/posamezne_zadeve/fukushima/ www.ursjv.gov.si/en/info/posamezne_zadeve/reports/
Spain	www.csn.es/en/pruebas-de-resistencia www.csn.es/home
Sweden	www.stralsakerhetsmyndigheten.se/In-English/About-the-Swedish-Radiation-Safety-Authority1/News1/New-report-to-the-EU-on-work-following-the-stress-tests/ www.stralsakerhetsmyndigheten.se/Publikationer/Rapport/Sakerhat-vid-karnkraftverken/2015/201527-APRI-8-Accident-Phenomena-of-Risk-Importance-En-lagesrapport-om-forskningen-inom-omradet-svara-haverier-under-aren-2012-2014/
Switzerland	www.ensi.ch/en/topic/fukushima-action-plan/
United States	www.nrc.gov/reactors/operating/ops-experience/japan-dashboard.html
European Commission	www.ensreg.eu/EU-Stress-Tests/Follow-up http://cordis.europa.eu/projects/home_en.html

Annex II

List of abbreviations and acronyms

BSAF	Benchmark Study of the Accident at the Fukushima Daiichi Nuclear Power Plant (NEA)
BWR	Boiling water reactor
CRPPH	Committee on Radiation Protection and Public Health (NEA)
CNRA	Committee on Nuclear Regulatory Activities (NEA)
CSNI	Committee on the Safety of Nuclear Installations (NEA)
DiD	Defence in depth
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
LOCA	Loss-of-coolant accident
MCCI	Molten-core-concrete interaction
NEA	Nuclear Energy Agency
NLC	Nuclear Law Committee (NEA)
NPP	Nuclear power plant
OECD	Organisation for Economic Co-operation and Development
PAR	Passive autocatalytic hydrogen recombiner
PHWR	Pressurised heavy water reactor
PSA	Probabilistic safety assessment
PWR	Pressurised water reactor
SAM	Severe accident management
SAMGs	Severe accident management guidelines
SAREF	Senior Expert Group on Safety Research Opportunities Post-Fukushima (NEA)
SFP	Spent fuel pools

TEPCO	Tokyo Electric Power Company (Japan)
UHS	Ultimate heat sink
VVER	Russian light water reactor
WENRA	Western European Nuclear Regulators Association
WGAMA	Working Group on Analysis and Management of Accidents (NEA)
WGRISK	Working Group on Risk Assessment (NEA)

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Five Years after the Fukushima Daiichi Accident: Nuclear Safety Improvements and Lessons Learnt

Countries around the world continue to implement safety improvements and corrective actions based on lessons learnt from the 11 March 2011 accident at the Fukushima Daiichi nuclear power plant. This report provides a high-level summary and update on these activities, and outlines further lessons learnt and challenges identified for future consideration. It focuses on actions taken by NEA committees and NEA member countries, and as such is complementary to reports produced by other international organisations.

It is in a spirit of openness and transparency that NEA member countries share this information to illustrate that appropriate actions are being taken to maintain and enhance the level of safety at their nuclear facilities. Nuclear power plants are safer today because of these actions. High-priority follow-on items identified by NEA committees are provided to assist countries in continuously benchmarking and improving their nuclear safety practices.

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