IAEA Report on

Strengthening Research and Development Effectiveness in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant

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IAEA REPORT ON STRENGTHENING RESEARCH AND DEVELOPMENT EFFECTIVENESS IN THE LIGHT OF THE ACCIDENT AT THE FUKUSHIMA DAIICHI NUCLEAR POWER PLANT

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FOREWORD

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In response to the accident at the Fukushima Daiichi nuclear power plant, IAEA Member States unanimously adopted the Action Plan on Nuclear Safety. Under this Action Plan, the IAEA Secretariat was asked to organize International Experts Meetings to analyse all relevant technical aspects and learn the lessons from the accident. The International Experts Meeting brought together leading experts from areas such as research, industry, regulatory control and safety assessment. These meetings have made it possible for experts to share the lessons learned from the accident and identify relevant best practices, and to ensure that both are widely disseminated.

This report on Strengthening Research and Development Effectiveness in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant is part of a series of reports covering all the topics dealt with in the International Experts Meetings. The reports draw on information provided in the meetings as well as on insights from other relevant IAEA activities and missions. It is possible that additional information and analysis related to the accident may become available in the future.

I hope that this report will serve as a valuable reference for governments, technical experts, nuclear operators, the media and the general public, and that it will help strengthen nuclear safety.

EDITORIAL NOTE

CONTENTS

1. INTRODUCTION

Following the accident at the Fukushima Daiichi nuclear power plant (the Fukushima Daiichi accident), the IAEA Director General convened the IAEA Ministerial Conference on Nuclear Safety in June 2011 to direct the process of learning and acting upon lessons to strengthen nuclear safety, emergency preparedness and radiation protection of people and the environment worldwide. The Conference adopted a Ministerial Declaration on Nuclear Safety, which, inter alia, requested the Director General to prepare a draft Action Plan[1]. The draft Action Plan on Nuclear Safety (the Action Plan) was approved by the Board of Governors at its September 2011 meeting,[2] and was subsequently unanimously endorsed at the 55th regular session of the IAEA General Conference on 22 September 2011. The purpose of the Action Plan is to define a programme of work to strengthen the global nuclear safety framework.

The Action Plan includes 12 main actions. One of the actions is focused on communication and information dissemination, and includes six sub-actions, one of which mandates the IAEA Secretariat to "organize international experts meetings to analyse all relevant technical aspects and learn the lessons from the Fukushima Daiichi nuclear power station accident".[3]

Another action is focused on the effective utilization of research and development (R&D). This action requests relevant stakeholders, with the assistance of the IAEA Secretariat, to conduct, utilize and share R&D as appropriate, to the benefit of all Member States.

This International Experts Meeting (IEM) on Strengthening Research and Development Effectiveness in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant was organized in cooperation with the OECD Nuclear Energy Agency (OECD/NEA) at IAEA Headquarters in Vienna from 16 to 20 February 2015. The IEM was attended by over 150 experts from 35 Member States and 5 international organizations representing nuclear power plant operating organizations, research institutes, nuclear reactor vendors, nuclear regulatory bodies, and technical and scientific support organizations (TSOs).

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[1] Declaration by the IAEA Ministerial Conference on Nuclear Safety in Vienna on 20 June 2011, INFCIRC/821, IAEA, Vienna (2011), para. 23.

[2] Draft IAEA Action Plan on Nuclear Safety, Report by the Director General, GOV/2011/59-GC(55)/14, IAEA, Vienna (2011).

[3] Ibid., p. 6.

The objective of the IEM was to provide a forum for experts from Member States and international organizations to exchange information and experience related to R&D work undertaken in the light of the Fukushima Daiichi accident. This forum aimed to assist Member States in planning and implementing R&D activities in nuclear safety, technology and engineering for existing nuclear power plants and in the design of new nuclear power plants. The IEM participants shared information on nuclear power plant technologies for coping with severe accidents and the current status of R&D activities related to managing severe accidents. This included the effectiveness of technologies to prevent and mitigate severe accidents. An IEM Chairperson's Summary was produced (see Annex A). The areas where possible international collaboration would be beneficial and/or necessary to prioritize R&D activities were also identified (see Annex B). The experts' papers and presentations are contained in the CD-ROM attached to this report (see Annex C).

1.1. BACKGROUND

The Fukushima Daiichi accident confirmed the need to consider the possible effects of extreme natural hazards beyond those taken into account in the design basis for a nuclear power plant. Such events can overwhelm a number of levels of defence in depth at nuclear power plants and invalidate expectations or assumptions on the availability of essential safety systems and accident propagation.

Effective R&D activities make an important contribution to ensuring the continued safe operation of nuclear power plants. These activities ensure the development and maintenance of an adequate technical basis for the design, licensing and operation of new nuclear power plants as well as the operating lifetime extension of existing nuclear power plants.

At the time of the Fukushima Daiichi accident, an extensive R&D database for severe accidents at water cooled reactors existed and was very useful for predicting and understanding the progression of accidents. Nevertheless, the Fukushima Daiichi accident highlighted some areas where the knowledge and understanding of issues associated with severe accidents and other related topics needed to be strengthened. In particular, there is a need to re-evaluate the effectiveness and preparedness of technical measures for severe accident prevention and mitigation, as well as improve and develop the necessary technologies for effective and efficient severe accident management.

In response to the Fukushima Daiichi accident, national regulatory bodies, operating organizations, design organizations and research laboratories undertook several actions, including: (i) assessing the design and licensing basis of existing nuclear power plants, (ii) examining the means to strengthen nuclear power plant design basis; (iii) assessing the likelihood and impact of extreme external hazards; (iv) identifying effects of severely abnormal nuclear power plant behaviour; and (v) assessing the response of nuclear power plants to severe accidents.

1.2. OBJECTIVE

The objective of this report is to highlight the lessons learned for strengthening the effectiveness of R&D in the light of the Fukushima Daiichi accident. The report summarizes the key points expressed by international experts during the IEM and other relevant IAEA activities, and identifies areas where further R&D is needed and where further international cooperation would be beneficial in the following key areas:

- R&D strategies after the Fukushima Daiichi accident;
- Measures to protect nuclear power plants against extreme external and internal events;
- Technologies to prevent and mitigate severe accidents;
- Severe accident analysis;
- Emergency preparedness and response;
- Post-accident recovery.

It is expected that this information will be useful to Member States and international organizations in planning and implementing R&D activities in nuclear safety.

2. INTERNATIONAL PERSPECTIVES ON NUCLEAR SAFETY R&D IN THE LIGHT OF THE FUKUSHIMA DAIICHI ACCIDENT

The Fukushima Daiichi accident highlighted several areas where knowledge and understanding of severe accidents need further strengthening. For example, unexpected events were observed during the accident such as hydrogen explosions in the reactor buildings and the lack of information on relevant safety parameters due to the unavailability of necessary instruments. Consequently, the international nuclear community is reviewing the current technical knowledge and activities related to nuclear safety R&D, and the need for future work in this area.

At the International Experts Meeting:

International perspectives on R&D were provided by experts from the IAEA Secretariat, the OECD/NEA, the Electric Power Research Institute (EPRI) and the European Technical Safety Organisations Network (ETSON).

The experts recognized the role of the IAEA Secretariat in assisting Member States in their R&D efforts by providing a platform for international cooperation. The IAEA Secretariat organized and conducted a number of meetings on R&D topics and is also preparing to launch further projects to promote international cooperation. The experts provided an overview of the activities carried out under different R&D frameworks.

The OECD/NEA continues to provide a framework for international cooperation on R&D activities for nuclear safety. Some of the key research projects being conducted within this framework include:

- The Benchmark Study of the Accident at the Fukushima Daiichi Nuclear Power Station (BSAF);
- The Hydrogen Mitigation Experiments for Reactor Safety (HYMERES);
- The NEA Primary Coolant Loop Test Facility (PKL3);
- The Advanced Thermal-hydraulic Test Loop for Accident Simulation (ATLAS).

Certain technical aspects of the Fukushima Daiichi accident that were analysed by EPRI were presented at the IEM, including the analysis of accident sequences using the severe accident computer code Modular Accident Analysis Program (MAAP). Analyses conducted by EPRI identified further R&D work that is required in order to better understand issues such as external hazards, accident tolerant fuels, long term storage of spent fuel and technologies applicable to decommissioning activities.

In Europe, ETSON has identified some gaps in R&D, including issues such as the quantification of accident source terms,[4] prevention of large releases of radioactive material during an accident, understanding of how dispersion of radioactive material released into the environment can be predicted or assessed, mitigation of hydrogen hazards, cooling of degraded reactor cores,

[4] The amount and isotopic composition of material released in an accident at a nuclear facility.

and knowledge of fuel behaviour when stored and during accidents at spent fuel storage facilities.

The experts highlighted the need for the various regional and national R&D activities to converge in order to support enhanced designs for nuclear power plants, to prevent the occurrence of accidents and to improve emergency preparedness and response arrangements. New nuclear build programmes will place a high demand on nuclear safety expertise worldwide. One of the important goals of today's R&D activities will be to strengthen and increase this pool of expertise for the future. The experts noted that the IEM was a good opportunity to discuss and exchange information to improve international collaboration and strengthen the effectiveness of R&D.

3. R&D STRATEGIES AFTER THE FUKUSHIMA DAIICHI ACCIDENT

Lessons Learned: The Fukushima Daiichi accident revealed the need to reconsider several aspects of existing R&D strategies to ensure that they continue to be effective.

The focus on R&D in the light of the Fukushima Daiichi accident is moving more toward mid- and long term priorities, most of which will be resource intensive. Positive benefits can be gained from sharing R&D efforts through effective coordination among the existing national, regional and international frameworks. The first IEM on reactor and spent fuel safety[5] recognized the critical role of R&D in forming the technical basis for operational strategies and updates to regulations and guidance. Furthermore, cooperation in the area of R&D is essential in order to avoid unnecessary duplication, to reduce costs and to facilitate the efficient use of expertise worldwide. An integrated approach is necessary for R&D, which can be accomplished through international partnerships and programmes and integrated experimental or theoretical approaches.

Improving the computer codes that are used for severe accident analysis could help to strengthen the capabilities for predicting the progression and consequences of an accident. This may lead to the development of effective measures for severe accident management. Severe accident analysis processes

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[5] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA Report on Reactor and Spent Fuel Safety in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant, IAEA, Vienna (2012).

can also be strengthened by taking better account of specific plant features, and by improving the modelling of nuclear power plant response to external hazards and their impacts on multi-unit sites. The physical limitations of the barriers for confinement of radioactive material, such as fuel cladding, the reactor pressure vessel and the containment structure, need to be better understood and the associated safety margins need to be re-evaluated.

The areas requiring further R&D to strengthen severe accident management arrangements include investigating the means to protect the integrity of the containment structure, strengthening reactor core cooling by preserving or creating a heat sink, managing a molten reactor core (corium), controlling the risk of hydrogen explosions and investigating containment venting strategies to minimize the radiological consequences of an accident. Further work is needed on the application of accident management arrangements to multi-unit nuclear power plant sites, spent fuel storage pools and the development of tools to support technical assessment during an accident.

The Fukushima Daiichi accident showed that unexpected accidents may occur and operators need to be prepared to successfully perform actions to mitigate their consequences. In light of this, relevant human and organizational factors need to be better understood to support and improve the performance of operating personnel under the stressful conditions associated with a severe accident.

At the International Experts Meeting:

The experts recognized that R&D continues to play a strong role in supporting nuclear safety, however economic pressures can limit the resources that are available. The experts also noted that national strategies and priorities for R&D are dependent on issues such as the type of nuclear power plant technology used and the national regulatory framework. The experts expressed the opinion that the focus of R&D should ideally be on solutions that are expected to be efficient even when faced with challenges that could not have been previously specified. It was suggested that a large number of international or regional organizations are providing similar inputs into R&D activities, which may reduce their overall effectiveness. The issues raised during the discussions included the need for:

- A strategy for R&D on a national or international level;
- Alignment of R&D priorities among Member States and international organizations;
- International guidance on R&D strategies, prioritization and use of results;
- Further international coordination of R&D activities.

The experts emphasized that maintaining adequate R&D programmes needs to be a shared responsibility of both national and international organizations. The benefit of international collaboration in R&D could lead to sharing the cost of experimental work, providing better quality results and supporting the implementation of results into the national regulatory framework. The experts considered that cooperation is essential to securing continued availability of research facilities and expertise.

The experts reported on new R&D projects underway to improve the knowledge of severe accident phenomena and to validate accident mitigation strategies. Many of these projects are taking place at the regional and national levels, including:

— Regional projects to investigate properties and behaviour of nuclear fuel under normal and abnormal conditions, including severe accidents, reactor core damage and release of radioactive material from damaged fuel;
— National projects on severe accident phenomenology, the development of analytical models and computer codes, analyses of beyond design basis accidents for specific nuclear power plants and the development of accident management strategies.

One expert at the meeting presented examples of the BWR Owners Group[6] R&D activities that are focused on the identification of safety margins at existing nuclear power plants. Introducing improvements that make full use of these safety margins will have a significant impact on safety. In this regard, important considerations were given to equipment qualification, material performance and interpretation of instrument readings. The BWR Owners Group's R&D included the identification of equipment failure and important safety functions through alternative means, such as the use of portable equipment. For severe accident mitigation, the BWR Owners Group recommended an approach based on thorough knowledge of plant systems and performance, accident phenomenology and symptoms, predictions of analytical methods and expert opinion.

[6] Nuclear power plant owners groups are organizations dedicated to providing cooperation, mutual assistance and exchange of information for the successful support, development, operation and maintenance of specific types of nuclear power plants. Examples of such groups are the CANDU, BWR and WWER owners groups.

4. MEASURES TO PROTECT NUCLEAR POWER PLANTS AGAINST EXTERNAL AND INTERNAL EVENTS

Lessons Learned: The Fukushima Daiichi accident highlighted the need for further R&D activities to strengthen measures to protect nuclear power plants against external and internal events as well as to consider the impact of such events, also occurring simultaneously, on multi-unit nuclear power plant sites.

There is a need for further R&D efforts to focus on the impact of extreme external events such as earthquakes and flooding. In particular, the impact of potential combinations of extreme external events need to be taken into consideration. These include events that may have a very low probability of occurrence but may be associated with very large consequences.

The Fukushima Daiichi accident highlighted the need for further work on the application of probabilistic safety assessment (PSA) techniques to a combination of external events. Such events may not be independent and the probability of their simultaneous occurrence may be higher than the probability of their occurrence in isolation. Further development of the models and methods to address seismic related issues is needed to ensure that seismic hazard estimates are appropriate and sufficiently conservative.

The identification of the dependencies between external hazards needs further investigation to avoid assumptions of independence so that these hazards can be properly taken into account in the PSA methodology. There is also a need to improve the application of the PSA methodology when dealing with extended periods of time, including long term station blackout and loss of ultimate heat sink. The application of PSA to multi-unit nuclear power plant sites and spent fuel pools is needed, as well as the consideration of human performance under severe accident conditions.

At the third IEM on protection against seismic and tsunami hazards[7], the experts proposed that future research activities on safety margin assessment for nuclear power plants under the impact of multiple hazards need to address improved analytical modelling capabilities. The experts also noted the need to further develop tools for assessing multi-unit sites under the impact of correlated multiple hazards induced by complex natural event scenarios. In addition, experts recognized that methodologies and tools need to be developed for calculating safety margins for multiple correlated hazards using a probabilistic approach.

[7] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA Report on Protection against Extreme Earthquakes and Tsunamis in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant, IAEA, Vienna (2012).

At the International Experts Meeting:

Measures to enhance defence in depth at existing nuclear power plants

The experts discussed activities carried out to reassess the design basis of existing nuclear power plants, including the means for strengthening defence in depth and for making the different levels of defence in depth more independent.

The need to further improve the safety of existing nuclear power plants requires resources to conduct the necessary R&D and to introduce or ‘backfit’ the necessary safety improvements. The experts reported on the R&D efforts that are focused on measures to improve safety by decreasing the frequency of accidents that could lead to core damage and a large release of radioactive material.

Several examples were provided during the IEM of the review and updating of regulatory guides. In Finland, several regulatory guides applicable to nuclear power plant design, PSA, risk management and emergency preparedness arrangements have been reviewed and updated. Proposed improvements to the Olkiluoto-1 and Olkiluoto-2 nuclear power plants relate to high and low pressure coolant injection and spent fuel interim storage. In addition, in the case of a multi-unit accident, the availability of mobile equipment and supplies of fresh water have been increased.

In the United States of America, the results of R&D have led to changes in regulatory requirements for a reliable hardened containment venting system for BWR Mark-I and Mark-II nuclear power plants.

In Japan, Units 6 and 7 of the Kashiwazaki-Kariwa nuclear power plant, have increased the tidal embankment to 15 metres above sea level, and watertight doors have been installed to safety significant areas to preclude inundation. Additional fire detection devices and fire proof or fire retardant materials have been installed and DC power supply has been enhanced.

Investigation of opportunities for further R&D

The experts presented key areas where R&D is considered necessary to further strengthen the robustness of nuclear power plants against external and internal events.

The R&D activities necessary to improve the understanding of the risks from external hazards is being addressed by EPRI. These activities include seismic fragility analyses[8], external flooding analyses and human reliability

[8] Seismic fragility of a component or system is defined by a curve that gives conditional probability of failure for a given value of a seismic input motion parameter.

analyses for external events. In addition, EPRI has also examined methods for assessing the risk of flooding, and is undertaking activities to provide guidance and tools to evaluate the risk of damage from high winds.

The experts reported that the knowledge and understanding of seismic hazards has improved significantly since the licensing of earlier nuclear power plants. This has, in some cases, resulted in increased estimates of seismic hazards relative to the design basis of these nuclear power plants. Further development of assessment models and methods is needed in order to more accurately address seismic related issues. For example, additional research is required to improve the understanding of the transfer of motion from near surface soil and rock to the nuclear power plant structures during seismic events. Improved methodologies are needed for performing soil structure interaction calculations that also take into account the uncertainty associated with these calculations. Methods are also being developed to support PSA through seismic fragility estimates that utilize the available design data.

Experts from Germany described a methodology to perform a comprehensive site specific PSA for the effects of a range of internal and external hazards on spent fuel storage and nuclear power plants in a variety of operational states. The methodology involves a systematic consideration of internal and external hazards and their potential combinations. The approach has been successfully applied for extending a Level 1 PSA[9] for an internal fire hazard with site specific external hazards, and to the spent fuel storage pool during post-operational shutdown. Future plans involve applying the methodology to Level 2 PSA[10].

The experts emphasized the importance of R&D to understand the causes and consequences of equipment failure from both internal and external events. An expert from France presented one example related to investigating the consequences of the operation of analogue converters[11] exposed to fire and smoke. The consequences of these events can significantly affect safety, as electrical cables are used in nuclear power plants for electrical power distribution to control plant systems and relay plant monitoring information to the operators. Temporary and permanent electrical failures of analogue converters were experienced during the fire tests owing to thermal stress and exposure to soot and smoke.

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[9] Level 1 PSA includes the assessment of plant failures leading to determination of the frequency of core damage.

[10] Level 2 PSA includes the assessment of containment response, leading, together with Level 1 results, to the determination of frequencies of failure of the containment and release to the environment of a given percentage of the reactor core’s inventory of radionuclides.

[11] Analogue converters are used to convert input signals from measurement instruments to output signals for data acquisition and control systems.

The experts noted that internal events at nuclear power plants have, in general, been comprehensively analysed and safety measures introduced to eliminate high risk scenarios. The key challenge is to focus on high risk external events and the ability to determine their initiating frequency with sufficient accuracy. There is sparse data available in historic records on the frequency of external events, and prehistoric knowledge from paleoseismology research can be used to supplement such data. A related challenge is understanding to what extent PSA results can be used, given the large uncertainties associated with external events and the limitations of PSA. There is also limited information on human performance under extreme conditions and on equipment fragility during extreme events.

The perspective of the BWR Owners Group on the benefit of PSA was presented at the IEM. It was considered that PSA was a useful tool to identify the dominant risk scenarios for a nuclear power plant. These scenarios can then be addressed by developing severe accident management procedures that consider what equipment would be available and what actions could be taken to mitigate the consequences of an accident. The experts considered that it is important to undertake R&D on severe accident phenomena so that more refined PSA can be performed to understand the progression of severe accidents and support the preparation of emergency procedures and operator training.

The experts emphasized the importance of taking into account, where possible, the uncertainties associated with mitigation actions. Examples of avoiding uncertainties include eliminating potential criticality issues during the flooding of a damaged core by using borated water, and limiting the water flow rates to minimize hydrogen generation.

5. TECHNOLOGIES TO PREVENT AND MITIGATE SEVERE ACCIDENTS

Lessons Learned: Continual R&D efforts are necessary to develop robust measures for core cooling and containment venting that can be implemented even under unexpected conditions.

The IEM on reactor and spent fuel safety[12] highlighted the importance of both preventing and mitigating severe accidents. In particular, the experts stated that:

> "The application of the defence in depth concept should be improved to clarify how to focus safety measures on both the prevention of accidents and the mitigation of accident consequences should an accident occur. In particular, the mitigation measures to ensure containment integrity should be strengthened."

The measures for core cooling at Fukushima Daiichi were not sufficient to prevent severe damage to the fuel in the reactor cores in Units 1–3. The Fukushima Daiichi accident has stimulated R&D activities and the further development of technologies for preventing and mitigating severe accidents.

Important lessons have been learned regarding the needs and capabilities to prevent and mitigate accidents and this has led to significant safety enhancements being introduced at existing nuclear power plants. R&D on preventive and mitigating measures needs to take into account the needs of nuclear power plant operators for the preparation of procedures and guidelines such as emergency operating procedures and severe accident mitigation guidelines.

Many existing nuclear power plants were built to earlier standards which did not require that beyond design basis accidents, including those involving severe core damage, be addressed in the design. Such accidents could result in excessive pressure increases in the containment that could cause leaks or even containment failure. The design basis for the containment at that time included the temperature and pressure conditions that could arise from a large loss of coolant accident, providing the emergency core cooling system and the containment cooling system remained operable. However, if these systems would not function, the containment pressure could increase, resulting in the loss of containment integrity from steam, hydrogen and other gases. Similar failures could result from long term station blackout, as experienced at the Fukushima Daiichi nuclear power plant.

Accident mitigation is very important for some of the early nuclear power plants, particularly those with small containment buildings. If containment pressurization is not mitigated during a beyond design basis accident, it could fail, as containments built at that time were not designed to maintain their integrity during accidents involving severe core damage.

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[12] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA Report on Reactor and Spent Fuel Safety in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant, IAEA, Vienna (2012).

At the International Experts Meeting:

Several participants presented R&D activities and the technologies that focus on preventing and mitigating severe accidents. These technologies can be broadly categorized into the following areas:

— Measures to prevent and mitigate core damage;
— Measures to maintain containment integrity;
— Measures to prevent hydrogen explosions;
— Instrumentation for safety related parameters and monitoring equipment;
— Measures to suppress radioactive material release.

Improvement and development of existing or new accident mitigation technologies

Strengthening severe accident mitigation at existing nuclear power plants has been the main focus of attention following the Fukushima Daiichi accident. Several examples were provided during the IEM. In the United States of America, the FLEX strategy provides reliable backup supplies of equipment for electrical power and cooling capability in order to prevent severe accidents. For example, pumps, generators, battery banks and battery chargers, compressors, and hoses are stored at locations away from the nuclear power plant to provide emergency power and water for reactor and spent fuel pool cooling. The FLEX strategy can also provide capability for accident mitigation in the event of severe core damage.

A strategy similar to FLEX involving emergency mitigation equipment has been adopted for existing nuclear power plants in Canada. The results of analyses by the CANDU operators and the CANDU Owners Group show that the large inventory of water in the CANDU nuclear power plants' coolant and moderator allow for valuable time for actions to protect the core from melting and damaging the reactor vessel.[13] All CANDU nuclear power plants have tie-in points for electrical power and water to maintain core cooling. CANDU plants are also improving the capability for limiting hydrogen buildup to below explosive concentrations through the installation of passive auto-catalytic recombiner units and emergency filtered venting systems.

[13] INTERNATIONAL ATOMIC ENERGY AGENCY, Benchmarking Severe Accident Computer Codes for Heavy Water Reactor Applications, IAEA-TECDOC-1727, IAEA, Vienna (2013).

The experts agreed that a general issue to address by further R&D is the efficiency of filters and filter systems. At the meeting, a R&D project being carried out by the European Commission's PASSAM[14] project was described. The project is investigating the effectiveness of devices to mitigate the release of radioactive material to the environment in the event of an accident. The effectiveness of techniques such as sand bed filters and metallic pre-filters as well as high pressure spray and acoustic agglomeration systems, electric filtration systems and zeolite filtration systems are being examined. Experimental tests are underway, or being set-up, at relevant locations such as the Forsmark 3 nuclear power plant and the Paul Scherrer Institute in Switzerland.

Assessment of mitigation strategies through the analysis of nuclear power plant behaviour

The behaviour of nuclear power plants during an accident, and the effectiveness of prevention and mitigation strategies, could be predicted by computer codes such as MELCOR[15], MAAP[16] and ASTEC[17]. These computer codes can be used to predict the impact of scenarios, such as extended loss of AC power, and also to examine the impact of operator actions to prevent damage to the reactor core or containment structure.

Several advanced designs of water cooled nuclear power plants rely on in-vessel retention[18] of a molten core to avoid challenging the integrity of the containment structure during a severe accident. Although considerable experimental data has been developed to support analyses of in-vessel retention, uncertainties remain as to the effectiveness of the strategy. The experts noted the need for further R&D to be performed to reduce these uncertainties.

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[14] PASSAM: Passive and Active Systems on Severe Accident Source Term Mitigation project. The objective of the PASSAM project on source term mitigation is to enhance the performance of in-plant devices for source term reduction so that their decontamination efficiency is not jeopardized under any expected or unexpected conditions.

[15] MELCOR: Methods for Estimation of Leakages and Consequences of Releases. This code was developed by Sandia National Laboratory.

[16] MAAP: Modular Accident Analysis Program. This code was developed by Westinghouse Electric Company.

[17] ASTEC: Accident Source Term Evaluation Code. This code was jointly developed by the Institute for Radiological Protection and Nuclear Safety and the Gesellschaft für Anlagen und Reaktorsicherheit gGmbH.

[18] In-vessel retention is a severe accident management strategy based on flooding the reactor pressure vessel. This strategy is aimed at arresting the downward progression of a molten core.

A number of experts described passive safety systems for nuclear power plants such as removing heat from the reactor core by natural circulation of coolant.[19] Examples of passive systems for BWRs and PWRs were provided, such as prevention of hydrogen generation using alternative types of fuel cladding and passive autocatalytic recombiners. Also described were improvements to heat transfer from the lower external surface of the reactor vessel to support in-vessel retention, and evaluations of the effectiveness of external cooling water injection strategies.

Severe accident mitigation strategies for Mark I and Mark II BWR nuclear power plants have been, and are being, analysed using MELCOR and MAAP and the effects of operator actions have been evaluated. The analysis of an extended loss of AC power when DC power is available for a Mark I BWR has shown that:

- A combination of venting and water addition at appropriate times is required to maintain containment integrity.
- Water injection into the reactor pressure vessel or into the drywell minimizes releases of radioactive material.
- Timely injection of water can arrest core damage, reduce the release of radioactive material and prevent reactor pressure vessel failure.
- Vent cycling[20], particularly before reactor pressure vessel failure, can reduce the release of radioactive material.

The experts noted that for some nuclear power plant designs, there may not be sufficient time available to implement severe accident mitigation strategies to ensure the integrity of the containment without venting. This issue is currently being reviewed in the United States of America for Mark I and Mark II BWR containments. It was noted that in France, containment venting is not allowed during the first 24 hours of an accident, and it is allowed only if the associated radioactive releases are maintained below prescribed levels.

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[19] INTERNATIONAL ATOMIC ENERGY AGENCY, Passive Safety Systems and Natural Circulation in Water Cooled Nuclear Power Plants, IAEA-TECDOC-1624, IAEA, Vienna (2009).

[20] Vent cycling is the opening and closing the containment vent system during an accident scenario.

6. SEVERE ACCIDENT ANALYSIS

Lessons Learned: Increased attention needs to be given to R&D for severe accident management, both for existing nuclear power plants and for the design of future nuclear power plants.

National R&D initiatives need to be complemented by international collaboration, and, where possible, incorporated within existing frameworks. Examples of these frameworks are those of the European Commission and the OECD/NEA. Some challenges that these international collaborative projects need to consider include:

— Different risks for different sites;
— Different nuclear power plant reactor technologies and different severe accident management approaches;
— Different safety requirements and criteria;
— Different assessment methods such as probabilistic and deterministic methods.

Important efforts are underway for the use of severe accident analysis codes to support removal of fuel and core debris and decommissioning activities at the Fukushima Daiichi Nuclear Power Plant.

At the International Experts Meeting:

An expert from Japan presented the development of the Roadmap on R&D and Human Resources for Light Water Reactor Safety. The Roadmap will be an important means of introducing effective future safety improvements and clearly defining the roles of organizations involved in R&D.

An expert from China noted that the high level safety goals for severe accident prevention and mitigation measures need to be thoroughly considered in the design. In China, core damage frequency and large release frequency need to be assessed to be lower than 10^{-5}/reactor-year and 10^{-6}/reactor-year, respectively. For new nuclear power plants, the high level safety goal is to practically eliminate by design the possibility of large radioactive release. The introduction of the high level safety goals will promote R&D efforts in the areas of spent nuclear fuel storage and seismic safety assessments.

Severe accident computer code development and applications

Despite the significant amount of R&D, including the development of computer codes, uncertainties remain regarding the complexity of some of the phenomena associated with severe accidents.

The experts agreed that additional research on the effect of severe accident behaviour on the source term, and on hydrogen mitigation measures, is needed to expand the data sets for use in computer codes. Sharing of such data sets was strongly recommended by the experts to better examine the capabilities of the severe accident analysis codes. The efforts to advance severe accident analyses and further develop the severe accident modelling tools were reported at the IEM.

The MAAP computer code is being used to model the progression of the core melt process and to examine the influence of water injection into the reactor pressure vessel using portable equipment. In addition, MAAP is being used to predict the buildup of hydrogen in the reactor building. Such calculations are important to accurately predict the corium/debris relocation paths for the actual reactor configuration, and are critical for enhancing emergency procedures and guidelines and for supporting decommissioning.

The European severe accident management code ASTEC, developed by the Institute for Radiological Protection and Nuclear Safety of France and GRS of Germany to model BWR issues, is being improved for the application to severe accident management analysis of different types of nuclear power plants. Further validation of ASTEC models will be conducted for scenarios such as flooding of degraded reactor cores, pool scrubbing, hydrogen combustion and spent fuel pool behaviour. The next version will include new models for flooding of degraded reactor cores and improvements to the models for gas chemistry kinetics and corium coolability during molten core to concrete interactions. Comparisons with other computer codes such as MELCOR or MAAP will also be performed.

In Japan, the SAMPSON[21] severe accident analysis code has been used to predict the status of the reactor core materials in Fukushima Daiichi Units 1–3. Attention was given to important phenomena such as:

- The leakage of steam from the reactor pressure vessel through damaged safety relief valve gaskets;
- The buckling of in-core monitor guide tubes and control rod guide tubes, which would result in the release of steam into the drywell;

[21] SAMPSON: Severe Accident Analysis Code with Mechanistic Parallelized Simulations Oriented towards Nuclear Fields.

— The melting of guide tubes, which would result in corium release into the drywell.

The effectiveness of the high pressure cooling injection system was investigated, as well as the reactor core isolation cooling system, taking into account deterioration in their function.

The results of these calculations predict that around 90% and 97% of the reactor cores of Units 1 and 3 have relocated onto the pedestal floor below the reactor pressure vessel. The calculations predict that around 30% of the reactor core of Unit 2 has relocated into the lower plenum inside the reactor pressure vessel. The experts highlighted the need to have good knowledge of the functioning of safety systems, such as the high pressure coolant injection system and the reactor core isolation cooling system and leakage paths, to better understand the accident.

In Spain, the Research Centre for Energy, Environment and Technology (CIEMAT) has analysed the Fukushima Daiichi Units 1–3 accident sequences with the MELCOR computer code using data recorded during the accident. This analysis examined some of the computer code models, the performance of the safety systems during the course of the accident and the status of the Units 1–3 some 6 days from the beginning of the accident. Additionally, CIEMAT has also examined some of the uncertainties associated with the models that strongly influenced results.

Research on severe accident progression

The experts discussed the ongoing investigations that are being performed by TEPCO on issues associated with the progression of the accident. These investigations aim to provide further information on the condition of the reactor cores and the containment structures. The investigations will also provide the necessary inputs for decommissioning activities. Some specific issues that need to be addressed include:

— Determination of the cause of the reactor core isolation cooling system shutdown in Unit 3.
— Determination of the amount of water injected to the reactor by fire engines. It is still not clear how much water was injected because of bypass flows to possible paths other than to the reactor.
— Determination of the cause of the rise in reactor pressure following forced depressurization in Unit 2.

An expert from the Japan Atomic Energy Agency reported on studies to support planning and conduct of decommissioning activities, such as determining the extent of fuel damage and degradation processes, understanding the behaviour of the core structural materials and the pressure vessel, and release and migration of radioactive material. These studies include a look into the effects of sea water on coolant heat transfer, examination of core melting and degradation, and investigation of the behaviour of molten fuel falling into coolant.

An expert from France reported on R&D activities that were launched to provide further knowledge on spent fuel pools during loss of cooling. These activities include studies on the processes of convective flow of coolant under natural circulation during loss of cooling. The studies also examine air ingress into partially uncovered fuel assemblies, zirconium oxidation under air/steam mixture and the efficiency of spray systems to cool the fuel assemblies.

An expert from the Nuclear Regulatory Commission of the United States of America reported on a study of the risks and consequences of a postulated beyond design basis earthquake on the spent fuel storage pool for a Mark I BWR nuclear power plant. The structural analysis showed that the spent fuel pool under these conditions had a 90% probability of surviving the earthquake with no coolant leakage. The MELCOR computer code was used for the accident progression analysis, assuming a range of fuel loading patterns. It was predicted that radioactive releases could start from eight hours to several days after the start of a leak in the spent fuel pool if mitigation measures were unsuccessful. The expert considered that the likelihood of such releases and the associated risks are appropriately low.

The experts discussed severe accident management issues, and issues related to corium behaviour. They noted that severe accident management strategies require improved data related to the properties of materials that are specific to each nuclear power plant and new systems for accident termination or mitigation, such as core catchers, need to be considered.

An expert from the Republic of Korea reported on the investigations of corium interaction with penetration tubes in the lower portion of the reactor pressure vessel of a PWR. Penetration tube failure mechanisms can take two forms; tube ejection out of the lower head of the vessel and rupture of the penetration tube outside the vessel. Tube ejection may happen if the penetration tube weld strength degrades as the weld is exposed to temperatures as high as the weld melting temperature. Tube rupture assumes that the debris bed has melted the instrument tube inside the reactor vessel, and the melt migrates down into the tube to a location below the vessel wall where a tube failure can occur, thus breaching the pressure boundary.

An expert from Canada reported on the development of complementary design features, procedures and guidelines for the prevention and management of beyond design basis accidents and severe accidents at CANDU nuclear power plants. This included, for example, analysis of the effectiveness of various methods of cooling the reactor core, determining the options for ensuring in-vessel retention of corium and analysis of the response of the containment system during the accident, with and without the presence of passive containment filters. The results were used to develop emergency mitigating equipment guidelines and to improve severe accident management guidelines to include multi-unit sites, low power operations and spent fuel storage events.

An expert from Germany presented the analysis of a severe accident for a PWR as an example of reactor response to a station black out sequence with multiple safety system failures. The analysis provided an understanding of the relatively short time available to implement strategies to restore safety functions by providing backup power and cooling capability to stop the accident progression.

R&D on the means for predicting accident source terms

The experts discussed the source term prediction tools that are essential for assessing the consequences of severe accidents. These tools can support the diagnosis of the progression of the accident using measurements made in the environment.

An expert from the Japan Atomic Energy Agency described an analysis of the extent of reactor core damage and the releases of radioactive material from the Fukushima Daiichi accident. The results indicated that a significant amount of the radioactive iodine was released in elemental and organic forms. In addition, the amount of caesium iodide released in particulate form was predicted to be much lower than the elemental or organic iodine. These results were consistent with observations from environmental monitoring data in which the amount of gaseous (elemental and organic) iodine exceeded that of iodine in particulate form.

In France, source term evaluations were performed using ASTEC. Data from the Phébus FP[22] programme were used to test the validity of ASTEC results. The use of the Phébus FP data indicated that some results were not properly reproduced by existing models, particularly those related to fission

[22] The purpose of the Phébus FP was to improve the understanding of the phenomena occurring during a core meltdown accident in a light water reactor and to validate the computational software used to represent these phenomena in reactor safety evaluations.

product chemistry in the reactor coolant system and containment. Consequently, several experimental programmes were launched that focused on studying fission product release from the fuel and examining iodine and ruthenium chemistry inside the reactor coolant system and containment. The radionuclides of iodine and ruthenium are of particular interest as they make a significant contribution to the radiological consequences of an accident.

Details of this work were presented at the IEM, including the kinetics of chemical reactions involving iodine, oxygen and hydrogen and the impact of the presence of other elements, such as caesium, molybdenum, cadmium and boron, on iodine chemistry. The behaviour of iodine in the reactor coolant system during an accident is fairly well reproduced when compared with the Phébus FP data. The chemistry issues associated with ruthenium are currently being investigated within the NEA Source Term Evaluation and Mitigation (STEM) project.

The complex behaviour of iodine in the containment structure has been investigated using several computer codes. Several processes are not well understood, including the complex chemical equilibrium between gaseous organic and inorganic iodine compounds, adsorption of iodine on surfaces (such as paint) and the formation of iodine oxides and metallic aerosols. However, the effects of aged paints, the stability of iodine aerosols under irradiation and the impact of organic impurities remain to be fully quantified. This will be done through the STEM and the NEA Behaviour of Iodine (BIP) projects.

The experts noted the importance of further studies to improve the analysis of fission product transport. For example, there is a further need to investigate the effect of boron carbide on fission product transport and revaporization processes for boiling water reactors.

Human and organizational factors

The importance of human and organizational factors during a severe accident were discussed by the experts and the relevant issues included:

— Multi-unit accidents: The six nuclear power plant units at Fukushima Daiichi were affected to varying extents that caused the overall accident to follow multiple progression paths. This posed a severe challenge to accident management as the team for each unit faced different scenarios.
— Multi-unit interactions: There were several interactions between the nuclear power plant units that raised issues of prioritization in managing the accident, including hydrogen explosions on one unit that affected other units.

— Accident management experience: While the accident progressed in different ways at Units 1, 2 and 3, several common activities were necessary for these units. The experiences gained from performing these activities were exchanged between the management teams for each unit.
— Extreme working conditions: As a result of the loss of electric power and communication difficulties, the operators needed to carry out many activities under very severe conditions.

7. EMERGENCY PREPAREDNESS AND RESPONSE

Lessons Learned: R&D efforts are needed to harmonize rapid response strategies to nuclear or radiological emergencies at the national, regional and international levels. Harmonization of R&D will also contribute to improved emergency assessment and prognosis by supporting improved modelling of radionuclide transport and dispersion, and exchange of data and key information.

The Action Plan mandates the IAEA Secretariat to provide Member States, international organizations and the general public with timely, clear, factually correct, objective and easily understandable information during a nuclear or radiological emergency on its potential consequences, including analysis of available information and prognosis of possible scenarios based on evidence, scientific knowledge and the capabilities of Member States. The IAEA Response and Assistance Network (RANET)[23], as part of the IAEA's strategy for supporting the practical implementation of the Assistance Convention[24], aims to facilitate the provision of requested international assistance following a nuclear or radiological emergency, the harmonization of emergency assistance capabilities, and the relevant exchange of information and feedback of experience. R&D plays an important role in improving assessment tools which could be used by Member States to adequately respond to an accident and to exchange dynamic data during the course of an accident. The experts noted that the availability of radiation monitoring data plays an important role in the decision making process. Therefore, timely provision of high quality data is of utmost importance.

[23] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA Response and Assistance Network, EPR–RANET 2013, IAEA, Vienna (2013).

[24] Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency, INFCIRC/336, IAEA, Vienna (1986).

At the International Experts Meeting:

The experts noted that there are extensive challenges with respect to modelling the transport of radioactive material in the environment. For example, the transport of radioiodine in different chemical forms is complex, as is modelling of the effects of precipitation deposition of radioactive material. The experts emphasized the importance of having the means to conduct rapid assessment and prognosis during a nuclear or radiological emergency. The arrangements between the IAEA, the World Meteorological Organization and the Preparatory Commission for the Comprehensive Nuclear-Test-Ban Treaty Organization play an important role in information exchange during an emergency.

An expert from the World Meteorological Organization described the support provided in the framework of the Joint Radiation Emergency Management Plan of the International Organizations[25]. This support includes the provision of meteorological information and forecasts, atmospheric transport and dispersion model predictions, and the re-transmission of general emergency notifications to all national meteorological and hydrological services. Areas for future improvements and developments of support through the World Meteorological Organization include the following:

— The ability to provide high resolution atmospheric transport and dispersion model results to identify areas where there may be a high deposition of radionuclides;
— Reducing uncertainties inherent in the atmospheric dispersion and transport modelling predictions;
— Methods to deal with unspecified source terms.

Improvements to atmospheric transport and dispersion models have resulted in implementation of high resolution weather prediction modelling and data assimilation techniques. This takes better account of factors such as terrain and precipitation and can be used to support the deployment of radiation monitoring activities. Continued efforts are required to combine prognostic data and measured data in the early phase of an emergency. While high resolution predictions are needed to better coordinate radiation measurement activities, a seamless transition between the local and regional scale would ensure that predictions are consistent.

[25] INTERNATIONAL ATOMIC ENERGY AGENCY, Joint Radiation Emergency Management Plan of the International Organizations, EPR-JPLAN 2013, IAEA, Vienna (2013).

Arrangements between international organizations play an important role in effective information exchange during a nuclear or radiological emergency. Development work is underway to create international standards for data harmonization and exchange. The integration of existing frameworks for information exchange should be encouraged.

In one Member State, a centre for providing tools and expert staff for predicting and analysing the impacts of hazardous atmospheric releases was activated as part of response to the Fukushima Daiichi accident. This centre provided daily weather forecasts, estimates of possible doses in Japan for a range of hypothetical scenarios, predictions of potential plume arrival times and doses, and plume model refinement and source estimation based on meteorological analyses, atmospheric dispersion modelling and the available field data. Since the accident, new tools have been developed to improve response capabilities for nuclear power plant accidents. Future work could involve coupling atmospheric dispersion models with a severe accident analysis code.

In the early phase of an emergency situation, the ability to combine prognostic data and measured data is important in order to understand the radiological situation, to identify affected areas and to assess the radiation dose to the public and to emergency workers. On-line monitoring data from stationary and mobile radiation monitoring devices can generate nuclide specific ground contamination maps. In addition, data from airborne and vehicle monitoring can be integrated.

An expert from Germany described a research project to develop a computer code which estimates a source term based on radiological measurements in the environment of a nuclear facility during an accident. The computer code will calculate the source term from the measurements and provide a diagnosis of the plant state based on backward calculations.

8. POST-ACCIDENT RECOVERY

Lessons Learned: The circumstances resulting from severe accidents are usually unprecedented and unplanned. A number of challenges in the phase of post-accident recovery arise, particularly with regard to decommissioning a damaged reactor. Post-accident recovery activities will need considerable R&D effort, and international collaboration and information exchange in this respect is essential.

Decommissioning of reactors damaged in an accident, and removal of spent fuel and fuel debris, requires innovative engineering approaches and methods, and equipment that can be used under extreme and severe conditions. One of the lessons learned identified during the IEM on decommissioning and remediation[26] was that characterization is key to technical decision making, planning, engineering and conduct of activities. Obtaining information and data regarding actual conditions and characteristics is essential for post-accident cleanup and for proper planning for final decommissioning. It is therefore necessary to gather knowledge and information domestically and internationally for developing an overall strategy for retrieving fuel debris.

The important role of R&D in the preparation of the decommissioning of TEPCO's Fukushima Daiichi nuclear power plant was acknowledged by the IAEA in the third mission report[27]. The IAEA team acknowledged the continual efforts of the Government of Japan, TEPCO and other organizations on the development of a strategy and an integrated plan for decommissioning the Fukushima Daiichi nuclear power plant. Furthermore, the IAEA team acknowledged further progress in developing and implementing a comprehensive R&D programme to support the decommissioning works with the construction of advanced research facilities and the establishment of the International Research Centre for Reactor Decommissioning.

A follow-up IAEA mission[28] also highlighted the importance of research to form the basis for consideration of site specific remediation of the affected areas. The experts at the sixth IEM[29] noted that when modelling the movement of radionuclides through the environment, research is often needed to establish site specific parameters that will result in better predictions of the transport of radionuclides in the environment.

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[26] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA Report on Decommissioning and Remediation after a Nuclear Accident, IAEA, Vienna (2013).

[27] INTERNATIONAL ATOMIC ENERGY AGENCY, Mission Report: IAEA International Peer Review Mission on Mid-and-long-term Roadmap Towards the Decommissioning of TEPCO'S Fukushima Daiichi Nuclear Power Station Units 1–4 (Third Mission), IAEA, Vienna (2015), available at:
https://www.iaea.org/sites/default/files/missionreport130515.pdf

[28] INTERNATIONAL ATOMIC ENERGY AGENCY, The Follow-up IAEA International Mission on Remediation of Large Contaminated Areas Off-Site the Fukushima Daiichi Nuclear Power Plant, IAEA, Vienna (2013), available at:
https://www.iaea.org/sites/default/files/final_report230114.pdf

[29] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA Report on Radiation Protection after the Fukushima Daiichi Accident: Promoting Confidence and Understanding, IAEA, Vienna (2014).

Most of the research areas in post-accident recovery are very challenging and require long time periods for investigation and development. They are also resource intensive and require knowledge and expertise from different specialties. Collaboration and regular exchange of information and knowledge is therefore important for the success of this R&D work.

At the International Experts Meeting:

The experts discussed the major challenges posed by decommissioning the Fukushima Daiichi nuclear power plants' Units 1–4. The start of fuel debris retrieval from the damaged plants is planned for 2021. Given the limited information available on conditions at the damaged reactors, some experts expressed the view that the condition of the buildings will deteriorate and will become less stable with time. There is a need to find a middle ground between taking the time in order to gain more information for making sound decisions, and acting earlier, but with limited information for decision making.

Investigations into the location and condition of the fuel debris and the reactor internal structures will need to be performed prior to fuel debris retrieval. This will contribute to establishing the optimal method of fuel debris retrieval. Robotic techniques have been developed for conducting visual inspections inside the primary containment vessel and the reactor pressure vessel.

To support planning for fuel debris removal, methods for fuel debris cutting, remote operation and contamination prevention are being tested. Technologies for collecting, transferring and storing fuel debris, as well as for nuclear criticality control, have been developed. The use of robots for remote decontamination inside the buildings has significantly reduced the radiation levels inside the buildings.

The experts discussed the R&D efforts required to deal with the very large amount of radioactive waste resulting from the Fukushima accident. The need for large scale environmental remediation has triggered research to improve knowledge and understanding of radionuclide transfer in the environment. This research included deriving site specific parameters for the transfer of radionuclides in the environment in Japan to improve the prediction of dispersion of radionuclides in the biosphere.

The experts described three projects that address the transfer of radionuclides in the environment, including a study of the movement of caesium in forests, an examination of the radionuclides transferred from the terrestrial environment to the marine environment through rivers and a study to address the impact of the Fukushima Daiichi accident on the sea.

The Fukushima Daiichi accident demonstrated how emergency preparedness arrangements would benefit from the availability of an apparatus for treatment of contaminated waters that are generated through severe accident mitigation activities. The experts discussed the European approach to post-accident management of food and goods based on research conducted in the aftermath of the Chernobyl accident and Japan may be able to benefit from the findings of this research.

9. CONCLUSIONS

The IEM provided the opportunity to examine R&D strategies in the light of the Fukushima Daiichi accident, particularly those strategies directed at measures to protect nuclear power plants against internal and external events. The experts also discussed R&D for the technologies that prevent or mitigate severe accidents, the analysis of severe accidents, emergency preparedness and response, and post-accident recovery activities.

One focus of R&D is to reduce the uncertainties associated with severe accident phenomena or models. Experts worldwide are currently engaged in research on severe accident phenomena such as core melt behaviour, hydrogen production and control, molten corium to concrete interaction in the containment structures and fission product transport. These efforts will improve the understanding of the means to protect containment integrity, including containment venting and heat removal, and the understanding of the dispersion of radioactive material in the environment.

The IEM emphasized the need to strengthen the sharing of R&D results among all the Member States to improve awareness of the kinds of work being done in the different Member States. The IEM provided an opportunity to discuss the value of a platform for the continual exchange of information on R&D work and the key role the IAEA Secretariat can play in assisting Member States in their preparations to respond to severe accidents. The IAEA Secretariat was encouraged to continue providing a forum for discussing R&D related to nuclear safety and was recognized for having a central role in collecting and disseminating R&D information related to the Fukushima Daiichi accident.

The IEM recognized the important contribution that R&D activities can make toward strengthening the safety of nuclear power plants. While some R&D activities may take some time to be completed and fully implemented, they will ultimately lead to strengthening the measures to prevent accidents and to mitigating possible releases of radioactive material to the environment.

The IEM identified several areas for future R&D and international cooperation along with suggested approaches for sharing of information on R&D activities through international collaboration (see Annex A).

Annex A

CHAIRPERSON'S SUMMARY[1]

International Experts Meeting
Strengthening Research and Development Effectiveness in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant
16–20 February 2015, Vienna

A–1. BACKGROUND

The IAEA Action Plan on Nuclear Safety (the Action Plan) was unanimously endorsed by the Member States in September 2011 and set down 12 main actions and 39 sub actions with the aim of defining a programme of work to strengthen the global nuclear safety framework. The Action Plan addresses a number of different issues including assessing the safety vulnerabilities of nuclear power plants, strengthening emergency preparedness and response, strengthening the effectiveness of regulatory bodies and operating organizations, improving the international legal framework, infrastructure development and capacity building and research and development (R&D).

One of these actions requests the IAEA Secretariat to organize international experts meetings to analyse all relevant technical aspects and learn the lessons from the Fukushima Daiichi accident. In addition, another action addresses R&D and encourages all relevant stakeholders and the IAEA to utilize the results of research and development and to share them, as appropriate, to the benefit of all Member States.

In response to these two actions, the IAEA in cooperation with OECD/NEA organized an International Experts Meeting on the topic of Strengthening Research and Development Effectiveness in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant on 16–20 February 2015 at the IAEA Headquarters in Vienna, Austria.

[1] The opinions expressed in this Summary — and any recommendations made — are those of the Chairperson and do not necessarily represent the views of the IAEA, its Member States or other cooperating organizations.

This is the eighth in a series of IEMs that have been organized in the framework of the Action Plan. The first seven meetings dealt with the subjects of:

— Reactor and spent fuel safety;
— Enhancing transparency and communication effectiveness in the event of a nuclear or radiological emergency;
— Protection against extreme earthquakes and tsunamis;
— Decommissioning and remediation after a nuclear accident;
— Human and organizational factors in nuclear safety;
— Radiation protection after the Fukushima Daiichi accident: promoting confidence and understanding;
— Severe accident management.

In line with the approach for the previous IEMs, the IAEA has made the presentations available on the IAEA web site and will publish a report on strengthening R&D effectiveness, summarizing the key points, conclusions and recommendations of the meetings, in due course. This Chairpersons' Summary will be a part of that report.

A–2. OBJECTIVES OF THE INTERNATIONAL EXPERTS MEETING

The main objective of this IEM was to provide a forum for experts from Member States and international organizations to exchange information and experience related to R&D work undertaken in the light of the Fukushima Daiichi accident. The IEM was aimed to assist Member States in planning, implementing and collaborating their R&D activities in nuclear safety, technology and engineering both for existing nuclear power plants and in the design of future new nuclear power plants. The specific objectives of the IEM were to:

— Collect and disseminate information from Member States and international organizations on reactor technologies that are designed to cope with severe accidents, including those technologies already proven or under development;
— Share among Member States and international organizations the most recent information on R&D activities dealing with severe accidents;
— Discuss and assess the features and effectiveness of the technologies to prevent or mitigate severe accidents, as well as the challenges presented by these technologies;
— Identify and prioritize the R&D areas in which possible future international collaboration would be beneficial and/or necessary;

— Summarize the current status of R&D activities in Member States on severe accidents after the Fukushima Daiichi accident.

The meeting comprised an opening session, six technical sessions, one poster session and a closing session. The technical and poster sessions covered the topics of:

— R&D strategies after the Fukushima Daiichi accident;
— Measures to protect nuclear power plants against external and internal events;
— Technologies to prevent/mitigate severe accidents;
— Severe accident analysis;
— Emergency preparedness and response;
— Post-accident recovery.

The IEM was attended by approximately 150 experts from 35 Member States and 5 international organizations. The participants represented nuclear power plant operating organizations, research institutes, nuclear reactor vendors, nuclear regulatory bodies and technical support organizations (TSOs). The IEM featured 75 expert presentations from keynote speakers, invited speakers, contributing speakers and posters.

These presentations strongly contributed to a framework for open and informal discussions held throughout the course of the meeting and reflected the willingness of the experts in sharing their experiences, results, lessons learned and views on future R&D activities. They also pointed to areas where R&D activities in the aftermath of the Fukushima Daiichi accident may need to be strengthened and how more effective use of the results can be made. This could be carried out under the auspices of the existing and future international arrangements for collaboration, including those of the IAEA and OECD/NEA.

The IEM recognized the significant work done by the R&D community under the coordination of international organizations, such as the IAEA, OECD/NEA and the EC. In addition, it provided an excellent opportunity to take stock of existing activities and examine potential future collaboration in R&D in light of the Fukushima Daiichi accident.

A–3. LESSONS LEARNED AND RECOMMENDATIONS

The Fukushima Daiichi accident re-emphasized the need for the nuclear community to recognize the importance of properly considering low probability/high consequence beyond design basis accidents in the design and operation of nuclear power plants. The accident also highlighted the importance of R&D in analysing beyond design basis accidents and identifying potential prevention and mitigation measures.

It is important when identifying necessary safety related research that the underlying safety concerns that form the basis for the research are clearly identified. Specifically, the proposed safety research needs to identify how the results will be used to make decisions regarding the safety of both operating and future nuclear power plants.

In particular, it is recognized that probabilistic safety assessments can play a strong role in the identification of any future research needs. A probabilistic safety assessment can help identify what effect certain phenomena (such as core concrete interaction) could have on the overall risk posed by a nuclear power plant and the potential benefit if improved knowledge or models are available.

A–4. SUGGESTED AREAS FOR ADDITIONAL R&D AFTER THE FUKUSHIMA DAIICHI ACCIDENT

Research activities after the Fukushima Daiichi accident contribute to the resolution of scientific gaps in knowledge, phenomena, expertise, infrastructure, education and training. The process of identifying scientific gaps also needs to address what needs to be done at the national, regional or the international levels.

By extending its peer review services to the area of scientific and technical support capabilities, the IAEA could review the R&D infrastructure and capabilities of Member States to recommend improvements to support their nuclear programmes.

The following list of topics, without any order of importance, were identified as areas for either ongoing or for future R&D:

- Source term estimation, in particular, fast running tools for source term evaluation and inverse modelling;
- Rapid evaluation of direct atmospheric transport of radionuclides (in particular fission products);
- Accident tolerant fuels;
- Spent fuel pool and fuel assembly accident phenomenology;
- Fire hazards and their impact during severe accidents;
- Hydrogen generation, transport prediction and risk management;
- Alternative ultimate heat sink;
- Containment cooling and venting under severe accident conditions;
- Risk of breach of the containment by corium to concrete interactions;

— Multi-unit site risk assessment and risk management;
— Interaction of a molten corium jet with water;
— Degraded core cooling capability;
— Performance of passive safety systems;
— Innovative and robust instrumentation in absence of on-site power and in a harsh environment;
— Human and organizational factors, ‘centres of excellence’;
— Non-linear soil structure interaction effects on the calculation of seismic forces on components and structures;
— Development of multiphysics/multiscale simulation tools for severe accident analysis and their validation and verification;
— Ageing management;
— Innovative detector and techniques to locate the melted core in the reactor pressure vessel and in the containment (e.g. by the use of muons);
— Decommissioning related R&D, such as using data from the Fukushima Daiichi reactors to understand the behaviour of systems structures and components;
— Debris removal — robotics;
— High resolution weather forecasts;
— Reactor core damage progression;
— Instrumentation performance under severe accident conditions;
— Spent fuel pool under severe accident conditions.

A–5. SHARING OF INFORMATION ON R&D ACTIVITIES THROUGH INTERNATIONAL COLLABORATION

The IEM made clear that understanding the behaviour of nuclear power plants under a spectrum of accident conditions, including severe accidents, needs to be promoted for ensuring nuclear safety worldwide.

This meeting was a good opportunity to collect and share information on who is doing what and why (i.e. what is the final goal of the R&D programme/project at all levels from facility to international levels). Programmes for R&D related to the Fukushima Daiichi accident in many Member States have already been completed or are currently in progress. It was agreed that an outcome of this IEM was a starting point for further discussion identifying potential future R&D activities.

Additionally, safety improvements made in response to the Fukushima Daiichi accident need to be shared and appropriately made available to all Member States. In addition, it would be useful to identify research programmes and specialized facilities addressing beyond design basis accident related issues (including severe accidents, prevention and mitigation) particularly the programmes open to international collaboration. It is recommended to the IAEA to take the lead in both of these efforts.

The IAEA is requested to continue to organize meetings focusing on the evaluation of the performance engineered safety features, through balanced use of deterministic and probabilistic approaches, particularly the assessment of low probability yet high consequence events.

The IAEA needs to continue to strengthen the coordinated research programme framework and to ensure effective dissemination of research information to enhance nuclear safety worldwide.

The IAEA needs to continue to encourage networking and scientific cooperation between Member States. International coordination of research strategies needs to be a focus area between the IAEA, OECD/NEA, the EC and relevant R&D organizations, to maximize synergies and effectiveness of research activities.

This also requires the IAEA to provide a platform for closer cooperation worldwide of research organizations, regulators, designers, vendors, utilities, operators, TSOs and the different owners groups (such as BWR, PWR, CANDU and WWER) to exchange information and best practices, while respecting the different roles and independence of the various stakeholders/bodies.

A–6. INTEGRATE LESSONS LEARNED FROM THE FUKUSHIMA DAIICHI ACCIDENT INTO NEW R&D ACTIVITIES

In light of the lessons learned from the Fukushima Daiichi accident it is important to continue to:

(a) Develop and disseminate assessment tools that allow a rapid and reliable estimation of doses to the public after nuclear accidents;
(b) Provide better assurance that assessment tools can incorporate the results of monitoring of environmental media to improve predictions;
(c) Apply research results, and in particular Fukushima related R&D results, in ways that result in measurable improvements in safety;
(d) Encourage the publishing and wide dissemination of the results of R&D activities.

Research by regulatory bodies and/or their associated TSOs, is essential for providing sound technical bases for regulatory decision making. Cooperation and collaboration among regulatory bodies, utilities, TSOs and owners groups is also important for effective utilization of resources, and for maximizing the results in research led by the regulatory bodies. However, it was recognized at the IEM that this was not to be done at the expense of regulatory independence.

A–7. CONCLUDING REMARKS

In addition to the recommendations provided earlier in this report, the following are overarching conclusions:

— This IEM was considered as a good opportunity for discussing how to organize a platform for the continuous exchange of information. It was noted that the IAEA plays a crucial role in assisting its Member States to prepare their capability to respond to severe accidents.
— Many Member States have robust research programmes either underway, planned or completed that are designed to address issues highlighted by the Fukushima Daiichi accident.
— There are many areas where more R&D would be desirable and in many instances this is country specific. However, there are no major R&D gaps that require immediate international attention in the light of the Fukushima Daiichi accident.
— The IAEA needs to continue work with its Member States to continue to coordinate R&D activities to support their R&D efforts, along with OECD/NEA, the EC and other organizations.
— The IAEA was encouraged to continue to provide, with the assistance of the other international bodies, a forum for discussions on R&D for strengthening nuclear safety.
— The IAEA has a central role in collecting and disseminating Fukushima Daiichi related R&D information to Member States. Therefore, the IAEA is recommended to provide a summary of these ongoing research activities and document them in an appropriate manner.
— The IAEA needs to consider developing a programme to identify and address the needed R&D activities in the light of the Fukushima Daiichi accident.
— The Fukushima Daiichi accident will provide opportunities to the international community to strengthen long term research programmes to learn about severe accidents and associated decommissioning activities.

Annex B

RECOMMENDATIONS FOR FURTHER R&D AND INTERNATIONAL ACTIVITIES

B–1. RECOMMENDATIONS FOR FURTHER R&D

The experts considered recommendations and suggestions for further R&D and international collaborative R&D. Some examples of these are summarized in Table B–1 below.

TABLE B–1. RECOMMENDATIONS AND SUGGESTIONS FOR FURTHER R&D

Topics	Areas	Examples of recommended R&D activities
External and internal events	Assessment of external and internal events and the associated issues	Frequency of external events and their uncertainties Modelling of cliff edge effects Better understanding of effects of internal events (e.g. fires), and for internal events caused by external hazards
Technology development to prevent/mitigate severe accidents		Better understanding of the existing plant equipment and materials safety margins and their role in plant robustness Consideration of severe accidents during shutdown when the reactor pressure vessel is open, containment isolation may not be well maintained, and some equipment may be unavailable
	Measures for preventing severe accidents	Robust measures for reactor core cooling, depressurization and removing heat to the ultimate heat sink Accident tolerant fuels

TABLE B–1. RECOMMENDATIONS AND SUGGESTIONS FOR FURTHER R&D (cont.)

Topics	Areas	Examples of recommended R&D activities
	Measures for mitigating the consequences of severe accidents	Alternative ultimate heat sink Containment cooling and venting under severe accident conditions Measures for preventing hydrogen explosions both inside and outside the containment vessel
Severe accident analysis	Forensic analysis of the Fukushima Daiichi accident	Forensic analysis of the Fukushima Daiichi accident, addressing: systems functioning; corium/debris relocation paths; effect of suppression pool thermal stratification; and fission products behaviour Corrosion tests of spent BWR fuel in sea water and in deionized water Experimental and computational simulations to better understand the accident progression at Fukushima Daiichi
	Better understanding of accident progression (severe accident phenomenology)	Experimentation and analysis of in-vessel melt retention and ex-vessel corium cooling Examinations of reactor pressure vessel penetration tube failure mechanisms Hydrogen generation, transport prediction and risk management
	Severe accident analysis models and codes development including benchmarking	Improving severe accident analysis codes (scaling & improved understanding of uncertainties) Benchmarking of analysis codes against other codes and against results of experiments Improvements of safety assessment methods, models and tools including PSA, addressing key uncertainties and cliff edges
	Management of corium melt progression	Assessment of in-vessel retention strategies for existing and future reactors Ex-vessel corium cooling by top flooding

TABLE B–1. RECOMMENDATIONS AND SUGGESTIONS FOR FURTHER R&D (cont.)

Topics	Areas	Examples of recommended R&D activities
	Knowledge of the source term	Source term estimation; fast running tools for source term evaluation and inverse modelling in particular Re-emission processes from deposits on the reactor coolant system and on containment walls
	Spent fuel safety issues	Spent fuel pool and fuel assembly accident phenomenology Measures to enhance robustness of spent fuel cooling
Emergency preparedness and response (EPR)	Assessment and prognosis	Development of prognosis/diagnosis tools for accident consequences Rapid evaluation of direct atmospheric transport of radionuclides (in particular fission products) Means of combining measured data and prognostic data to understand a radiological situation in the early phase of an emergency
	Tools for determining the source term resulting from severe accidents and for establishing EPR	Improvement of atmospheric transport and dispersion models Modelling of release from multiple reactors at a site; complicated radionuclide mixes and long duration releases
Post-accident recovery	Longer term accident management and recovery (issues related to post-emergency phase)	Handling of contaminated water and solids Specialized equipment for use in a radiation environment Long term studies to improve knowledge and understanding of radionuclide transfer to the environment and improve the predicting models for emergency and post-accident situations

TABLE B–1. RECOMMENDATIONS AND SUGGESTIONS FOR FURTHER R&D (cont.)

Topics	Areas	Examples of recommended R&D activities
	Decommissioning of damaged reactors	Development of technologies for fuel debris detecting, removal, packaging, transfer and storage
		Development of robotics for direct inspection of the conditions inside the Fukushima Daiichi reactor pressure vessels and primary containment vessels
Common issues	Multi-unit sites and multi-site issues	Better understanding of safety issues concerning multi-unit sites and multiple sites
		Multi-unit site risk assessment and risk management
	Instrumentation and monitoring under severe accident conditions	Post-accident instrumentation for safety related parameters and monitoring equipment
		Innovative and robust instrumentation in the absence of on-site power and in a harsh environment
	Human and organizational factors	Systematic consideration of organizational performance and human factors in safe design, operation, maintenance and accident management
		Human performance and intervention under extreme conditions
		Issue of organization resilience to a major crisis

B–2. RECOMMENDATIONS FOR INTERNATIONAL COOPERATIVE ACTIVITIES

Many frameworks exist for promoting, coordinating and supporting R&D work. There is a need to avoid unnecessary duplication of effort and to assure optimum use of the existing infrastructure. Integrated approaches through international R&D partnerships lead to a more efficient use of resources and provide benefits by exploiting the expertise and research facilities that are available among different organizations.

While the needs for prioritization of R&D in each Member State can be different, there can be common areas of interest. The experts recommended that the IAEA Secretariat consider organizing a forum of experts to establish high level principles and guidance and means of prioritizing the R&D necessary for nuclear safety in cooperation with international organizations. To further assist Member States, the IAEA Secretariat could facilitate international cooperation on R&D and the sharing of results. It was also suggested at the IEM that the IAEA Secretariat consider leading the development of guidance on the roles and functions of R&D, and evaluate its effectiveness.

The experts recommended that to strengthen R&D effectiveness in the light of the Fukushima Daiichi accident, the IAEA Secretariat continue to share the lessons learned from the Fukushima Daiichi accident by disseminating technical information and updates on R&D status and trends. The experts recommended that the IAEA Secretariat continue to provide encouragement to its Member States to strengthen international collaborative R&D work through coordinated research projects, technical meetings and other fora to share information and to preserve knowledge on technologies to prevent and mitigate severe accidents.

The experts summarized the extensive severe accident studies carried out and identified the following questions to be addressed to obtain the best results from severe accident R&D:

(a) What are the remaining key issues or phenomena to be investigated and clarified to enhance accident analysis for beyond design basis accidents and spent fuel storage?
(b) What are the means to prioritize R&D issues for accident analyses?
(c) What issues are effectively and efficiently covered through international collaboration?
(d) What remains to be improved in severe accident modelling and severe accident computer codes, and what is needed for accident prognosis and diagnostic tools?
(e) What are the remaining issues related to:
    (i) Containment behaviour and quantification of the source term;
    (ii) Mitigation of corium melt progression;
    (iii) Spent fuel pool accident analysis;
    (iv) Human and organizational factors;
    (v) Management of post-emergency phases?

Regarding international cooperation on severe accident analysis, the experts pointed out the need for the following considerations:

- — Stronger interaction and better complementarity between international initiatives;
- — Promotion of international collaborations and exchanges on the topics that were not covered during the meeting;
- — Promotion of information sharing;
- — Identification of key issues for international cooperation;
- — Enhanced understanding of the Fukushima Daiichi accident progression, including the condition of core debris inside the reactor and containment vessels;
- — Making further progress toward source term modelling and evaluations;
- — Establishment of lessons learned from the Fukushima Daiichi accident regarding human and organizational factors.

Enhancements of international emergency preparedness and response require harmonization among decision makers and improvements to nuclear installation assessment capabilities, atmospheric transport and dispersion models, weather forecaster capabilities and measurement capabilities.

In the area of post-accident recovery, R&D plays an important role, and international cooperation is necessary. International cooperation is recommended for gathering knowledge and information to support the development of an overall strategy, including the associated technologies, for retrieving fuel debris and reactor internals from the damaged Fukushima Daiichi units. The experts agreed that a key issue for determining the procedures for recovery of fuel debris and reactor internals in the damaged Fukushima Daiichi reactors is the distribution of this material in the reactor and containment vessels. International cooperation in development and testing of techniques for debris removal from the Fukushima Daiichi nuclear power plant, the containment vessel and the reactor pedestals would be invaluable. The possibility of recriticality in the damaged reactors must also be addressed.

International cooperation in planning and conduct of decommissioning activities to obtain useful samples of corium and reactor materials for research analysis at different institutes would be very useful. Examination of samples of the damaged reactors and of the fuel debris and reactor internals from Fukushima Daiichi is recommended and would advance the global understanding of severe accidents.

At the experts meeting, international cooperation on the general topic of decommissioning and remediation was recommended.

The need for environmental remediation of large areas has triggered research on the long term evolution of contamination in different ecosystems, like in forests and in the sea. These are long term studies to improve the knowledge and understanding of radionuclide transfer to the environment and to improve the predicting models for emergency and post-accident situations. Earlier studies provide a starting point and international cooperation could be beneficial to build on the findings of those studies.

It would also be beneficial to share information between the Member States on the European approach to post-accident management of foods and goods, and the new management requirements that the European Union has adopted.

Annex C

CONTENTS OF THE ATTACHED CD-ROM

The following papers and presentations from the International Experts Meeting on Strengthening Research and Development Effectiveness in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant are available on the attached CD-ROM.

OPENING SESSION

Opening Remarks
M. Chudakov
Deputy Director General and Head of the Department of Nuclear Energy, International Atomic Energy Agency (IAEA)

Opening Remarks
D. Flory
Deputy Director General and Head of the Department of Nuclear Safety and Security, International Atomic Energy Agency (IAEA)

(**Keynote**) IAEA Activities under the Nuclear Safety Action Plan
G. Caruso
Special Coordinator, Nuclear Safety Action Team, International Atomic Energy Agency (IAEA)

(**Keynote**) Main Benefits from Half a Century of NEA Collaborative Projects in Nuclear Safety
N. Blundell
OECD Nuclear Energy Agency (OECD/NEA)

(**Keynote**) The Case for Global Research & Development Following Fukushima
N. Wilmshurst
Electronic Power Research Institute (EPRI), USA

(**Keynote**) Enhancing the Science Basis of Nuclear Safety and Radiation Protection: A Collective Change
J. Repussard
European Technical Safety Organisations Network (ETSON)

PRESENTATIONS

Session 0 (Monday): R&D Strategies after the Fukushima Accident

(**Keynote**) Research and Development Activities at NEA following Fukushima
B. Sheron
NEA Committee on the Safety of Nuclear Installations

Roles and Effectiveness of R&D in Support of Nuclear Safety
A. Viktorov
Canadian Nuclear Safety Commission (CNSC), CANADA

Post Fukushima R&D in the Framework of the European Union
G.B. Bruna
Institute for Radiological Protection and Nuclear Safety (IRSN), FRANCE

Safety Research Activities on Severe Accident Management in S/NRA/R after the Fukushima Daiichi Nuclear Power Plant Accident
K. Aono, H. Hoshi, A. Hotta and M. Fukasawa
Nuclear Regulation Authority (NRA), JAPAN

Nuclear Safety Research in Light of the Fukushima Daiichi Accident at the European Commission — Joint Research Centre
V.V. Rondinella, et al.
Joint Research Centre/European Commission (JRC/EC), EU

Representativeness of Beyond Design Basis Accidents List: How it can be Reached?
M. Lankin
Scientific and Engineering Centre for Nuclear and Radiation Safety (SEC NRS), RUSSIAN FEDERATION

BWROG Recommendations for Short and Long Term Research
J. Grubb, L. Hill, B. Williamson, C. Patel and P. Ellison,
Boiling Water Reactors Owners Group (BWROG), USA

CEA Post-Fukushima R&D Programmes on PWR Severe Accidents
C. Journeau, et al.
French Alternative Energies and Atomic Energy Commission (CEA), FRANCE

Session 1 (Tuesday): Measures to Protect Nuclear Power Plants against External and Internal Events

(**Keynote**) Actions to Protect Nuclear Power Plants against External and Internal Events and R&D Activities in Finland
L. Heikinheimo
Teollisuuden Voima Oyj (TVO), FINLAND

Current and Future Application of Seismic Research Activities at the NRC in Response to the Accident at the Fukushima Daiichi Nuclear Power Plant
J. Ake, J. Pires and C. Munson
Nuclear Regulatory Commission (NRC), USA

Electrical Failure during Nuclear Power Plant Cable Fires
L. Rigollet, P. Zavaleta, M. Piller and L. Audouin
Institute for Radiological Protection and Nuclear Safety (IRSN), FRANCE

Safety Measures taken at Kashiwazaki Kariwa Nuclear Power Station based on the Fukushima Daiichi Accident
T. Matsuo
Tokyo Electric Power Company (TEPCO), JAPAN

Recent Research on Hazards Probabilistic Safety Assessment
M. Röwekamp, H. Holtschmidt and M. Türschmann
Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) gGmbH, GERMANY

EPRI Risk and Safety Management Program: Research Priorities
S. Lewis
Electric Power Research Institute (EPRI), USA

Implementation of External Event Modeling in Advanced Probabilistic Safety Assessment Studies
L. Burgazzi
Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA), ITALY

Session 2 (Tuesday): Technologies to Prevent and Mitigate Severe Accidents

(**Keynote**) Technologies to Prevent and Mitigate Severe Accidents
M. Korsnick
Exelon Generation, USA

CAP1400 Core-melt In-vessel Retention Measure Design and Research
K. Cao
Shanghai Nuclear Engineering Research and Design Institute (SNERDI), CHINA

Automatic Safety Valve for Accumulator Depressurization (ASVAD): The Simple Answer to a Serious Problem
A. Laborda Rami
Automatic Safety Valve for Accumulator Depressurization (ASVAD), SPAIN

Assessment of the Mitigative Strategy using External Coolant Injection for the OPR-1000 Plant
S.Y. Park and K.I. Ahn
Korea Atomic Energy Research Institute (KAERI), REPUBLIC OF KOREA

Severe Accident Mitigation Strategies Considered for U.S. Mark I Boiling Water Reactors (BWRs)
E. Fuller, S. Basu and H. Esmaili
Nuclear Regulatory Commission (NRC), USA

The European PASSAM Project on Severe Accident Source Term Mitigation: Halfway Status
T. Albiol, et al.
Institute for Radiological Protection and Nuclear Safety (IRSN), FRANCE

Development of Inherently Safe Technologies for BWRs
K. Kitou, et al.
Hitachi Ltd, JAPAN

Application of Technologies in CANDU Reactors to Prevent/Mitigate the Consequences of a Severe Accident
L. Gilbert
Bruce Power, CANADA

Session 3 (Wednesday): Severe Accident Analysis

(**Keynote**) Roadmap on R&D and Human Resources for Light Water Reactor Safety in Japan: Nuclear Safety Visions and Technical Basis Reconstruction after the Fukushima Accident
N. Sekimura
University of Tokyo, JAPAN

Lessons Learned from Fukushima on Modeling of Severe Accidents and Future Research Directions for MAAP
R. Yang, D. Luxat and R. Wachowiak
Electric Power Research Institute (EPRI), USA

Code for European Severe Accident Management (CESAM): Overview on the EC Project on ASTEC Code Improvement and Applications
M. Sonnenkalb, H. Nowack and N. Reinke
Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) gGmbH, GERMANY

Major Influential Phenomena on the Accident Progressions of the Fukushima Daiichi Nuclear Power Plant
M. Naitoh
Institute of Applied Energy (IAE), JAPAN

The ROSA-SA Project on Containment Thermal Hydraulics
T. Yonomoto, Y. Sibamoto, M. Ishigaki and S. Abe
Japan Atomic Energy Agency (JAEA), JAPAN

The DENOPI Project: A Research Program on SFP under Loss of Cooling and Loss of Coolant Accident Conditions
N. Trégourès, H. Mutelle, C. Duriez and S. Tillard
Institute for Radiological Protection and Nuclear Safety (IRSN), FRANCE

Consequence Study of a Beyond Design Basis Earthquake Affecting the Spent Fuel Pool for a US Mark I Boiling Water Reactor
H. Esmaili, S. Coffin and R. Lee
Nuclear Regulatory Commission (NRC), USA

(**Keynote**) Applying Probabilistic Safety Assessment for CAP1400 and Additional R&D after the Fukushima Accident
W. Zhan
Shanghai Nuclear Engineering Research and Design Institute (SNERDI), CHINA

Recent Progress in Source Term Research and Evaluations with the ASTEC Code
D. Jacquemain, D. Vola, L. Cantrel, K. Chevalier-Jabet and C. Mun
Institute for Radiological Protection and Nuclear Safety (IRSN), FRANCE

Development and Application of Methodologies for Source Term Analysis
Y. Maruyama
Japan Atomic Energy Agency (JAEA), JAPAN

Research Needs for Improvement of Severe Accident Management Strategies at Czech Nuclear Power Plants
J. Duspiva
ÚJV Řež, a.s., CZECH REPUBLIC

Study on the In Core Instrumentation Tube Ejection Failure at APR1400 Lower Reactor Vessel
H. Yeol Kim
Korea Atomic Energy Research Institute (KAERI), REPUBLIC OF KOREA

The Effect of Fukushima on Research Activities in CIEMAT related to Severe Accidents
J. Fontanet, L.E. Herranz and E. Riera
Research Centre for Energy, Environment and Technology (CIEMAT), SPAIN

Analysis of the Fukushima Daiichi Accident from a Human and Organizational Perspective
Q. Baudard, H. Pesme and P. Le Bot
Electricité de France (EDF), FRANCE

Research and Development in Support of Beyond Design Basis Accidents (BDBA) Response in CANDU Nuclear Power Plants
G. Balog
CANDU Owners Group, CANADA

Session 3 (Thursday): Severe Accident Analysis (continued)

Fundamental Studies to Improve Analysis of Accident Progression at the Fukushima Daiichi Nuclear Power Plant
F. Nagase, H. Yoshida, Y. Nemoto, M. Amaya and S. Yamashita
Japan Atomic Energy Agency (JAEA), JAPAN

TEPCO's Activities on the Investigation into Unsolved Issues in the Fukushima Daiichi Nuclear Power Station Accident
D. Yamauchi
Tokyo Electric Power Company (TEPCO), JAPAN

Analyses of the Plant Behaviour of a PWR during Severe Accidents with Multiple Failures of Safety Systems
G. Mayer
Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) gGmbH, GERMANY

Session 4 (Thursday): Emergency Preparedness and Response (EPR)

(**Keynote**) Enhancing the Emergency Preparedness and Response Expertise with the Use of Advanced Response and Assistance Network Capabilities
O. Isnard
Institute for Radiological Protection and Nuclear Safety (IRSN), FRANCE

Atmospheric Dispersion of Radionuclides from Fukushima Daiichi Nuclear Accident and Dose Assessment
A. Ioannidou, E. Giannakaki, S. Manenti, L. Gini and F. Groppi
Aristotle University of Thessaloniki, GREECE

WMO Nuclear Emergency Response Activities in the Framework of the Joint Plan: Current Status and Lessons Learned from Fukushima
G. Wotawa
Zentralanstalt für Meteorologie und Geodynamik (ZAMG) and World Meteorological Organization (WMO)

National Atmospheric Release Advisory Center (NARAC) R&D to Improve Atmospheric Dispersion Modeling for Nuclear Power Plant Accidents
G. Sugiyama, et al.
Lawrence Livermore National Laboratory (LLNL), USA

Measurement and Data Analysis Concepts Combined with Data Assimilation Techniques for Source Term Reconstruction and Dose Assessment
U. Stöhlker, M. Bleher and F. Gering
Federal Office for Radiation Protection (BfS), GERMANY

Session 5 (Thursday): Post-accident Recovery

(**Keynote**) Rebuilding the Strategy for the Decommissioning of the Fukushima Daiichi Nuclear Power Plant: The Recent Situation of NDF's New Approach
H. Yamana
Nuclear Damage Compensation and Decommissioning Facilitation Corporation (NDF), JAPAN

Post-Fukushima Environmental Research Program within the Framework of the Franco–Japanese Collaboration
J.-C. Gariel
Institute for Radiological Protection and Nuclear Safety (IRSN), FRANCE

Feasibility Study of Pyrochemical Treatment on Fuel Debris by Performing Uranium and Zirconium Electrochemistry in LiCl-KCl Molten Salt
S. Phongikaroon
Virginia Commonwealth University, USA

R&D Activities related to the Fuel Debris Retrieval from the Fukushima Daiichi Nuclear Power Station
T. Satoh
International Research Institute for Nuclear Decommissioning (IRID), JAPAN

Closing Session (Friday)

Summary of Session 0
A. Viktorov
Canadian Nuclear Safety Commission (CNSC), CANADA

Summary of Session 1
J.P. Sursock
Electric Power Research Institute (EPRI), USA

Summary of Session 2
D. Lee
Korea Institute of Nuclear Safety (KINS), REPUBLIC OF KOREA

Summary of Session 3
D. Jacquemain and F. Nagase
Institute for Radiological Protection and Nuclear Safety (IRSN), FRANCE and Japan Atomic Energy Agency (JAEA), JAPAN

Summary of Session 4
U. Stoehlker
Federal Office for Radiation Protection (BfS), GERMANY

Summary of Session 5
L. Hubbard
Swedish Radiation Safety Authority (SSM), SWEDEN

Poster Sessions

Poster 72: Armenian Nuclear Power Plant Unit 2 Response to Feedwater Restoration Techniques in Case of Ultimate Heat Sink Loss
T. Malakyan, H. Hovhannisyan, A. Amirjanyan, J.E. Ramsey and P. Kohut
Nuclear and Radiation Safety Centre, ARMENIA

Poster 73: Preliminary Study on Passive System Experimental with Water Initial Temperature Variation in Transient Condition using NC-Queen Apparatus
M. Juarsa, S. Widodo and J.H. Purba
National Nuclear Energy Agency (BATAN), INDONESIA

Poster 74: Thermal Parameters of Elongated Heat Conductors of Evaporation-Condensation Type for Passive Emergency Cooling of Reactor Equipment
A.N. Gershuni, A.P. Nishchik, E.N. Pis'mennyi and V.G. Razumovskiy
National Technical University of Ukraine, UKRAINE

Poster 75: Introduction of a Research Project on Development of an Accident Management Support Tool for a BNPP (WWER-1000) Based on the Lessons Learned from the Fukushima Accident
M. Saghafi and M.B. Ghofrani
Sharif University of Technology, ISLAMIC REPUBLIC OF IRAN

Poster 76: Spent Fuel Pool and Release of Fission Products in the Fukushima Daiichi Nuclear Power Plant Accident
A. Haghighi Shad and H. Abbasi
National Nuclear Safety Department, ISLAMIC REPUBLIC OF IRAN

Poster 77: Thermalhydraulic Analysis of the Spent Fuel Pool using RELAP5 taking Insight from the Fukushima Accident
M.A. Nagrah, M.N. Mayo, Z.A. Baig, Z.H. Shah and M. Iqbal
Pakistan Nuclear Regulatory Authority (PNRA), PAKISTAN

Poster 78: Impact of Safety Relevant Severe Accident R&D Topics and Uncertainties on the Mitigation Features Selection
G. Azarian and B. de L'Epinois
AREVA NP, FRANCE

Poster 79: Lessons Learned from Analyses of the Fukushima Accident (Units 2 and 3)
M. Sonnenkalb and S. Band
Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) gGmbH, GERMANY

Poster 80: Assess and Mitigate the Early Offsite Consequences of an Accident for Nuclear Power Plants
F. Tawfik and M.M. Abdelaal
Egyptian Nuclear and Radiological Regulatory Authority (ENRRA), EGYPT

Poster 81: ENEA Activities in the Field of Emergency Preparedness and Response in the Aftermath of the Fukushima Accident
F. Rocchi, A. Guglielmelli, F. Rossi and F. Bertozzi
Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA), ITALY

Poster 82: Input of I-129 into the Western Pacific Ocean resulting from the Fukushima Nuclear Event
S.J. Tumey
Lawrence Livermore National Laboratory (LLNL), USA

Poster 83: An Overview of Nigeria's Preparedness for Response to Nuclear and Radiological Emergency Situations
J.D. Abafoni and O.N. Ofodile
Nigeria Atomic Energy Commission (NAEC), NIGERIA

Poster 84: Radioactive Contamination of Japanese Soils and Possible Ways for their Rehabilitation
L. Maskalchuk, A. Baklay, T. Leontieva and D. Strelenko
National Academy of Sciences of Belarus (NASB), BELARUS

Poster 85: Research Approach of MCCI Products Characterization for Debris Removal
T. Kitagaki, K. Yano and T. Washiya
Japan Atomic Energy Agency (JAEA), JAPAN

Poster 86: Preparation and Characterization of Simulated Fuel Debris Specific to the Fukushima Accident
M. Takano, T. Nishi and A. Onozawa
Japan Atomic Energy Agency (JAEA), JAPAN

Poster 87: Establishing Criteria for Reuse of Disaster Wastes Contaminated by the Fukushima Daiichi Nuclear Power Plant Accident
S. Takeda, S. Takai and H. Kimura
Japan Atomic Energy Agency (JAEA), JAPAN

Poster 88: Treatment and Radiological Characterisation of Contaminated Soil at Nuclear Power Plant A1 Slovakia
M. Listjak, M. Baca, M. Svitokova and A. Slaninka
VUJE, a.s., SLOVAKIA

Poster 89: Time Evolution of Radiological Conditions in the Marshall Islands: Experiences and Lessons Learned in Relation to Fukushima
T. Hamilton
Lawrence Livermore National Laboratory (LLNL), USA

Poster 92: Design of Treatment Procedure for Reprocessing of a Large Volume of Highly Radioactive Liquid Waste after a Severe Accident on the VVER Reactor
V. Brynych, et al.
ÚJC Řež, a.s., CZECH REPUBLIC

Poster 93: Institute for Nuclear Research Pitesti Activity Developed in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant
C. Gentea
Institute for Nuclear Research (ICN), ROMANIA