IAEA Report on

Reactor and Spent Fuel Safety in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant

International Experts Meeting
19–22 March 2012, Vienna, Austria

IAEA
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

The following States are Members of the International Atomic Energy Agency:

AFGHANISTAN
ALBANIA
ALGERIA
ANGOLA
ARGENTINA
ARMENIA
AUSTRALIA
AUSTRIA
AZERBAIJAN
BAHRAIN
BANGLADESH
BELARUS
BELGIUM
BELIZE
BENIN
BOLIVIA
BOSNIA AND HERZEGOVINA
BOTSWANA
BRAZIL
BULGARIA
BURKINA FASO
BURUNDI
CAMBODIA
CAMEROON
CANADA
CENTRAL AFRICAN REPUBLIC
CHAD
CHILE
CHINA
COLOMBIA
CONGO
COSTA RICA
CÔTE D'IVOIRE
CROATIA
CUBA
CYPRUS
CZECH REPUBLIC
DEMOCRATIC REPUBLIC OF THE CONGO
DENMARK
DOMINICA
DOMINICAN REPUBLIC
ECUADOR
EGYPT
EL SALVADOR
ERITREA
ESTONIA
ETHIOPIA
FIJI
FINLAND
FRANCE
GABON
GEORGIA
GERMANY
GHANA
GREECE
GUATEMALA
HAITI
HOLY SEE
HONDURAS
HUNGARY
ICELAND
INDIA
INDONESIA
IRAN, ISLAMIC REPUBLIC OF
IRAQ
IRELAND
ISRAEL
ITALY
JAMAICA
JAPAN
JORDAN
KAZAKHSTAN
KENYA
KOREA, REPUBLIC OF
KUWAIT
KYRGYZSTAN
LAO PEOPLE'S DEMOCRATIC REPUBLIC
LATVIA
LEBANON
LESOTHO
LIBERIA
LIBYA
LIECHTENSTEIN
LITHUANIA
LUXEMBOURG
MADAGASCAR
MALAWI
MALAYSIA
MALI
MALTA
MARSHALL ISLANDS
MAURITANIA
MAURITIUS
MEXICO
MONACO
MONGOLIA
MONTENEGRO
MOROCCO
MOZAMBIQUE
MYANMAR
NAMIBIA
NEPAL
NETHERLANDS
NEW ZEALAND
NICARAGUA
NIGER
NIGERIA
NORWAY
OMAN
PAKISTAN
PALAU
PANAMA
PAPUA NEW GUINEA
PARAGUAY
PERU
PHILIPPINES
POLAND
PORTUGAL
QATAR
REPUBLIC OF MOLDOVA
ROMANIA
RUSSIAN FEDERATION
RWANDA
SAUDI ARABIA
SENEGAL
SERBIA
SEYCHELLES
SIERRA LEONE
SINGAPORE
SLOVAKIA
SLOVENIA
SOUTH AFRICA
SPAIN
SRI LANKA
SUDAN
SWEDEN
SWITZERLAND
SYRIAN ARAB REPUBLIC
TAJIKISTAN
THAILAND
THE FORMER YUGOSLAV REPUBLIC OF MACEDONIA
TOGO
TRINIDAD AND TOBAGO
TUNISIA
TURKEY
UGANDA
UKRAINE
UNITED ARAB EMIRATES
UNITED KINGDOM OF GREAT BRITAIN AND NORTHERN IRELAND
UNITED REPUBLIC OF TANZANIA
UNITED STATES OF AMERICA
URUGUAY
UZBEKISTAN
VENEZUELA
VIETNAM
YEMEN
ZAMBIA
ZIMBABWE

The Agency's Statute was approved on 23 October 1956 by the Conference on the Statute of the IAEA held at United Nations Headquarters, New York; it entered into force on 29 July 1957. The Headquarters of the Agency are situated in Vienna. Its principal objective is "to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world''.

IAEA REPORT ON REACTOR AND SPENT FUEL SAFETY IN THE LIGHT OF THE ACCIDENT AT THE FUKUSHIMA DAIICHI NUCLEAR POWER PLANT

INTERNATIONAL EXPERTS MEETING
VIENNA, 19–22 MARCH 2012

Organized in connection with the implementation of the IAEA Action Plan on Nuclear Safety

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 2012

Marketing and Sales Unit, Publishing Section
International Atomic Energy Agency
Vienna International Centre
PO Box 100
1400 Vienna, Austria
fax: +43 1 2600 29302
tel.: +43 1 2600 22417
email: sales.publications@iaea.org
http://www.iaea.org/books

Printed by the IAEA in Austria
November 2012
IAEA/IEM/1

FOREWORD

by Denis Flory
Deputy Director General
Department of Nuclear Safety and Security

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 Meetings 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 Reactor and Spent Fuel Safety 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 am grateful to the participants of all the International Experts Meetings and to the members of the International Nuclear Safety Group (INSAG) for their valuable input.

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

INSAG PERSPECTIVE

This report reflects a thoughtful effort by IAEA staff to summarize the extensive efforts by many in the nuclear community to derive lessons from the accident at the Fukushima Daiichi nuclear power plant (the Fukushima Daiichi accident) in order to improve the safety of nuclear power plants. As this report shows, the community's efforts have resulted in many new insights and innovative ideas that will no doubt result in a significant enhancement of nuclear safety. Some of the suggestions have already been implemented by regulators and operators, and many of the others are subject to implementation in the future, following further study and analysis. The work is well begun.

This effort by the nuclear community to extract lessons from the Fukushima Daiichi accident reflects an impressive commitment to 'go the extra mile' to enhance safety. It would have been possible to view the Fukushima Daiichi accident as the product of serious flaws in the Japanese safety system with limited implications for others. It might also have been possible to limit the response to assessing the adequacy of the design basis for external events, such as the tsunami that initiated the challenge to the Fukushima Daiichi nuclear power plants, and to verify that the safety systems at nuclear power plants are adequate to cope with such events. It might have been possible, in taking the next step, to limit the focus to ensuring adequate power to operate safety systems and not to expand the scope to all the other systems that were compromised as a result of the loss of power at the Fukushima Daiichi plant. Similarly, it might have been possible to limit the scrutiny of the many 'softer' elements of safety — the importance of safety culture, of accident management and response, of communications, and of the variety of other matters that will be the addressed in other reports in this series on lessons learned. It is a credit to the nuclear community that the Fukushima Daiichi accident has instead caused a wide-ranging examination of safety matters that could have been deemed 'out of scope'. The willingness of those involved in the nuclear enterprise to address the widest range of implications of the accident both forthrightly and aggressively is no doubt a major factor in the maintenance of trust in nuclear safety by political decision makers and the general public in those countries that have retained their commitment to nuclear power in the aftermath of the accident.

In this connection, however, we must add a note of caution. As this report reflects, there are many, many actions that have been suggested in order to respond to the Fukushima Daiichi accident. Not everything can or should be accomplished at once. Indeed, the implementation of Fukushima related improvements should not distract operators and regulators from the hard, day-to-day work of ensuring that important existing safety requirements are met. This means that the implementation of Fukushima related improvements has to be prioritized. Every operator and regulator should consider the vulnerabilities that the Fukushima Daiichi accident has exposed, and, no doubt, the response might appropriately differ from regulator to regulator and from plant to plant. Nonetheless, as a tentative prioritization of the matters covered in this report (other important matters will be discussed in other reports on the lessons learned), we would suggest that the initial focus be on the following items:

(1) Assessing the adequacy of the design basis for external events and evaluating the capacity of each nuclear power plant to cope with realistic and up to date design basis events, while also seeking to ensure that the nuclear power plant can respond to beyond design basis events without major off-site public health or environmental impacts.
(2) Examining and upgrading the capacity to provide power from both off-site and on-site sources, as well as the capability to cope with station blackout for the period until such sources could reasonably be restored (through restoration of off-site or on-site power or usage of portable generators from off-site locations).
(3) Upgrading the capacity to provide cooling water to the reactor and the spent fuel pool in circumstances in which normal cooling is lost. The objective is to provide an ultimate heat sink under accident conditions.
(4) Ensuring the adequacy of instrumentation for monitoring critical parameters in the reactor and the spent fuel pool under accident conditions.
(5) Ensuring the adequacy of the means to prevent or mitigate hydrogen deflagration and detonation.
(6) Providing additional mobile equipment such as pumps, hoses and portable generators, and planning for its use to address extraordinary events of whatever origin that could compromise public health and safety.

Indeed, we recognize that many regulators have already implemented most or all of these actions. It is important to evaluate and, as appropriate, to implement in an orderly fashion the many further steps outlined in this report, guided by the reduction in risk that each provides.

At the end of the day, however, it must always be recognized that there is no way to eliminate all risk entirely. As history has shown, despite all the design improvements that we conceive, systems still fail; despite all the training and exercises based on lessons learned that are conducted, human beings will still make mistakes, particularly when confronted with once-in-a-lifetime events. Although the various safety measures identified in this report will serve to improve safety, the key will always be constant vigilance. No matter how safe we make reactors, there is no room for complacency or anything less than a total commitment to safety. The establishment of an enduring safety culture will remain the key.

As a final note, we should emphasize that ensuring nuclear safety is a global obligation. We are all linked together not only because an accident could have direct physical implications beyond national borders, but because any accident affects the climate for nuclear power everywhere. We thus have a common interest in ensuring adequate safety across the globe. The effort to evaluate various possible safety improvements can be more thorough, rapid, and thoughtful if pursued as a joint effort, rather than in isolation. The IAEA, the OECD Nuclear Energy Agency, the World Association of Nuclear Operators and the various other institutions that enable the participants in the global nuclear community to interact with one another thus have an important role in ensuring that lessons from the Fukushima Daiichi accident are carefully analysed and understood everywhere. This report is an important step in fulfilling that obligation.

1. INTRODUCTION

Following the accident at TEPCO's 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. Subsequently, the Conference adopted a Ministerial Declaration on Nuclear Safety, which 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] On 22 September 2011, the IAEA General Conference unanimously endorsed the Action Plan, the purpose of which is to define a programme of work to strengthen the global nuclear safety

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]

In the light of the activities undertaken by regulatory bodies and operating organizations, and others such as technical support organizations, the IAEA organized an International Experts Meeting (IEM) on Reactor and Spent Fuel Safety in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant, held on 19–22 March 2012, to share experience and lessons learned in this regard. The IEM was attended by approximately 230 experts from 44 Member States and four international organizations, including experts from utilities, research and design organizations, regulatory bodies, manufacturing and service companies, and other stakeholders.

The overall objectives of the IEM were to analyse relevant technical aspects of reactor and spent nuclear fuel management safety and performance related to severe accidents; to review what was known up to that point about the Fukushima Daiichi accident in order to understand more fully its root causes; and to share the lessons learned from the accident. The meeting provided a forum for technical

---

[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., pp. 5.

experts from Member States to discuss and exchange information on reactor and spent nuclear fuel safety and performance under severe conditions.

The specific objectives of the IEM were to:

- Identify and analyse reactor and spent nuclear fuel safety and performance issues;
- Consider the design, engineering and analysis of current and new systems for accident prevention and mitigation;
- Exchange information on national assessments of reactor and spent nuclear fuel safety and performance;
- Identify potential priority areas for research and development, and technology development.

1.1. BACKGROUND

The initiator of the Fukushima Daiichi accident was the Great East Japan Earthquake, a seismic event of extreme magnitude. The event was caused by a sequential rupture of successive fault segments and resulted in the massive release of seismic energy, generating a tsunami beyond the design basis of the Fukushima Daiichi nuclear power plant. The defence in depth (DID) provisions at the Fukushima Daiichi nuclear power plant were insufficient to provide the appropriate levels of protection for critical safety systems. Consequently, there was a failure of the power supplies needed to provide ongoing support to key safety functions, including cooling of the reactor and spent fuel. This led to severe core damage in the reactor and the release of radioactivity into the environment.

The actions of the plant operators were severely hampered by the lack of reliable essential instrumentation for monitoring safety related parameters such as the reactor temperature and coolant level during the accident. The installed systems failed to meet the operators' needs during the accident and recovery phases. In addition, the measures in place for the management of accident scenarios, and to prepare the plant to respond without significant damage, were insufficient to alleviate the severe accident consequences.

Apparently, mitigation measures were not in place, in particular for preventing hydrogen accumulation and explosions, and for ensuring operability of the containment venting system. Issues such as hydrogen generation and accumulation, prevention of explosions, and actions to protect groundwater from basemat melt-through should also be included in these guidelines.

Member State regulatory bodies and operating organizations responded to the Fukushima Daiichi accident by reassessing reactor safety, including: (i) assessment of the existing nuclear power plant design and licensing basis; (ii) assessment of the impact of extreme external hazards; (iii) identification of ‘cliff edge’ effects; (iv) assessment of the ability to respond to extended station blackout and loss of heat sink; and (v) assessment of the response to severe accidents.

1.2. OBJECTIVE

The objective of this report is to highlight the lessons learned on the topic of reactor and spent fuel safety in the light of the Fukushima Daiichi accident. The central components of the report are the insights gained from presentations by keynote speakers and panellists, and from discussions and contributions by participants during the IEM on Reactor and Spent Fuel Safety held in March 2012. These insights are supplemented by experience from other relevant IAEA activities, including the first IAEA fact finding mission to Japan and the discussions of the Extraordinary Meeting of the Contracting Parties to the Convention on Nuclear Safety held in August 2012.

The report summarizes the discussions and conclusions of the IEM, including an update by experts from Japan, and highlights the lessons learned to date in the following nine key technical areas important for strengthening reactor and spent fuel safety:

— Defence in depth;
— Extreme events/external hazards;
— Station blackout and loss of ultimate heat sink;
— Hydrogen management;
— Containment systems and venting;
— Severe accident management;
— Instrumentation and control (I&C);
— Spent fuel pools;
— Research and development (R&D).

2. HIGHLIGHTS OF THE IEM ON REACTOR AND SPENT FUEL SAFETY

2.1. UPDATE ON THE FUKUSHIMA DAIICHI ACCIDENT AND THE INTERNATIONAL RESPONSE

An update of the Fukushima Daiichi accident was presented by experts from Japan, who outlined their views on the causes of the accident, reform of the nuclear safety regulatory system in Japan and the decommissioning roadmap for the Fukushima Daiichi nuclear power plant.

The experts from Japan considered the following to be the root causes of the accident:

— Lack of incorporation of new knowledge about tsunamis into hazard evaluation;
— A regulatory system that did not adequately cover severe accidents;
— Insufficient application of state of the art technologies and international good practices in the regulatory programme.

The measures taken to reform the nuclear safety regulatory system in Japan were highlighted, together with the ongoing investigation of the accident sequence, in order to address the above root causes in a practical manner. This resulted in the formulation and extraction of technical knowledge as well as the establishment of countermeasures in the following areas:

— Off-site power supply systems;
— On-site power supply systems;
— Cooling systems;
— Containment systems;
— Communication, I&C systems and emergency response arrangements.

An update of the status of the units at the Fukushima Daiichi nuclear power plant was also provided, together with a roadmap for decommissioning. More details of the sequence, causes of and countermeasures against the accident were then presented based on the interim report on "Technical Knowledge of the Accident at Fukushima Daiichi Nuclear Power Station of Tokyo Electric Power Co., Inc."[4].

[4] Available on the web site of the Nuclear Regulation Authority (formerly NISA) at: http://www.nsr.go.jp/archive/nisa/english/press/2012/06/en20120615-1.html

The presentation closed with the following conclusions: (i) the legislation being enacted to reform the regulatory system will contribute to increased regulatory effectiveness; (ii) some technical knowledge has been extracted through investigation of engineering aspects of the accident and will be utilized to enable the new regulatory framework to function practically and effectively; and (iii) many issues are still uncertain and need to be investigated further on the way toward safe decommissioning and remediation of the Fukushima Daiichi site.

The international response to the accident was comprehensive, as was evidenced by several presentations from Member State experts outlining actions taken by regulators and operators to reassess reactor safety in response to the Fukushima Daiichi accident. These actions had elements in common, such as:

— Assessment of the existing design and licensing basis;
— Assessment of the impact of extreme external hazards;
— Identification of cliff edge effects;
— Assessment of the ability to respond to extended station blackout and loss of heat sink;
— Assessment of the response to severe accidents.

In general, the experts concluded that existing nuclear power plants had sufficient margins of safety to continue operation. However, safety could be further strengthened by the introduction of additional measures to improve protection against beyond design basis accidents (BDBAs), regardless of the postulated initiating events or their likelihood. Measures were proposed not only to improve prevention of BDBAs, but also to mitigate their consequences if prevention were to fail. Examples of proposed measures included additional installed and/or mobile equipment to improve the capability of ensuring essential safety functions (e.g. reactor core cooling to prevent core damage), and strengthened severe accident management guidelines and emergency response capabilities. These measures are being implemented by Member States in a staged approach in the short, medium and long term, and are expected to strengthen the application of the DID principle.

3. KEY TECHNICAL AREAS IMPORTANT FOR STRENGTHENING REACTOR AND SPENT FUEL SAFETY

3.1. DEFENCE IN DEPTH

Lessons Learned: 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 DID concept has been the basis for design and operation of nuclear facilities since the early days of the nuclear era, and its application remains fundamental to nuclear safety. In the 1970s and 1980s, when most of the currently operating nuclear power plants were built, the DID concept was most often applied by using three consecutive levels of defence. After the accidents at Three Mile Island and Chernobyl, it became a common practice to add two further levels of defence. The entire concept was thoroughly discussed in the INSAG report on Defence in Depth in Nuclear Safety[5], issued in 1996. This concept is embodied in IAEA safety standards[6]. However, experience — including that from the Fukushima accident — has shown that certain improvements in the application of the concept should be considered.

In the application of the DID concept, the main efforts are concentrated on prevention of significant reactor core damage. This objective should continue, but in addition, more effort should be directed at the mitigation of radiological consequences in the event that prevention fails. In this case, special emphasis should be given to preserving the containment function.

One objective of the DID concept is to control accidents within the design basis to prevent their evolution to severe reactor core or spent fuel damage. Experience has shown that events may take place that were not specifically addressed in the original design of currently operating plants and that were not protected against with specific safety systems. Such events are often called BDBAs, and the current requirements generally imply that also the conceivable BDBAs are addressed in the design of new facilities and in the emergency

[5] INTERNATIONAL NUCLEAR ADVISORY SAFETY GROUP, Defence in Depth in Nuclear Safety, INSAG-10, IAEA, Vienna (1996).

[6] INTERNATIONAL ATOMIC ENERGY AGENCY, Safety of Nuclear Power Plants: Design, IAEA Safety Standards Series No. SSR-2/1, IAEA, Vienna (2012).

operating procedures available to the facility operators. Examples of BDBAs are events where one or more safety systems designed for a certain design basis accident (DBA) are completely lost due to a common mode failure or a common cause failure. BDBAs can also be accidents initiated by a very rare event — such as a large aircraft crash or a beyond design basis earthquake — that was not considered possible in the original design. The practical approaches for identifying BDBAs differ among Member States and are not always consistent. It is important to make it clear that, in coping with BDBAs, the objective is still to prevent the accident from evolving into a severe accident.

In the updated IAEA safety standard on nuclear power plant design[7], BDBA events are called design extension conditions (DECs), as a step toward improved inclusion of BDBAs in the design requirements for nuclear power plants. At nuclear facilities currently in operation, the BDBAs have to be considered in connection with the safety reassessment or periodic safety evaluation. Consequently, 'compensatory measures' such as new back-fitted systems or the provision of transportable equipment may be found to be necessary. The result is a balanced safety concept that prevents any accident from evolving into a severe accident. For prevention of severe accidents, it is important to emphasize the high reliability of reactivity control and decay heat removal from the reactor core and the spent fuel.

For the mitigation of accidents — that is, for the prevention of radioactive releases to the environment — the protection of containment integrity is most important. However, after severe core damage, reactivity control and decay heat removal are also needed in order to maintain containment integrity. In practice, it is necessary to separately consider all physical phenomena that could endanger the containment integrity, and to plan adequate protection against each of them.

It is important that systems for the prevention of accidents and for the mitigation of accidents be separate and fully independent. Without such separation, it is probable that a single incident would cause the loss of several levels of DID. Independence and separation also need to be emphasized between redundant subsystems within each DID level and between diverse systems within each DID level.

At the International Experts Meeting:

The majority of the presentations in the keynote, plenary, and reactor and spent fuel parallel sessions of the IEM expressed expert views on the reassessment of the application of the DID concept, particularly the safety

[7] See footnote 6.

analysis transition from DBAs to BDBAs. The common view on lessons learned was that measures against low probability/high consequence events can be as critical to the prevention of severe core or spent fuel damage as are the systems dedicated to providing reactivity control and decay heat removal in connection with postulated DBAs. Thus, it was stressed that thorough consideration should be given to systems and strategies that could be made available to prevent a complex accident from evolving into a severe accident or to mitigate the radiological consequences of a severe accident. The specific areas highlighted in the expert presentations included:

- Demonstrating that the safety systems designed to protect against DBAs are sufficiently robust to also provide protection against many events that are beyond the design basis, that the safety system design for the postulated initiating events also covers beyond design basis events (BDBEs), and/or that existing safety systems are supplemented by permanent or mobile backup systems that would extend the protection, taking into account the vulnerabilities identified;
- Revisiting and redefining the concept of BDBAs, the associated regulatory requirements, and the associated design aspects of necessary equipment and its qualification, redundancy, independence, diversity and potential for common cause failure, as well as reviewing the compatibility and applicability of the functions that may be utilized during BDBAs against their original design basis;
- Re-evaluating and/or expanding the severe accident management and emergency response strategies, taking into consideration the availability or unavailability of on-site and off-site equipment and personnel, as well as the potential plant conditions that had already brought the Fukushima Daiichi accident to the severe accident stage.

The experts also presented methods and measures to accomplish this, as follows:

- Re-evaluate the hazards, robustness and vulnerabilities of the existing designs, and provide permanent and mobile equipment for identified vulnerabilities, especially for electrical power and cooling water capabilities;
- Use existing knowledge and continue R&D of design improvements that would support accident mitigation, especially as regards confinement/ containment (e.g. filtered containment venting, hydrogen control, molten core control);
- Make design changes to improve protection of the core from severe damage and to increase the acceptable time for ‘no action’ on the part of the

operators (e.g. spent fuel pool cooling, flood-proofing of structures, addition of permanent water and power sources).

It was also noted that although many of the issues and lessons learned applied to both prevention and mitigation, there were some small differences in the corrective actions to enhance the robustness of nuclear power plants against hazards, due to site and design specific issues and to the different regulatory frameworks in Member States. These differences mainly involved the schedule and priority of corrective actions, the extent of regulation required and the extent of the DBA envelope. There were also varying approaches to the methods used for identification of robustness or vulnerabilities, for example, targeted walkdowns versus a detailed review of the design basis, or the utilization of deterministic versus probabilistic approaches for severe accidents.

3.2. PROTECTION AGAINST EXTREME EVENTS AND EXTERNAL HAZARDS

Lessons Learned: Site and nuclear power plant specific external hazards and extreme events should be periodically re-examined and updated to ensure the adequacy of safety margins and protective measures.

The Fukushima Daiichi accident highlighted the need to protect nuclear power plants against extreme natural hazards that may be significantly greater than those considered in the original plant design. The topic of extreme external events was considered in more detail at an IEM on Protection against Extreme Earthquakes and Tsunamis[8] held in September 2012. Periodic reviews of the site hazard assessment and incorporation of improved knowledge and understanding of potential hazards are important for protecting key safety functions, especially those affecting power and cooling water resources.

Important factors that need to be taken into consideration to protect key safety systems against extreme external hazards include the combination of external events that could lead to prolonged impairment of safety systems, the site layout and the impact of common cause failures on multi-unit nuclear power plant sites.

[8] International Experts Meeting on Protection against Extreme Earthquakes and Tsunamis in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant, 4–7 September 2012, Vienna, Austria,

At the International Experts Meeting:

Member States reported on the targeted safety reviews of the emergency and safety systems for their nuclear power plants during the IEM. In Japan, the sequence of events of the Fukushima Daiichi accident was thoroughly investigated in order to understand the root causes of the multiple safety system failures, to discover weaknesses, to draw valuable lessons and to define appropriate countermeasures. On the basis of these investigations, seismic events and flooding coupled with induced fires were considered the main external hazards for the Fukushima Daiichi nuclear power plant. Recommended improvements to design and configuration areas where weaknesses were brought to light included the following:

— Hardening and improvement of the reliability of the external power system through:
  - Separation and diversification of the off-site electrical supply equipment;
  - Installation of fault locators to improve failure detection and diagnostic capabilities;
  - Implementation of modifications to achieve earthquake resistance and flood protection of essential substations and switchyard components;
  - Addition of measures to improve the capability to mitigate and quickly recover from a loss of off-site power.

— Hardening and improvement of the reliability of the on-site power supply systems through:
  - Better separation and diversification of the emergency AC power supply trains and of their essential buses and switchboards;
  - Enhancement of the DC power supply system and battery capacity;
  - Procurement of additional mobile battery sets and battery charging systems;
  - Installation of alternate backup power supplies (either mobile or fixed);
  - Implementation of a flood protection programme for buildings containing equipment essential to safety;
  - Provision of two or more outdoor, flood protected electrical tie-in points to facilitate connectivity of mobile equipment;
  - Deployment in safe storage of sufficient portable lighting systems, cabling and other electrical supplies.

— Improvement of the reactor cooling systems through:
  - R&D programmes to improve the tsunami prediction capability;
  - Improvement of flood resistance and mitigation capability of cooling water systems and inventories;

  - Enhancement of ultimate heat sink defences and ultimate heat sink failure mitigation capabilities, including the adoption of air cooled equipment;
  - Improved operability of isolation valves;
  - Installation of water injection ports outside the reactor building.
- Improvement of containment systems through:
  - Provision for adequate diversity of the primary containment vessel (PCV) cooling systems for boiling water reactors (BWRs), such as by adding an air cooled alternative or a gravity driven spray system that can also capture radioactive substances without having to rely on AC power or on the residual heat removal systems;
  - Provision of cooling capability to the PCV top-head flange;
  - Improvement of the venting system operability, such as by adding an emergency battery and manual operation of the valves;
  - Installation of a valved bypass line to the rupture disk and increased filtering capability in the vent;
  - Preclusion of vent interconnectivity between units to avoid hydrogen and fire propagation;
  - Monitoring of hydrogen release rates and hydrogen concentration by controlling its concentration and providing adequate and rapid venting capabilities.

Concrete examples from a number of countries participating in the IEM were provided with regard to this topic. For example, in the United States of America, licensees were asked to perform studies and walkdowns to verify that nuclear power plants were fully in conformance with their design basis. Specifically, licensees were asked to re-evaluate their seismic and flood hazards and to review their flood protection/mitigation features, as well as to re-evaluate other hazards that could occur simultaneously, such as high winds, hail and lightning. The re-evaluation was to address all flood-causing mechanisms. Licensees were also asked to identify and address cliff edge effects.

For the seismic hazard re-evaluation, licensees were required to reassess the ground motion response spectrum (GMRS) for the site using a probabilistic method. Furthermore, they were required to determine the seismic source models, the ground motion models and the site response evaluation, and to compare the GMRS with the safe shutdown earthquake (SSE) and the plant spectra and, depending on the screening criteria, perform a seismic margin analysis (SMA) or a seismic probabilistic risk assessment (SPRA) with an estimate of the large early release frequency (LERF). Results were to be used to determine whether additional regulatory actions would be necessary.

In another example, brought up by the Russian Federation, relevant lessons learned from the Fukushima Daiichi accident were taken into consideration in the reassessment of the protection provided against external hazards. This included: re-evaluation of the seismic zoning for nuclear power plants and of ground motion; analysis of the higher seismic impacts on the reactor unit, on the fuel pools and on the on-site spent nuclear fuel storage facilities; and implementation of all supplementary design solutions.

In Europe and South America, regulators requested that licensees conduct targeted reassessment of safety margins and of plant robustness. These were evaluated by reassessing the natural hazards specific to individual nuclear power plants. All Member States reviewed their current methodologies for assessing risk due to postulated internal and/or external initiating events. They conducted technical assessments of earthquakes, fire, flooding and other extreme environmental conditions, and reviewed the effectiveness of the use of operating experience regarding internal and/or external initiating events. A gradual increase of the severity of external hazards and cliff edge effects was modelled using deterministic and probabilistic analysis tools to consider gradual destruction of essential structures, systems and components that would eventually lead to core damage, in order to evaluate the extent of the safety margins and to optimize mitigation measures.

In Canada and other countries operating pressurized heavy water reactors, licensees carried out inspections of their nuclear power plants focusing on seismic qualification, fire, flooding and other hazards. The technical review criteria included confirmation of the design basis, establishment of the degree of protection against external hazards of lower frequency and higher magnitude than assumed in the design basis, and assessment of the impact of BDBEs.

3.3. RESPONSE TO STATION BLACKOUT AND LOSS OF ULTIMATE HEAT SINK

Lessons Learned: The availability and operability of resources to cope with prolonged station blackout and loss of ultimate heat sink with or without concurrent extreme external events should be ensured.

While redundant sources of power can be incorporated into the plant design, the Fukushima Daiichi accident demonstrated that common cause failure can lead to a long term loss of all AC power supplies. Therefore, there is a need to ensure that power can be restored in a timely manner and that backup power supplies are capable of supporting the key safety functions in the interim. In addition to providing better protection for existing off-site and on-site power supplies, additional measures such as storage of mobile equipment off-site should be taken.

To strengthen protection against station blackout, the availability of off-site power should be ensured through redundancy of sources of off-site power and enhanced robustness of the on-site electrical switchyards and electrical distribution network. Protection of on-site backup power against extreme events and common cause failures should be ensured by, for example, locating equipment at different elevations for protection against flooding. Further measures such as increasing the capacity of on-site batteries and introducing the capability to recharge these batteries with mobile equipment should be considered.

Additional power supplies from mobile equipment stored off-site need to be sufficiently well protected against any external events that could affect the nuclear power plant. The equipment should be available for use in a timely manner, and should be easily connected and thoroughly tested through regular training and drills.

The heat rejection capability of the ultimate heat sink can also be degraded by common cause failures. During an accident, the availability of the ultimate heat sink needs to be restored in a timely manner or an alternative heat sink capable of operating over prolonged periods of time should be provided. Measures should be introduced to strengthen the adequacy of cooling for the core and spent fuel in the event of a loss of ultimate heat sink. These measures should include ensuring the availability of multiple and diverse means of heat removal such as additional water reserves and alternative heat rejection capabilities as in air cooled cooling towers. Alternative cooling systems for spent fuel pools can be provided through mobile means of water supply such as fire extinguishing systems.

At the International Experts Meeting:

There was a wide range of discussions on the response to station blackout and loss of ultimate heat sink events, as these topics were a central theme of the targeted safety reviews performed by Member States. As stated in the presentations of the Japanese experts, “the accident at the Fukushima Daiichi [nuclear power plant] was caused by long lasting complete power loss due to common cause failure of electrical equipment following the earthquake and tsunami”. Thus, enhancement of both off-site and on-site power systems, together with additional measures for ensuring the availability and recovery of cooling and residual heat removal systems, were leading corrective actions being implemented around the world.

As presented by Member State experts, immediate corrective actions carried out included the procurement of portable equipment such as mobile diesel generators, batteries, spent fuel pool level and temperature measuring equipment, and pumps and fire engines with high discharge pressures. An important consideration is the protection and robustness of the additional equipment against BDBEs, including strategies for diversifying the locations of redundant equipment and/or locating the equipment in hardened locations. The additional equipment should be capable of being delivered where it is needed in the event of serious infrastructure damage. The storage of such additional equipment on a national, regional and international basis was also discussed. Appropriate systems for classification of the additional equipment and its regulation should be considered. Longer term improvements included adding permanent structures such as extra trains of diversely cooled (water/air) emergency diesel generators, tie-in points for power and water sources, tanks, water reservoirs and third level backup ultimate heat sinks. The measures discussed included:

— Improvements to the diversity and reliability of off-site power sources and associated systems, such as multiple power transmission lines from diverse routes and sources, and improved seismic resistance of the switchyard and substations;
— Additional high voltage and temporary cables along with backup electrical equipment;
— Provisions for additional equipment (installed, on-site and off-site) with permanent connections such as mobile power vehicles and necessary cables, diesel generators, power transformers, switchgear mobile batteries and battery charging systems, and additional diesel driven pumps;
— Portable alternative residual heat removal systems and/or air cooling equipment along with enhanced water injection capabilities from pumps with high discharge pressures and water injection ports located outside the reactor building;
— Air driven pumps for flood response and supplies of fuel pumps, sump pumps, hose couplings and connections;
— Improved manoeuvrability of essential isolation valves by ensuring the availability of portable air compressors and DC power sources along with measures to manually operate essential isolation valves;
— Design changes such as installation of low leakage reactor coolant pump seals, permanent and qualified spent fuel pool cooling systems, additional steam driven and/or independently powered emergency feed pumps, and longer lasting DC power sources;

— Revision of station blackout emergency procedures through the identification of optimal strategies and necessary equipment for use during an extended station blackout;
— Revision of existing station blackout regulations to include the implementation of corrective actions for identified vulnerabilities;
— Reconsideration of the current practice of assuming only a single unit station blackout at multi-unit sites by examining common cause failures affecting multiple units at the same time.

3.4. HYDROGEN MANAGEMENT

Lessons Learned: Implement measures for hydrogen removal and mitigation as well as measures for more efficient monitoring and control of hydrogen accumulation and propagation.

While the risks of hydrogen explosions are well known, the Fukushima Daiichi accident demonstrated that existing provisions for monitoring and controlling hydrogen accumulation and propagation following a severe accident may be insufficient. The robustness and capacity of hydrogen monitoring and removal equipment in the containment and reactor buildings (and if considered necessary, in the spent fuel pool) should be reviewed, along with the capabilities of its associated instrumentation. Installation of passive safety systems such as autocatalytic recombiners should be considered.

Further studies to mitigate hydrogen deflagration and to prevent detonation should be carried out, along with studies of the risks associated with hydrogen propagation between units on multi-unit sites. Provisions to render the primary containment vessel inert (such as the case in the Fukushima plants) should not lead to a relaxation of the requirement to control (monitor and remove) hydrogen in other parts of the plant, such as the reactor building.

At the International Experts Meeting:

Participants discussed the fact that during the accident at the Fukushima Daiichi nuclear power plant, explosions occurred in the reactor buildings of Units 1, 3 and 4 that were attributed to the presence of hydrogen. These explosions not only delayed or stopped mitigation work around the reactor buildings, but they were also suspected of causing physical damage to those buildings. This was inferred from the sudden changes in parameters, such as the pressure drop in the Unit 2 pressure suppression chamber and increased water leakage from the containment and other buildings. Furthermore, it was understood that connections between the reactor units may have resulted in hydrogen propagation from those units damaged by the accident to the unaffected units on the site. Thus, the topic of hydrogen management was extensively discussed by the experts in the meeting. Based on the lessons that were learned, corrective actions have been implemented at various stages by Member States. These corrective actions have ranged from installation of passive hydrogen removal systems (e.g. passive autocatalytic recombiners (PARs)) to the review of longer term operation of active/passive hydrogen removal systems, PARs, igniters, etc. The experts also discussed other actions that have been investigated, as follows:

— Design and installation of hydrogen monitoring systems that would remain functional under severe accident conditions;
— Design and installation of emergency gas release systems for use under severe accident conditions that would be separate from existing operational or stand-by gas control systems;
— Ensured separation of neighbouring units on multi-unit sites by avoiding common release paths and cross-ties that would allow transfer of hydrogen from affected units to unaffected units;
— Review of hydrogen monitoring inside the containment and other buildings that would be susceptible to hydrogen propagation;
— Improvement of the understanding of hydrogen generation, accumulation and propagation, as well as of the effectiveness of hydrogen removal with respect to means and timing.

3.5. CONTAINMENT SYSTEMS AND VENTING

Lessons Learned: Strengthen containment integrity by ensuring availability of monitoring, cooling and venting functions under severe accident conditions.

As the containment is the last physical barrier for preventing the release of radioactive material to the environment, it is important to ensure that the containment function is protected through dedicated containment safety systems (cooling and venting, including monitoring of important safety parameters) that are always available.

Containment integrity should be maintained in the event of extreme hazards and severe accidents. Control and mitigation of hydrogen levels in the containment and the fuel building are necessary, along with heat removal and robust containment filtration and venting systems to preclude over-pressurization.

Filtered containment vents should be considered, if they are not currently available, and best international practices for venting should be adopted, including filtering/venting strategies that take into account resistance to hazards such as hydrogen combustion.

At the International Experts Meeting:

It was discussed that during the accident, the capability to cool the PCV and to conduct depressurization was lost or became ineffective due to the loss of power, resulting in damage to the flanges and to the PCV itself. There was extensive discussion on mitigation of severe accident consequences, particularly regarding measures for protecting the containment/confinement systems through both cooling and venting functions.

With respect to cooling functions, the experts discussed the need to ensure heat removal functions using diverse systems that would remain functional even under a loss of power; for example, the design and installation of passive heat removal systems such as containment sprays and air cooling.

The experts considered the need to revisit the impact of BDBAs on structures, systems and components important to safety, including their qualification, redundancy, independence and diversity, and their susceptibility to common cause failures. Design considerations of structures, systems and components, taking into account severe accident conditions and the failure mode of such systems, were also discussed. Specific examples included design of vessel flange seals that preclude damage from overheating, fail-safe design of containment isolation valves, and the impact of the isolation condenser on the cooling functions. Furthermore, the qualification and reliability of the instrumentation inside the containment to correctly observe and understand the state of the containment, as well as the ability to control the containment pressure and temperature under accident conditions, were discussed.

On the topic of containment venting, there was extensive discussion on actions that have been taken by Member States. These actions are largely in agreement, but with some differences in the schedule of implementation. The following corrective actions were presented as having been taken or as needing to be taken to ensure appropriate venting of the containment:

- Installation of hardened vents for Mark I and Mark II type containments;
- Installation of containment vents with a filtering function designed for prevention of hydrogen explosion/combustion in filtering systems and for long term operation under BDBA conditions;

— Design considerations of structures, systems and components and instrumentation under accident conditions, for example, cooling of upper vessel flange seals to prevent failure under accident conditions;
— Isolation of gas vent systems from other operational and/or stand-by gas treatment systems;
— Avoidance of cross-ties and influence from other units on multi-unit sites.

3.6. SEVERE ACCIDENT MANAGEMENT AND GUIDELINES

Lessons Learned: Strengthen the severe accident management practices, guidelines and regulations to be used by the operating organizations and regulatory bodies.

The Fukushima Daiichi accident demonstrated that the provisions against a severe accident were insufficient, especially as the accident was compounded by the devastation caused by the earthquake and tsunami. The availability of on-site Emergency Response Centres that are able to withstand severe events and have the capabilities to monitor essential plant safety parameters and to communicate with other centres both on and off the site is essential. In this regard, the identification of a hardened safety core of necessary equipment and organizational arrangements to cope with severe accidents is one approach to dealing with severe accidents.

Specific goals should be established to mitigate the consequences of each severe accident state identified, with a focus on retaining the integrity of safety barriers. The accident management strategy and methods should be focused on achieving goals such as the retention of damaged fuel inside the reactor vessel and the prevention of damage to the containment.

Mitigation measures for severe accidents should be based on permanently installed systems, supplemented by mobile or portable equipment, that are capable of dealing with, for example, decay heat removal from the molten core and the reactor containment, management of hydrogen and venting of the containment through appropriate filters. Severe accident management guidelines should identify actions to strengthen plant autonomy to compensate for long term loss of off-site power and loss of heat sink, along with the implications of the devastation of roads and infrastructure around the site.

Sufficient resources should be identified and be available in terms of trained experienced personnel, equipment, supplies and external support, along with procedures that incorporate the latest technical knowledge and best practices. The procedures should take into account the minimum necessary emergency team required to be permanently present at nuclear power plants and the impact of an extreme event on the supporting infrastructure both on and off the site. The potential unavailability of instruments, lighting and power, and abnormal conditions including plant state and high radiation fields, should also be considered.

Regulatory requirements for severe accident management should be considered that cover the coordination of emergency operating procedures with severe accident management guidelines (SAMGs) and that are applicable to multi-unit nuclear power plant sites.

SAMGs should be developed for low power and shutdown (LPSD) conditions and for spent fuel pools. Their application to severe accidents at multi-unit nuclear power plant sites should be considered, and the advantages and disadvantages of sharing systems and resources can be explored. SAMGs can be validated during emergency exercises and drills. The influence of other industries in close proximity to a nuclear power plant should also be considered for the purposes of severe accident management.

At the International Experts Meeting:

One of the root causes of the Fukushima Daiichi accident, as explained by the Japanese experts, was insufficient provisions against severe accidents. The Member State experts were largely in agreement with this explanation from the administrative, operational and regulatory perspectives. In response, they considered that SAMGs should be introduced for all operating nuclear power plants, and where they already exist, these SAMGs should be reviewed to take into account the lessons learned. General propositions by the experts for the revision and expansion of severe accident management also included:

- Re-evaluation and/or expansion of the severe accident management and emergency response, taking into consideration the availability/unavailability of on-site and off-site plant equipment and personnel, as well as the potential plant conditions that would bring the accident to the severe accident stage;
- Establishment of a clear scope and clear definitions, criteria and goals, as well as appropriate and continuous training for SAMGs, with better integration with abnormal and emergency operating procedures, and accident progression scenarios;
- Provision of qualified and reliable equipment for monitoring and control functions in order to manage the accident effectively;
- Design and installation of hardened emergency command centres that would not deteriorate during severe accident conditions, and improvements to ensure communication among centres where the responsible and

accountable parties (at the plant, national, regional and international levels) operate by obtaining and maintaining robust communication equipment;

— Improved use of the latest R&D and technical knowledge concerning severe accident management, with a strong emphasis on accident mitigation through the prevention/minimization of the release of radioactive material;
— Possible development of tools to predict the physical phenomena leading to severe core damage and causing a consequent threat to the containment integrity, with the aim of improving SAMGs.

In addition, complicating factors such as destruction of support infrastructure, total site isolation and area devastation, common mode failures and failure propagation on a multi-unit site, the coincidence of radioactive releases, the unavailability of post-accident instrumentation, and severely damaged monitoring facilities need to be taken into consideration in order to efficiently design hardened and improved external communication and intervention capabilities.

3.7. INSTRUMENTATION AND CONTROL (I&C)

Lessons Learned: Ensure robust capability to monitor essential plant safety parameters and to facilitate actions that may become necessary during severe accidents.

It is necessary to monitor essential plant safety parameters during any conceivable accident, including a severe accident, to facilitate prevention of reactor core or spent fuel damage, or mitigation of radiological consequences if preventive actions fail. Examples of these safety parameters include reactor and spent fuel pool water levels, and reactor and containment temperature and pressure. Measures to improve the robustness of essential safety parameter monitoring should include ensuring that instrumentation has the capability to withstand severe accident conditions and is supplied with a reliable source of emergency power. This should include instrumentation for monitoring radiation and meteorological conditions along with on-site and off-site communication systems.

At the International Experts Meeting:

It was noted that in most Member States, licensees were asked to begin their safety reviews with a check of their design basis compliance. During a DBA, while the reactor is subcritical, I&C should function as designed if power is available. Core cooling is provided, monitored and controlled as designed. In terms of containment integrity in BWR Mark I and Mark II designs, one of the deficiencies noted was that direct pressure level information was not provided for the containment. The level was only inferred through differential pressure measurements, but these measurements by themselves were not considered sufficient.

Under severe accident conditions in the Fukushima Daiichi nuclear power plant, some of the instrumentation systems failed. In terms of core cooling, misleading information was reported about the reactor pressure vessel inventory, and there was confusion about pressure measurements. Moreover, the validity of temperature data was questionable, with no means available to validate the data. It was difficult under these circumstances to assess the accident's progression.

The need for a more robust I&C system to enable the necessary monitoring of safety parameters and plant conditions is an important lesson learned from the Fukushima Daiichi accident. In addition, any engineering review of I&C modifications should consider BDBEs.

Under severe accident conditions, the instrumentation needs to support the SAMGs. The need to improve the robustness of instruments and their power supply under an accident environment was recognized, together with the need for an appropriate operability time and the ability to continue instrument performance over the long term.

The general countermeasures proposed in the I&C area to improve the reliability of the I&C system and to increase its resistance to external and internal threats included promoting R&D to expand the range and specification of the instruments to cover extreme accident conditions and enhancing the emergency monitoring functions (e.g. by supplying power from emergency power sources, by adding dedicated power sources for monitoring equipment and by installing earthquake and flood resistance components).

Some Member States require their licensees to provide reliable hardened vents in the case of BWR Mark I and Mark II containments. For other containment designs, some Member States require control of containment pressure through the removal of decay heat if active containment heat removal capability is lost, even under station blackout conditions. To control hydrogen hazards, licensees are required to provide hydrogen control and mitigation capabilities inside the containment or in other buildings, and emergency power enhancements for prolonged station blackout and multi-unit events. The licensees are also required to incorporate specific additional measures to harden and improve their I&C systems to deal with all possible operational states.

In the presentation by Japan, recovery of crucial instrumentation was identified as an important issue. The safety related instrumentation that needed to be retrieved included: the reactor water level indication, the reactor pressure indication, the dry well pressure and the wet well pressure (suppression chamber pressure). In addition, the need for portable batteries was evident from the accident.

Also very useful in powering critical I&C during a prolonged station blackout are engine driven generators and engine driven air compressors. Engine driven generators were needed at the Fukushima Daiichi nuclear power plant, but were not readily available to provide power for the control room panels for lighting and for PCV vent valves. In addition, most of the existing tools for communication between the Emergency Response Centre and the control room were unavailable. Securing redundant communication measures is critically important when highways are damaged and public telecommunications services are disrupted.

Another area where I&C improvements are needed is in damage mitigation monitoring strategies and environmental monitoring, in order to support decision making by local authorities for the purposes of considering protective actions for the surrounding population.

3.8. SAFETY OF SPENT FUEL POOLS

Lessons Learned: Design and defence in depth evaluations of spent fuel pools and associated structures, systems and components should consider events that may lead to spent fuel damage in storage (e.g. loss of cooling, loss of pool inventory, re-criticality, hydrogen production, zirconium fire).

The lessons learned in other technical areas are also applicable to spent fuel pools (e.g. protection against extreme events, improved instrumentation). The integrity of spent fuel pools needs to be ensured, even in the event of a prolonged loss of cooling and the potential for boiling. Sufficient water level in the pools needs to be ensured, along with additional measures for water make-up, including the use of fire extinguishing systems as an alternative source of cooling, if necessary. Use of spent fuel storage racks made of borated steel would allow for cooling with fresh unborated water.

Adequate power supplies and instrumentation are needed to ensure continuous availability of reliable information for monitoring key parameters indicating the status of spent fuel storage under all conditions, in particular, instrumentation for monitoring the water level in the pool for post-event monitoring.

Analysis of severe accidents in spent fuel pools has not been widely carried out. Studies should be undertaken related to hydrogen production and accumulation in spent fuel pools. The implications of the increased use of high density spent fuel storage systems should be considered, and the scope of SAMGs should be expanded to include spent fuel pools.

At the International Experts Meeting:

Improvements to spent fuel pool safety in Japan and in various other Member States were proposed based on lessons learned from the Fukushima Daiichi accident. They included further enhancement of the diversity, flexibility and operability of the spent fuel pool cooling equipment, such as through the adoption of mixed water and air cooling, and the addition of fixed or portable cooling and make-up facilities, and of wet/dry fuel storage. Proposed improvements to the reliability of the make-up water injection system for the spent fuel pool included ensuring diversity and redundancy of the cooling and make-up injection functions and sufficient cooling water inventory, and the provision of a decentralized fuel storage configuration, of air cooled facilities and of sufficient dry storage capacity to reduce the high incidence of high heat loads.

In parallel, improvements to procedures and manuals, and to organizational and personnel training, were deemed necessary to reflect changes to the plant configuration. Feedback from operating experience worldwide and advances in science and technology will dictate further enhancements. It was also deemed essential to reach a consensus and consistency on international standards and practices.

Areas of improvements were identified, including reliability enhancements of the water make-up injection systems for the spent fuel pool (e.g. ensuring diversity and redundancy and sufficient cooling water inventory).

To reduce the risk of re-criticality in spent fuel pools, Japan is considering decentralization of its fuel storage. A more conservative spent fuel management policy favouring reduction of the spent fuel inventory in spent fuel pools and in reactor buildings coupled with a more effective use of dry cask storage is being proposed in order to avoid concentrating spent fuel inventory in one place.

Following the earthquake, concern was also expressed in Japan about the spent fuel pool structures being weakened by the abnormal temperature in the spent fuel pool. A weakened structure makes the spent fuel pool more prone to damage following aftershocks. As a result, additional support structures were installed at the bottom of the spent fuel pool in the damaged units.

During the Fukushima Daiichi accident, the spent fuel pool cooling function was lost due to the loss of off-site power, hydrogen explosions and falling debris. In addition, the seawater pumps were inoperable and, as a result, recovery of the regular cooling function became very difficult.

To better protect spent fuel pools, regulators in Japan and in other countries issued additional requirements such as that of ensuring that equipment and facilities are sufficient for dealing with multi-unit and prolonged station blackout scenarios. Some countries considered it essential to always have one source of on-site emergency electrical power remain operable for the spent fuel pool make-up and to have reliable spent fuel pool instrumentation available whenever there is irradiated fuel in the spent fuel pool, regardless of the external events or the operational mode of the reactor. In addition, licensees in the United States of America, for example, will be required to install instrumentation capable of identifying when water in the spent fuel pool reaches the following levels:

— Level adequate for normal fuel pool cooling system.
— Level adequate to provide radiation shielding for a person standing on the operating deck.
— Level at which the injection of make-up water should no longer be deferred. This corresponds to the top of the fuel elevation plus an appropriate margin.

Another area where critical instrumentation and its protection should be made more robust is resistance to seismic loads and protection from missiles.

3.9. RESEARCH AND DEVELOPMENT (R&D)

Lessons Learned: An international coordinated approach is needed to efficiently manage and perform the R&D required to implement measures to improve safety and severe accident knowledge, and to obtain and disseminate data and information from the Fukushima Daiichi accident.

Many of the measures proposed to enhance the robustness and safety of nuclear power plants will require additional R&D. In addition, information and data from the Fukushima Daiichi accident will contribute to improved understanding of phenomena related to severe accidents. R&D has a critical role going forward, as new lessons are learned that will form the basis for implementation of operational strategies and updating of regulations and regulatory guidance. It is clear that cooperation in the area of R&D is necessary in order to avoid unnecessary duplication, reduce costs and facilitate the efficient use of expertise available worldwide.

Important factors that need to be considered for R&D strategies include the availability of new data and methods for future assessments, and re-examination of the possible impact of climate change on the use of historical meteorological data. The risk considerations associated with multi-unit nuclear power plant sites should be explored, along with the potential impact of nearby industries on nuclear power plant risk.

Other specific issues include validation of design codes to support future plants and the topics of corium–water and corium–concrete interaction issues and human and organizational aspects.

At the International Experts Meeting:

It was noted that the implementation of some of the measures to improve plant robustness against extreme hazards will require further R&D or a modification of existing safety R&D programmes. Several presentations addressed R&D needs and the initiation and/or redirection of research in response to the Fukushima Daiichi accident. Examples included:

— Review of past safety research and lessons learned from past research on accidents (e.g. large data and knowledge bases available on the properties and behaviour of irradiated fuel under accident conditions, from basic actinide science to atomistic mechanisms to operational fuel properties; refocusing of activities on areas such as high temperature properties and behaviour, spent fuel corrosion in water, impact resistance and response, and storage of spent fuel).
— Mechanisms relevant to spent fuel storage: spent fuel swelling/pressurization, cladding properties evolution, microstructure alterations at high dose and fuel composition/irradiation history effect.
— Gap analysis based on research issues from the accident, particularly on molten fuel/corium properties, source term assessment for high temperature release, corrosion effects in seawater, spent fuel behaviour in the pools, and storage and/or treatment of molten fuel.
— Expansion of existing projects on accident prevention and mitigation.
— Improved tools and means to evaluate external hazards and loss of safety functions.
— Fuel degradation in the spent fuel pool and countermeasures.
— Better modelling capabilities of BWR systems and comparisons of computer models of thermal hydraulics, fuel behaviour, severe accident phenomenology, and systems and event databases.
— I&C improvements in reactor pressure vessel level sensing, validation of accident monitoring data, thermocouple behaviour, the capability to confirm the safe state of the reactor when core configuration is unknown, monitoring of containment integrity, monitoring of critical hydrogen parameters, provision of more robust communications of data to off-site

locations, environmental monitoring, robustness and longevity of the power supply, and adaptation of instrumentation requirements for new SAMGs.

- Research on hydrogen flammability patterns in the pools in order to recommend, if necessary, preventative measures such as the installation of PARs. Spent fuel pool bundle coolability tests are also being conducted at low water levels and under various severe accident scenarios for both pressurized water reactors (PWRs) and BWRs.
- R&D programmes have been launched, including: studies of the cooling of a partly molten core, of fission product releases from the core and of fission product retention inside the wet well of BWR plants; saltwater cooling experiments; calculations of air-transported radiological dispersion; and studies of fission product retention in filtered venting systems to address the question of the adequacy of filter designs.
- Comprehensiveness/completeness of accident analyses:
  - Selection of BDBAs to be analysed;
  - Improved methodologies;
  - Combinations of hazards (independent, interdependent);
  - Time interval covered by analyses, criteria for success, ensuring safe end state will not be impacted by a subsequent event such as battery depletion, etc.
- Continued detailed investigations of the accident sequence, including assessment of computer code applicability to observed severe accident phenomena.
- Internationally coordinated effort needed to improve knowledge from continued Fukushima Daiichi accident evaluation and post-accident inspections.
- Passive safety systems for new nuclear power plants.

It was emphasized that an integrated approach is necessary for R&D. This can be accomplished through international partnerships and programmes and integrated experimental and/or theoretical approaches. In addition, access to and examination of the reactors at the Fukushima Daiichi nuclear power plant provide an opportunity to improve our understanding of BWR accident phenomena. The IAEA could play an important role in coordinating these R&D efforts.

4. CONCLUSIONS

This report summarizes key technical lessons learned in the area of reactor and spent fuel safety drawn from the evolving understanding of the Fukushima Daiichi accident and taking into consideration insights gained from a key technical meeting, the IEM on Reactor and Spent Fuel Safety in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant, organized by the IAEA in March 2012.

Throughout this IEM and other related activities, there were a number of recurring themes. One of particular note was that mitigation capabilities should be enhanced to adequately complement the already extensive accident prevention features of nuclear power plants, including updating and strengthening the SAMGs, training, and drills and exercise programmes to improve the overall response capability of both the essential staff at the nuclear power plant and the experts in support centres. In the absence of absolute confidence that all severe, adverse situations have been considered and defended against, it becomes important to ensure that generic measures have been taken to mitigate the consequences of such situations. For example, unless the possibility of hydrogen generation resulting from an incident or accident can be precluded, it is appropriate to consider including technologies for the management of hydrogen. Similarly, without ensuring the timely recovery of power to spent fuel pool cooling systems, the loss of power for an extended period of time needs to be managed. This improved balance between prevention and mitigation is expected to enhance the application of the DID concept.

In addition to the need to provide a better balance between prevention and mitigation of accidents, there is a need to take into consideration the special aspects of some multi-unit nuclear power plant sites and the need for improved assessment of accident propagation to other units (e.g. an accident at one unit should be considered as a potential external hazard to an adjacent unit) and of the corresponding impact on emergency preparedness.

It should be emphasized that the proposed additional measures to mitigate the impact of severe accidents do not mean a reduction in attention to the prevention of accidents. The constant and full compliance of nuclear power plants with their licensing basis should continue, to provide assurance that safety margins are guaranteed to allow the time necessary to respond to an initiating event and to adequately mitigate and properly manage accident progression, when necessary. In addition, it is evident from many national and international activities that there are intentions to improve plant resistance to hazards beyond the design basis, such as extreme earthquakes, tsunamis, flooding, tornadoes, hurricanes, etc., by providing nuclear power plants with a more robust and flexible capacity to respond in varied and diverse ways. For example, portable equipment capable of surviving extreme events could be used to mitigate the consequences of situations such as prolonged station blackout, prolonged loss of heat sink or combinations of both, as well as any other conditions that could lead to extensive damage to the fuel and the containment.

The meeting recommended that the IAEA Secretariat make the information from the IEM available to the Safety Standards Committees so that the lessons discussed and learned at the IEM can be considered and evaluated for incorporation into the IAEA safety standards.

It is important to note that, at the time this IEM was held, not all Member States had completed their assessments of the consequences of the Fukushima Daiichi accident for their existing plants and/or for those yet to be built or completed. There is still much to be learned and shared. The development of a full set of lessons learned will likely take several years, based on the experience from the accidents at Three Mile Island and Chernobyl. The meeting recommended that the IAEA reconvene a similar IEM in two years’ time and that the information collected be periodically evaluated for incorporation into the IAEA safety standards.

Annex A

CHAIRPERSON’S SUMMARY

International Experts Meeting on Reactor and Spent Fuel Safety in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant 19–22 March 2012, Vienna

GENERAL REMARKS

In furtherance of the IAEA Action Plan on Nuclear Safety (the Action Plan) unanimously endorsed by the Member States as a result of the accident at the Fukushima Daiichi nuclear power plant, the IAEA held an International Experts Meeting (IEM) from 19 to 22 March 2012. The primary objectives of this IEM were to analyse relevant technical aspects of reactor and spent nuclear fuel management safety and performance; to review what is known to date about the accident in order to understand more fully its root causes; and to share the lessons learned from the accident. These objectives served to pursue several purposes of the Action Plan:

- To discuss the results of Member States’ national assessments of the safety vulnerabilities of nuclear power plants in the light of lessons learned to date (Action Plan, Safety assessments in the light of the accident at TEPCO’s Fukushima Daiichi Nuclear Power Station, bullet #11[1]);
- To analyse all relevant technical aspects and learn the lessons from the Fukushima Daiichi accident (Action Plan, Communication and information dissemination, bullet #4);
- To help facilitate and to continue to share with Member States a fully transparent assessment of the accident in cooperation with Japan (Action Plan, Communication and information dissemination, bullet #5).

The IEM was attended by approximately 230 experts from 44 Member States and four international organizations. There were wide-ranging and open discussions and a full exchange of information. This summary is intended to reflect observations that were made at the IEM but does not necessarily reflect the consensus of the participants.

---

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

The IEM revealed that the Member States (including regulators, industry and technical support organizations), the IAEA Secretariat and other relevant organizations had undertaken very significant efforts to analyse the Fukushima Daiichi accident and to take appropriate actions to respond to it. The overall efforts have been comprehensive, thoughtful and impressive. It is anticipated that nuclear safety will be greatly strengthened as a result.

The presentations and discussions revealed that the Member States had taken a variety of largely independent efforts to examine the accident. It was reassuring to note that, despite somewhat different terminology and emphases, the analyses had largely converged on the same conclusions. The similarities in actions provide confidence that significant issues have not been overlooked. There were expected common elements in the efforts of the various Member States directed at ensuring protection from extreme events (e.g. earthquakes, tsunamis, flooding, tornadoes or other site specific external hazards), at a capacity to respond to station blackout and to ensure a heat sink, to improve communications and emergency response, to control hydrogen deflagration and detonation, and to respond to threats to spent fuel pools. But the discussions also revealed a widespread undertaking to strengthen the overall safety framework. Just as the Three Mile Island and Chernobyl accidents brought about an overall strengthening of the safety system, it is already apparent that the Fukushima Daiichi accident will have a similar effect.

One important element of a broadened safety agenda is the concerted effort to establish a robust capacity to protect against a beyond design basis accident. In effect, the presentations revealed an intention to establish an additional layer of protection to prevent a severe accident regardless of the initiating event. This is to be accomplished by additional installed and/or mobile equipment that provides increased assurance of a capacity to meet essential functions, such as a need for electrical power or cooling water. There was emphasis as well on efforts to place a priority not only on preventing accidents, but also on mitigating them, and to place a priority on preserving containment. Moreover, there are efforts to strengthen severe accident management guidelines and to improve emergency response capacity. The result should be greatly strengthened defence in depth.

In short, good progress has been made on improving safety, and a large number of activities are in process. Both regulatory bodies and operators in Member States are taking aggressive actions to increase safety. And the Action Plan is providing an appropriate framework for the development and sharing of essential lessons learned. These efforts should continue.

A detailed update of the current understanding of the accident sequence was presented to the IEM by Japan. There is much still to be learned, and continuing investigations will progressively allow an even deeper analysis of the accident. The availability of appropriate data on the accident will be of importance in enabling detailed lessons on a number of matters — hazards evaluation, safety prevention measures, accident mitigation, and on-site and off-site emergency management capabilities. The IEM thus could provide only initial insights.

In addition to the themes discussed above, the presentations identified a variety of elements to improve safety in the framework of the Action Plan:

- The response to the threat from external hazards should include combinations of hazards and include consideration of complications that can arise on multiple-unit sites and from disruption of infrastructure.
- Continuing efforts in the estimation of tsunami and earthquake hazard are appropriate, and adjustment in regulatory requirements should reflect evolving knowledge.
- More attention is necessary concerning the mitigation of severe accidents.
- Accident analyses should include careful consideration of the time sequence of the possible progress to a severe accident, thereby providing operators with a clear understanding of the time for intervention.
- The severe accident management framework should be strengthened by including it more centrally in regulatory systems, with due regard for organizational, human, technical and safety culture related issues.
- Key systems to respond to beyond design basis events in order to return the plant to a safe and stable state should be identified and be strengthened.
- The I&C systems necessary for monitoring of critical safety parameters during any accident condition should be hardened.
- The spent fuel pools at the Fukushima Daiichi accident appear, based on current knowledge, to have survived the earthquake and tsunami well, but the accident revealed the need for more capable instrumentation to monitor the status of the pools and for a robust capability to restore water to the pools.
- On-site and off-site resources, including mobile equipment and facilities for dealing with multi-unit and disrupted infrastructure, should be available at the regional, national or even international level.
- Realistic exercises are necessary to ensure effective emergency response capability.

— The on-site emergency centre at Fukushima, which was in a seismically qualified building with appropriate air filtration, proved to be crucial in enabling accident response.
— Careful evaluation of radiation protection standards under accident and post-accident circumstances should be undertaken.
— The lessons learned from the Fukushima Daiichi accident should be taken into account in designing, siting, constructing, operating and licensing new nuclear power plants.
— The Japanese experience in the recovery from the accident, including the decommissioning of the damaged reactors and the cleanup of contaminated land, will provide important lessons for the world community.
— The IAEA should enhance its interaction with the industry — including operators, research organizations and vendors.
— The IAEA should disseminate information derived from Fukushima related safety research undertaken by relevant international organizations such as the OECD Nuclear Energy Agency, and regional and national research organizations;
— The response to the Fukushima Daiichi accident should reflect the need to consider both safety and security, and to ensure that actions reflect consideration of both.
— There should be strengthened IAEA support for countries embarking on nuclear power in order to identify relevant lessons learned to be applied to new nuclear programmes.
— Objective, factual and critical IAEA peer reviews are essential for design, site evaluation, operation and a sound regulatory framework.
— An effective nuclear safety regulatory framework, including an independent regulator, is essential.
— Regulatory bodies should have sufficient competence and resources, and focus their efforts on formulating and updating regulatory guidelines and standards, taking into account the IAEA safety standards and applicable knowledge.

At the same time, it was stressed that major safety issues associated with the continued operation of nuclear power plants should continue to receive proper and adequate attention. The interest in Fukushima should not interrupt the important obligation to pursue ongoing programmes to ensure that plants continue to operate safely. In particular, continued and full compliance with the licensing and design basis is of particular importance, as it provides assurance that estimated safety margins are actually available in the event of the occurrence of an accident-initiating event.

POSSIBLE NEXT STEPS

The information presented at this experts meeting should be further analysed and be used in the implementation of the Action Plan. The preparation of a report derived from this IEM is appropriate.

There remains a need to continue international interaction. Many attendees reported that they have not completely finished their assessments. There is much still to be learned and shared. Indeed, as noted above, the development of the full set of lessons learned will likely take several years. The high level of the presentations at the meeting and the quality of interactions among the participants justify convening a similar event in the future. In the meantime, the upcoming Extraordinary Meeting of the Contracting Parties to the Convention on Nuclear Safety will be an important opportunity for further exchange.

The IAEA should make the information from this IEM available to the Safety Standards Committees and the Commission on Safety Standards (CSS). The lessons that were discussed at the meeting should be considered in the response to the Action Plan and evaluated for incorporation into IAEA safety standards.

Many countries are pursuing strengthened severe accident management, including, for example, the venting of containment. This effort raises issues that would benefit from continued interaction among experts from around the world.

Richard A. Meserve
22 March 2012

Annex B

CONTENTS OF THE ATTACHED CD-ROM

The following papers and presentations from the International Experts Meeting on Reactor and Spent Fuel Safety in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant are available on the attached CD-ROM.

RELATED DOCUMENTS

Programme of the International Experts Meeting on Reactor and Spent Fuel Safety in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant

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

Chairperson’s Summary
R.A. Meserve
Chairman, International Nuclear Safety Group (INSAG)

Chairperson’s Summary: Reactor Safety
J. Repussard
Director General, Institute for Radiological Protection and Nuclear Safety, FRANCE

Chairperson’s Summary: Spent Fuel Safety
S. Chande
Vice Chairman, Atomic Energy Regulatory Board, INDIA

A Methodology to Assess the Safety Vulnerabilities of Nuclear Power Plants against Site Specific Extreme Natural Hazards

PRESENTATIONS

Plenary Session I (Monday)

One Year after Fukushima: Lessons for a Safer Nuclear Energy
D. Flory
Deputy Director General and Head of the Department of Nuclear Safety and Security, International Atomic Energy Agency (IAEA)

Causes and Countermeasures — The Accident at TEPCO's Fukushima Nuclear Power Stations
M. Yasui
Ministry of Economy, Trade and Industry (METI), JAPAN

Prevention and Mitigation — Equal Priorities
V. Asmolov
World Association of Nuclear Operators (WANO)

NEA Response to the Fukushima Daiichi Nuclear Power Plant Accident
L. Echávarri
OECD Nuclear Energy Agency (OECD/NEA)

Plenary Session II (Tuesday)

European Union Response to Fukushima — European Stress Tests and Peer Review
P. Jamet
European Nuclear Safety Regulators Group (ENSREG)

US NRC Fukushima Lessons-Learned Actions
B. Borchardt
United States Nuclear Regulatory Commission, USA

Nuclear Safety Measures of China for NPP after Fukushima Accident
Zheng Mingguang
Shanghai Nuclear Engineering Research and Design Institute, CHINA

Comprehensive Safety Assessment for Kashiwazaki Kariwa NPS
H. Masui
Tokyo Electric Power Company, JAPAN

Lessons Learned from the Accident at the Fukushima Daiichi Nuclear Power Plant and Technical Aspects of Russian NPPs Resistance Enhancement
A.V. Shutikov
JSC Concern Rosenergoatom, RUSSIAN FEDERATION

Plenary Session III (Wednesday)

Strengthening Nuclear Safety in Canada: Regulatory Perspective Post Fukushima
R. Jammal
Canadian Nuclear Safety Commission, CANADA

Focusing on Fukushima Daiichi Deficiencies rather than on Generic Nuclear Safety Issues
A. J. González
Argentine Nuclear Regulatory Authority, ARGENTINA

Main Conclusions of the French NPPs Stress-Tests: A Need for a “Hardened Safety Core”
C. Lavarenne
Institute for Radiological Protection and Nuclear Safety, FRANCE

First Recommendations and Research Needs from a TSO Perspective
T. Schimpfke
Gesellschaft für Anlagen-- und Reaktorsicherheit mbH, GERMANY

US Industry Response to the Fukushima Daiichi Nuclear Accident
W.E. Webster
Institute of Nuclear Power Operations, USA

OECD/NEA Technical Assessments and Nuclear Safety Research: Responding to the Members’ Needs Post-Fukushima
G. Lamarre
OECD Nuclear Energy Agency (OECD/NEA)

Reactor Safety Session (Wednesday)

The Facts in the Recovery Process of Fukushima Nuclear Accident
A. Kawano
Tokyo Electric Power Company, JAPAN

Safety Improvement of Ukrainian NPPs in the Light of the Fukushima Daiichi Accident
Y. Zinchenko
State Scientific and Technical Center for Nuclear and Radiation Safety, UKRAINE

NRC Activities Related to the Fukushima Task Force Flooding and Seismic Hazard Recommendations
C. Cook
United States Nuclear Regulatory Commission, USA

Present Day EOPs and SAMG — Where Do We Go from Here?
G. Vayssier
NSC, NETHERLANDS

New Approaches to Prevention and Mitigation of Severe Accidents in the Light of Fukushima-1 NPP Events
I. Kopytov
Moscow Engineering and Physical Institute, RUSSIAN FEDERATION

Prevention of Early Containment Melt-through during Severe Accident of Light Water Reactor VVER-1000 V320 at Units 5&6 of NPP Kozloduy
D. Popov
NPP Kozloduy, BULGARIA

Possible Reactor Safety Enhancements from Sample Examination and Evaluation at Fukushima Daiichi
J. Rempe
Idaho National Laboratory, USA

Reactor Safety Panel Discussion (Wednesday)

Strengthening Nuclear Safety in Canada: Post Fukushima Strategies
F. Dermarkar
Ontario Power Generation, CANADA

Stress Tests Methodology
F. Ménage
Institute for Radiological Protection and Nuclear Safety, FRANCE

Requirements for Safety Analyses in the Light of Fukushima-Daiichi Accident
M. Lankin
SEC NRS, RUSSIAN FEDERATION

Integrated Safety-Focused Approach to Implementing Fukushima Lessons Learned
A. Pietrangelo
Nuclear Energy Institute, USA

Post Fukushima Nuclear Safety Actions in Korea to Enhance the Safety of Nuclear Installations
Joo-Eon Yang
Korea Atomic Energy Research Institute, REPUBLIC OF KOREA

Spent Fuel Safety Session (Wednesday)

Fukushima Daiichi Accident: Spent Fuel Pools — Facts, Action Taken and Issues
H. Abe
Japan Nuclear Energy Safety Organization, JAPAN

Properties and Behaviour of Irradiated Fuel under Accident Conditions
V. Rondinella
European Commission, Joint Research Centre (EC/JRC)

IRSN Approach of the Safety of the Spent Nuclear Fuel Storage Pools after Fukushima Accident
V. Elbaz
Institute for Radiological Protection and Nuclear Safety, FRANCE

Experience in Handling Damaged Spent Nuclear Fuel
S. Komarov
R&D Company “Sosny”, RUSSIAN FEDERATION

Spent Fuel Storage System Management for a Typical Two-Loop PWR Nuclear Power Plant during Hypothetical Complete Loss of External Cooling
M. Matkovič
Jožef Stefan Institute, SLOVENIA

Spent Fuel Pool Safety and Performance: Development and Application of MAAP5 Spent Fuel Model for Enhancement of EOPs and SAMGs in Light of the Accident at the Fukushima Daiichi Nuclear Power Plant and Stress Test Evaluations
R. Prior
Westinghouse Electric Company, BELGIUM

Spent Fuel Safety Panel Discussion (Wednesday)

Ageing Management for Long Term Operation of Spent Fuel Facilities
R. Versaci
National Atomic Energy Commission, ARGENTINA

Safety of SNF “Wet” and “Dry” Storage Facilities
P.M. Gavrilov
Federal State Unitary Enterprise “Mining and Chemical Combine”, RUSSIAN FEDERATION

The Application of Resilience Learning to UK Spent Fuel Management Facilities
P. Hallington
Sellafield, UK

Rethinking Used Fuel Management
M. Chiguer
AREVA, FRANCE

Nuclear Fuel Storage in the United States
R. Tropasso
Institute of Nuclear Power Operations, USA

12-47171