IAEA Report on

Protection against Extreme Earthquakes and Tsunamis in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant

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PROTECTION AGAINST EXTREME EARTHQUAKES AND TSUNAMIS IN THE LIGHT OF THE ACCIDENT AT THE FUKUSHIMA DAIICHI NUCLEAR POWER PLANT

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FOREWORD

by Denis Flory
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In response to the accident at the Fukushima Daiichi nuclear power plant, IAEA Member States unanimously adopted the Action Plan on Nuclear Safety. Under this Action Plan, the IAEA Secretariat was asked to organize International Experts Meetings to analyse all relevant technical aspects and learn the lessons from the accident. The International Experts 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 Protection against Extreme Earthquakes and Tsunamis 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

The accident at the Fukushima Daiichi nuclear power plant was the first major accident initiated by an external event — an earthquake and a resulting tsunami. It has justifiably caused a worldwide re-examination of the vulnerability of nuclear power plants to such events. INSAG agrees with the need to review all plants on a regular basis during their operating lifetime to ensure that such events are taken into account.

The world's nuclear power plants were designed and constructed to accommodate reasonably anticipated external hazards. Under the traditional approach, the nature of such events was determined by estimation of the challenge at a particular site based on the historical record — for example, the largest known flood at the site — and the plant was designed with the addition of a safety margin to acknowledge the uncertainties associated with such estimates. Unfortunately, the historical record may often be short and may provide very incomplete information as to the actual risk. As a result, the uncertainty may be large and the original margin could prove inadequate.

The situation is complicated by several additional factors. First, as a result of climate change, the risk of certain types of extreme event will become more significant over time. Extreme storms are now more probable, and with the expected rise of sea level and heavier rainfall, flooding risk will inevitably grow for many plants. Second, some extreme events may present cliff edge effects in which risk may grow significantly with slight variations in the external event. A flood that is six inches below the top of the sea wall may present no hazard, whereas one that is six inches above it could compromise vital safety equipment. The margin is thus of critical importance in such situations. Third, there is always risk that can arise from a combination of hazards. The Fukushima Daiichi units confronted both an earthquake and a tsunami. One can also easily imagine extreme events, such as earthquakes, that are associated with fires. As a result, the evaluations should consider threats that arise in combinations.

This report endorses the application of both probabilistic and deterministic methods to address such hazards. INSAG fully endorses this approach, as it can enable a deeper understanding of uncertainties, of cliff edge effects and of risk. We are hopeful that the recent INSAG report entitled A Framework for an Integrated Risk Informed Decision Making Process[1] can help in this effort.

There are two potential issues that must be addressed to update the assessments of extreme external events for existing plants. First, as this report

[1] INTERNATIONAL NUCLEAR SAFETY GROUP, A Framework for an Integrated Risk Informed Decision Making Process, INSAG-25, IAEA, Vienna (2011).

makes clear, research and development can strengthen the detailed assessments of some events, such as tsunamis. Although it will likely take many years to achieve a complete understanding of some phenomena, this fact should not delay the application of sound technical judgement for such assessments now or the continued refinement of the assessments as new knowledge becomes available. Second, a key observation from this report is that many countries do not have practical experience with probabilistic safety assessment methodologies and do not have the full capability to carry out a complete reassessment of the effects of severe external events for their plants. The IAEA should enhance its facilitation of cooperation among Member States in order to lend assistance.

As this report shows, the nuclear community is engaged in ensuring that the unique challenges presented by external hazards are recognized and addressed. There is much work to be done.

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[2]. The draft Action Plan on Nuclear Safety (the Action Plan) was approved by the Board of Governors at its September 2011 meeting[3]. 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 framework.

The Action Plan includes 12 main actions; one of the actions is focused on communication and information dissemination, and includes six sub-actions, one of which mandates the IAEA Secretariat to "organize international experts meetings to analyse all relevant technical aspects and learn the lessons from the Fukushima Daiichi accident"[4].

The IAEA Secretariat held a four day International Experts Meeting (IEM) on Protection against Extreme Earthquakes and Tsunamis in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant from 4 to 7 September 2012 at IAEA Headquarters in Vienna, Austria. The meeting was attended by around 130 experts and government officials from 37 Member States, regulatory bodies, utilities, technical support organizations, academic institutions, vendors, and research and development organizations. The IEM consisted of a plenary session and two technical sessions dealing with seismic and tsunami hazards and seismic and tsunami safety, respectively. The technical sessions featured presentations by international experts, who focused on topics identified in seven main thematic areas: databases, hazard assessment, characterization of loading effects, event warning systems, safety assessment, protective measures and lessons learned.

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

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

[4] Ibid., p. 5.

The overall objectives of the IEM were to share among Member States the lessons learned from assessing the impact of extreme natural events on nuclear power plants, taking into consideration the Fukushima Daiichi accident, as well as to exchange knowledge and research results on the latest technologies relating to site evaluation and nuclear power plant safety to protect such plants against earthquakes and tsunamis. The experts discussed the development of recent technologies and the results of ongoing research programmes relating to site evaluation and nuclear power plant safety that aim to provide protection against earthquakes and tsunamis; shared the lessons learned from recent extreme earthquakes and tsunamis; and identified issues that should be investigated further.

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 earthquake damaged electricity transmission lines and substations at the Fukushima Daiichi nuclear power plant, resulting in a total loss of off-site power. The tsunami flooded the site and severely damaged essential systems needed to provide ongoing support to sustain key safety functions, including those for cooling the reactors and spent fuel pools, and for providing backup power (the emergency diesel generators), as well as the seawater cooling pumps and the plant electrical systems. The tsunami also destroyed other structures, systems and components (SSCs). Seawater from the tsunami inundated the reactor buildings and deposited a large amount of debris on the site, degrading the infrastructure and making access to and within the site extremely difficult. The failure of the essential safety systems eventually led to severe core damage in the reactors and to the release of radioactivity to the environment.

This was the first instance of a combination of extreme natural hazards initiating a nuclear accident, providing confirmation that such hazards can overwhelm a number of levels of defence in depth at nuclear power plants. Until the Fukushima Daiichi accident, only a few nuclear power plants around the world had experienced strong earthquakes in excess of their seismic design basis. In these cases, the affected plants were safely shut down and specific studies, investigations and evaluations were conducted to assess the implications of these strong earthquakes before the plants were allowed to return to normal operation.

Member State regulatory bodies and operating organizations responded to the Fukushima Daiichi accident by: (i) assessing the designs and licensing basis of existing nuclear power plants; (ii) assessing the impact of extreme external hazards; (iii) identifying 'cliff edge' effects[5]; (iv) assessing the ability to respond to extended station blackout and loss of heat sink; and (v) assessing the response to severe accidents.

1.2. OBJECTIVE

The objective of this report is to highlight the lessons learned on the topic of protection of nuclear power plants against extreme earthquakes and tsunamis in the light of the Fukushima Daiichi accident. The central components of the report are the insights gained from the presentations by keynote speakers and invited panellists, and the discussions and contributions from the participating experts during the IEM held in September 2012. This information is supplemented by the experience gained by the IAEA Secretariat from other relevant IAEA activities, including the first IAEA fact finding mission to Japan and the IAEA expert missions on external hazards. In addition, the discussions held at the Extraordinary Meeting of the Contracting Parties to the Convention on Nuclear Safety in August 2012 also provided an important contribution to the issues covered by this report.

The report summarizes the discussions and conclusions of the IEM in the following key technical areas important for strengthening protection of nuclear power plants against extreme natural hazards of earthquakes and tsunamis:

— Seismic hazard and tsunami hazard:
  - Hazard assessment;
  - Characterization of loading effects[6].
— Seismic safety and tsunami safety:
  - Safety assessment;
  - Protective measures.

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[5] In a nuclear power plant, a cliff edge effect is an instance of severely abnormal plant behaviour caused by an abrupt transition from one plant status to another following a small deviation in a plant parameter, and thus a sudden large variation in plant conditions in response to a small variation in an input.

[6] Loading effects include ground motion and fault displacement; wave height, inundation, hydrodynamic forces, scouring, current speed and sedimentation/debris; correlation between ground motion and inundation height; speed and sedimentation/debris; correlation between ground motion and inundation height.

2. MEMBER STATE ACTIONS RELATING TO PROTECTION AGAINST EXTERNAL HAZARDS

The IEM provided the opportunity to discuss aspects of the design and operation of nuclear power plants in relation to unforeseen extreme natural hazards and unexpected events that may not have been considered in the original design. In the aftermath of the Fukushima Daiichi accident, Member States carried out extensive analyses of the accident, the sequence of events and its consequences. The scope of the analyses included assessment of the effects of extreme natural hazards (earthquake, flooding, extreme weather conditions) and the response of nuclear power plants to prolonged loss of electric power and/or loss of ultimate heat sink, and the implications for severe accident management.

During the IEM, detailed updates of the programmes developed by Member States to improve the safety of their nuclear power plants in response to the Fukushima Daiichi accident were discussed. It was evident that these programmes had many aspects in common, sharing a generic approach that can be summarized as follows:

— A set of short term measures such as the consideration of additional sources of cooling water and electrical power supply, and improvement of emergency procedures;
— A set of medium term measures such as the detailed assessment of the potential impact of external hazards on nuclear power plants and of the effectiveness of the safety improvements implemented in the short term;
— A set of long term measures to implement the engineering improvements and changes to operational procedures arising from the medium term assessments.

The Member States' national assessments focused on the identification of issues and approaches to be considered for ensuring adequate safety margins for the entire lifetime of nuclear power plants. Specific lessons learned, assessment results and recommendations for site selection and evaluation are addressed in this report.

Member States have reassessed the impact of seismic events on the reactor buildings, spent fuel pools and on-site spent fuel storage facilities. They have identified and implemented design solutions to address several safety vulnerabilities. A key feature of these reassessments has been to consider the conformity of existing safety provisions of nuclear power plants with their licensing basis. The goal of these reassessments has been to evaluate safety margins against extreme natural hazards, including events of low probability and high consequence, and to assess their adequacy.

While the experts confirmed that the combination of the seismic and tsunami events was the initiator of the Fukushima Daiichi accident, major weaknesses were revealed in the systems for power supply, reactor core cooling, spent nuclear fuel cooling and containment, as well as in the severe accident management arrangements. These areas of weakness were considered in the IAEA report on reactor and spent fuel safety in the light of the Fukushima Daiichi accident[7], published as part of a series of reports on topics dealt with by the IEMs.

An important observation in relation to the actions for protection of nuclear power plants against extreme natural hazards taken by the Member States participating in the IEM was the need for harmonization of the approach used to assess safety margins. To contribute to this harmonization, the IAEA has issued a publication entitled "A Methodology to Assess the Safety Vulnerabilities of Nuclear Power Plants against Site Specific Extreme Natural Hazards"[8]. Additional guidance on the practical implementation of this methodology is also under development.

3. SEISMIC HAZARD ASSESSMENT

Lessons Learned: Seismic hazard assessments based on historical data are not sufficient to capture low frequency seismic events. Investigations to collect prehistoric data are needed.

Site characteristics that may affect the safety of nuclear power plants should be thoroughly investigated and fully assessed. These characteristics should be monitored throughout the lifetime of a nuclear power plant.

Nuclear power plant sites need to be examined with regard to the frequency and severity of extreme natural and human induced events and of phenomena that could affect plant safety. The hazards associated with extreme natural events that are to be considered in the design of nuclear power plants need to be determined.

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[7] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA Report on Reactor and Spent Fuel Safety in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant, IAEA/IEM/1, IAEA, Vienna, Austria (2012).

[8] Ibid.; see CD-ROM attached to IAEA/IEM/1.

For an extreme natural event (or a combination of events), the parameters and the values of those parameters that are used to characterize the hazards should be chosen so that they can be easily incorporated into the design process for a nuclear power plant. In this context, earthquakes pose a significant hazard to nuclear power plants and consequently are one of the most important natural hazards that need to be investigated and evaluated. These aspects are embodied in the published IAEA safety standards[9], which require:

— Information on prehistoric, historical and instrumentally recorded earthquakes in the region to be collected and documented.
— Hazards associated with earthquakes to be determined by means of seismotectonic[10] evaluation of the region of interest, with the greatest possible use of the information collected.
— Hazards due to earthquake induced ground motion to be assessed for the site, with account taken of the seismotectonic characteristics of the region. A thorough uncertainty analysis is to be performed as a part of the evaluation of seismic hazards.

In the light of the lessons learned from the Fukushima Daiichi accident and the initial results from the reassessment of safety vulnerabilities of nuclear power plants against extreme natural hazards, the seismic hazard at an existing nuclear power plant site should be periodically re-evaluated. The re-evaluation should consider potential seismic events that are greater than those observed or recorded in historical records and should take into account the analysis of data on prehistoric events.

At the International Experts Meeting:

The discussions at the IEM provided a useful opportunity to exchange experience and information related to current seismic hazard assessment methodologies. The following key points were among those arising from these discussions.

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[9] INTERNATIONAL ATOMIC ENERGY AGENCY, Site Evaluation for Nuclear Installations, IAEA Safety Standards Series No. NS-R-3, IAEA, Vienna (2003).

[10] Seismotectonics is the study of the relationship between the earthquakes, active tectonics and individual faults of a region. It seeks to understand which faults are responsible for seismic activity in an area by analysing a combination of regional tectonics, recent instrumentally recorded events, accounts of historical earthquakes and geomorphological evidence. This information can then be used to quantify the seismic hazard of an area.

A seismic hazard assessment for a nuclear power plant site based only on historical data is not sufficiently comprehensive to characterize low probability seismic events. Consequently, an investigation of prehistoric seismic data is necessary in order to adequately define the seismic characteristics of the site.

The experts considered that there is a large variability in the predicted ground motion for a given magnitude and distance from the source of a seismic event. Therefore, as a result of this variability, the use of a bounding value for design ground motion would be overly conservative, leading to an unbalanced design[11]. Based on deterministic and/or probabilistic criteria[12], a design ground motion less than the bounding value is typically used. In every design, there is considered to be a low probability that the ground motions at a site will exceed the design basis during the lifetime of the nuclear power plant.

The experts highlighted the significant quantity and quality of new records that are being collected on seismic events, including those from the Great East Japan Earthquake. They considered that this would lead to significant advances in seismology over the next few years. As consequence of these advances, new methods of seismic hazard assessment will be introduced to improve the quality of the evaluation of nuclear power plant seismic safety. These advances will require a periodic reassessment of the seismic hazard (e.g. every 10 years, or whenever new information becomes available) to be carried out and included in the periodic safety reviews[13] of nuclear power plants.

The experts considered that all Member States should be encouraged to use probabilistic seismic hazard assessment to define the ground motions within the design basis and beyond the design basis of a nuclear power plant.

4. TSUNAMI HAZARD ASSESSMENT

Lessons Learned: Tsunami hazard assessment should take into account recent advances in deterministic and probabilistic approaches, modelling, data gathering, data analysis, field investigations and other relevant activities.

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[11] An unbalanced design is when parts of a nuclear installation are overdesigned (high safety factors) and other parts have much lower safety factors.

[12] See discussion on Safety against Earthquakes and Tsunamis in Section 9.

[13] INTERNATIONAL ATOMIC ENERGY AGENCY, Periodic Safety Review of Nuclear Power Plants, IAEA Safety Standards Series NS-G-2.10, IAEA, Vienna, Austria (2003).

Tsunami waves and associated phenomena may produce severe damage to nuclear power plants located in coastal areas. The current IAEA safety standards[14] require that potential tsunamis that can affect the safety of nuclear power plants, together with their characteristics, be assessed. This assessment should consider prehistoric data as well as historical data. In addition, all other hazards that may arise as a consequence of a tsunami need to be considered and account needs to be taken of site specific effects such as potential amplification of the tsunami force due to the coastal configuration at the site.

When assessing the potential impact of tsunamis on nuclear power plant sites, there is a need to incorporate large safety factors in order to take into account issues such as:

— The large uncertainties associated with the parameters involved in tsunami hazard assessment, particularly the characteristics of the event that may generate the tsunami;
— The uncertainties associated with the potential inundation levels at different locations on a nuclear power plant site due to the plant layout;
— The difficulties in incorporating effective tsunami protection measures for operating nuclear power plants;
— The intolerance of a number of SSCs to increased flooding levels, for example, flood related cliff edge effects.

The potential for flooding to affect multiple units (and possibly multiple sites) needs to be fully and comprehensively investigated for new and existing nuclear power plants. If flood hazards cannot be screened out, compensatory measures need to be introduced to ensure that nuclear power plants are adequately protected. These measures can be in the form of engineered safety systems and/or operating procedures.

In relation to flood hazards, all items important to safety for a nuclear power plant should be located above the level of the design basis flood. The ‘dry site’ concept[15] considered in the nuclear power plant design has to be periodically confirmed by reviewing the site flood protection measures such as sea walls and watertight doors, all of which will require periodic inspection and maintenance.

[14] INTERNATIONAL ATOMIC ENERGY AGENCY, Meteorological and Hydrological Hazards in Site Evaluation for Nuclear Installations, IAEA Safety Standards Series No. SSG-18, IAEA, Vienna (2011).

[15] In the ‘dry site’ concept, all items important to safety are constructed above the level of the design basis flood.

At the International Experts Meeting:

With regard to tsunami hazard assessment, the experts discussed the following key issues:

- The understanding of mechanisms that can generate a tsunami and how it is propagated.
- The effects of coastal amplification on the force of the tsunami, for example, from phenomena such as:
  - Seiches[16];
  - Amplifications of waves due to resonance oscillations inside semi-enclosed basins;
  - Long waves resulting from large scale atmospheric pressure differences in the region.
- Thorough consideration of all associated phenomena in the mathematical modelling used for tsunami hazard assessment for nuclear power plants.
- The need for high resolution bathymetric and topographic data for a nuclear power plant site and its vicinity.
- Uncertainties of tsunami wave parameters for a given scenario. These uncertainties can have a large effect on both deterministic and probabilistic assessments.

Although the assessment of tsunamis generated by earthquakes is commonly undertaken for site evaluation purposes, there is a lack of experience concerning tsunamis generated by landslides and even more so concerning those generated by volcanoes.

Taking into account the available data from the Great East Japan Earthquake and its consequent tsunami, the participating experts considered that in the case of the Fukushima Daiichi nuclear power plant, the tsunami hazard was underestimated and the estimation of the inundation effects on the Fukushima Daiichi nuclear power plant was not appropriate.

While the tsunami hazard assessment had been periodically updated at the Fukushima nuclear power plant taking into account the latest accepted methodology in Japan, the magnitude of the tsunami hazard was underestimated because it was based solely on historical data on relatively recent events (occurring within the past few hundred years).

[16] A seiche is a long period oscillation of the water body in an enclosed or semi-enclosed body of water, such as a lake or harbour.

5. SPECIAL FLOODING ISSUES

Lessons Learned: Design safety margins for flooding, particularly for flooding induced by a tsunami, should be reviewed using a probabilistic approach to identify any severe cliff edge effects.

The accident at the Fukushima Daiichi nuclear power plant clearly demonstrated that cliff edge effects for different extreme natural hazards may vary considerably. Flooding induced by a tsunami has the potential for a severe cliff edge effect; therefore, there is a need to consider a higher design safety margin. While it is possible to adjust deterministic hazard assessments to account for these cliff edge effects, probabilistic approaches have been demonstrated to be especially well suited for this purpose. In particular, external event probabilistic safety assessments (PSAs) provide a framework for such evaluations. In addition, PSA based safety margin assessments have proved to be an effective tool for addressing such potential vulnerabilities.

At the International Experts Meeting:

Key issues arising from the experts' discussions of specific aspects related to protection against flooding caused by a tsunami included:

— The need to consider adequate safety margins for flood hazards beyond the design basis and to evaluate the provision of additional external barriers (e.g. breakwaters, dykes) to prevent flooding of a nuclear power plant site.
— The need to consider the effect of the mass of water and any accompanying debris that may impact these flood barriers, such as run-up energy and hydrodynamic forces.
— For new nuclear power plants, protection of SSCs needs to be carefully considered during the design stage. Safety vulnerabilities identified at existing nuclear power plants need to be compensated for through appropriate safety measures (e.g. mobile diesel generators).
— All SSCs that could be challenged by a tsunami should be identified, and adequate protection should be provided considering all related effects.
— The measures to protect SSCs important to safety from tsunami hazards should have an adequate safety margin and take into account the defence in depth approach and cliff edge effects.
— The application of the dry site concept should be re-examined on the basis of lessons learned from the Fukushima Daiichi accident.

— Performance targets should be developed for structural design of tsunami safety related SSCs.
— Criteria for preventing tsunami induced fire and related protective measures should be developed.
— Early tsunami detection systems and response programmes need to be considered.

6. UNCERTAINTIES ASSOCIATED WITH SEISMIC AND TSUNAMI HAZARD ASSESSMENT

Lessons Learned: Uncertainties associated with the assessment of natural events need to be further explored.

Assessment of the occurrence and effects of natural phenomena has many associated uncertainties. The Great East Japan Earthquake confirmed that assessment of the effects of natural phenomena is plagued by uncertainties, and existing nuclear power plant safety margins may fall short of ensuring adequate protection against extreme natural hazards.

Greater understanding is needed of the uncertainties associated with the absence or limitation of knowledge (epistemic uncertainty), on the one hand, and with the intrinsic variability of natural phenomena (aleatory uncertainty), on the other hand. How to account for uncertainties associated with rare extreme natural events is an important issue to be addressed. The current understanding of the source of uncertainties associated with natural phenomena and the availability of methods to account for them needs to be explored further.

At the International Experts Meeting:

During the discussions, the experts focused on the uncertainties associated with the assessment of extreme natural events, particularly those natural events that have a low probability of occurrence and a high magnitude. The understanding of various types of uncertainty and methods to account for them was extensively debated.

The epistemic uncertainty in a seismic hazard assessment can affect the results by a factor of about 100 for sites with limited data on natural hazards and by a factor of about 10 for sites with large amounts of data.

The experts emphasized how important it was for all those involved in making decisions that may affect the safety of nuclear power plants to recognize the implications of these uncertainties.

Where uncertainties cannot be reduced by means of further investigations of the characteristics of a site, the use of hazard values below certain threshold values should not be permitted. Consequently, uncertainties have to be properly considered and evaluated in both probabilistic and deterministic approaches to natural hazard assessment, to provide high levels of confidence that established design values are adequate and that the probability of exceeding these values is acceptably low.

7. APPROACHES TO ESTABLISHING DESIGN VALUES

Lessons Learned: The design of a nuclear power plant should provide for a sufficient margin of safety along with an evaluation of potential cliff edge effects for each natural hazard considered, to ensure that the values associated with such effects do not approach the design basis for external events.

The Fukushima Daiichi accident has emphasized the need for sound margins of safety for protection against natural hazards in the design of nuclear power plants. These margins should be reassessed on a periodic basis, and the possibility of cliff edge effects should be considered. These reassessments should also inform safety improvements at nuclear power plants, such as enhancing the existing design or providing diverse approaches to ensuring that the SSCs important to safety provide the necessary safety functions.

The principal protection against seismic and tsunami hazards is provided by the development of an adequate design basis and the qualification of safety related SSCs important to safety. Hazard assessments using a deterministic approach implicitly considered uncertainties by using the maximum historical events coupled with a margin of safety to compensate for incomplete knowledge. Currently, probabilistic methodologies allow explicit treatment of uncertainties and their propagation through the various stages of the hazard assessment process. This results in development of design values with specified confidence levels consistent with design criteria and better compensates for incomplete knowledge.

Safety margins need to be taken into account for different natural hazards, including earthquakes and tsunamis, along with their associated confidence value or levels.

At the International Experts Meeting:

The experts discussed several key topics associated with the design of nuclear power plants to protect against natural hazards, including the following:

- The methods for design evaluation, including beyond design basis events, need to include both probabilistic and deterministic approaches in the assessment of safety margins.
- For each type of natural hazard, the potential for cliff edge effects and measures to deal with such effects need to be addressed.
- Site selection and evaluation for new nuclear power plants should consider the incorporation of the lessons learned in relation to the design values for external hazards.
- Evaluation of the effectiveness of defence in depth levels needs to consider an appropriate balance between deterministic and probabilistic approaches.
- It is necessary to have clear and harmonized acceptance criteria associated with the design basis, events beyond the design basis and plant performance.

8. APPROACHES TO ADDRESSING BEYOND DESIGN BASIS EVENTS

Lessons Learned: Guidelines should be developed for criteria to select the beyond design basis events to be considered in safety assessments, taking into account the uncertainties associated with natural events.

Additional efforts should be put in place to improve the modelling capabilities for complex beyond design basis scenarios, including those resulting from natural events, and to consider site effects and the impact on the surrounding region.

With reference to these complex scenarios, the importance of the need for methodologies for calculating the available margins of safety should be further emphasized. Available methods, such as PSA and seismic margin assessment[17], should be further developed to account for the complexity of these scenarios.

Strategies for deployment of preventive and mitigation measures should be developed, with reference to beyond design basis scenarios. These measures may involve either engineering or operational aspects, and they should specifically address the applicability of emergency measures and procedures.

At the International Experts Meeting:

Discussions among the experts confirmed that the safety assessment of the design and its re-evaluation should incorporate beyond design basis natural events. Many Member States proposed to add beyond design basis measures and procedures for the protection of their existing nuclear power plants.

The panel discussions raised the need for a clear identification and understanding of the failure modes of critical SSCs, with reference to their respective safety function.

The discussions indicated that few Member States have practical experience in the application of probabilistic studies for scenarios such as tsunami, aircraft crash and flooding. A few Member States rely on deterministic safety margins applied to the design basis, without reference to potential cliff edge effects that are associated with some hazards (typically flooding). The discussions confirmed that site specific PSA studies were the appropriate approach for evaluation of safety margins and were preferred by many experts.

The experts confirmed the need for clear identification of the possible failure modes of critical SSCs, as a crucial step for safety margin assessment.

The experts highlighted the need for periodic reassessment of any extreme natural hazards that may affect nuclear power plants. Many Member States are taking urgent action to undertake these reassessments within the periodic review process. In this regard, Member States were encouraged to utilize the approach provided in the IAEA Safety Guide on Periodic Safety Review of Nuclear Power Plants[18].

Some experts described the plant walkdowns[19] that have been carried out to confirm that adequate protection measures are in place for natural events,

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[17] Seismic margin assessment is a method of assessing the capability of nuclear power plants to withstand earthquakes beyond their design basis.

[18] INTERNATIONAL ATOMIC ENERGY AGENCY, Periodic Safety Review of Nuclear Power Plants, IAEA Safety Standards Series No. NS-G-2.10, IAEA, Vienna (2003).

[19] A plant walkdown is a methodical, on-site, visual evaluation of all SSCs important to safety.

particularly flooding. The support for this procedure provided by the IAEA Safety Guides was highlighted.

The protective measure of seismic isolation[20] was discussed at the IEM. This technology appears to be an effective solution for protection against design basis and beyond design basis earthquakes, especially for sites in areas of high seismic activity.

Updated technical studies will provide new data and methods to be taken into account in future assessments, such as the influence of climate change on meteorological data. Further studies should use state of the art data and methods, and address trends in hazard data.

The experts described the pre- and post-event inspections that have been carried out at many nuclear power plants to consider the potential and actual implications of natural hazards. The IAEA Safety Guide on Periodic Safety Review of Nuclear Power Plants has been recognized as providing valuable guidance in this regard.

9. SAFETY AGAINST EARTHQUAKES AND TSUNAMIS

Lessons Learned: The response of a nuclear power plant to extreme natural hazards involves complex interactions of equipment and human performance, and therefore an integrated plant response assessment methodology is needed for evaluation of the effectiveness of various defence in depth features.

Deterministic methods provide the basis for hazard assessment and should be supplemented by probabilistic methods, including PSA. External hazards and their influence on the licensing basis should be reassessed periodically, using state of the art data and methods. The IAEA Safety Guide on Periodic Safety Review of Nuclear Power Plants was identified as a good reference to be used for an integrated plant response approach.

[20] Seismic isolation is the decoupling of a building or structure from the horizontal components of an earthquake ground motion by mounting isolation devices (e.g. rubber bearings) between the building or structure and its foundation.

At the International Experts Meeting:

In the discussions, participants extensively considered the methods used or planned to be used in the post-Fukushima assessments, the insights obtained from the assessments that have been completed and lessons learned from investigations of the occurrence of other recent natural events. During the discussions, it was recognized that there is a need to understand the integrated plant response to a natural event in order to properly consider the potential accident sequences, the interactions of equipment and human performance, and the effectiveness of various defence in depth features.

During the discussion on deterministic and probabilistic approaches, it was recognized that:

- The deterministic seismic design basis for a seismic level 2 (SL-2) or safe shutdown earthquake should correspond to a peak ground acceleration of not less than 0.1g[21], even for areas of low seismic activity in line with the IAEA safety standards.
- The deterministic safety analysis approach is characterized by:
  - Unquantified probabilities associated with hazard assessment and potential induced accidents;
  - Defence in depth and safety margins introduced by design rules (not explicitly quantified).
- Probabilistic approaches are characterized by:
  - Quantified probabilities;
  - Significant numbers of accident sequences considered.
- There are advantages and disadvantages to both deterministic and PSA methodologies, which are complementary:
  - The deterministic approach is based on a success path approach aimed at preventing the occurrence of an accident;
  - The probabilistic approach considers a large number of combinations of failures and accident sequences that may lead to an accident.
- The two assessment methodologies applied together (deterministic complemented by probabilistic safety assessment) provide the best basis for safety and licensing decisions by establishing an appropriate balance between defence in depth and risk considerations. This risk informed

[21] Peak ground acceleration (PGA) is a measure of earthquake acceleration on the ground. It is often expressed in a number of g (the acceleration due to Earth's gravity). A ground acceleration of 0.1g corresponds to an intensity of VI on the modified Mercalli scale, with strong perceived shaking and light potential damage.

approach uses the combination of traditional deterministic and risk based approaches.

In the framework of the evaluation of safety margins, it was recognized that the failure modes are not always easy to select. For example, in the case of the containment, reference is usually made to a failure of the concrete, but also to tearing of the liner or to generic loss of leaktightness. The need for a clear identification and understanding of failure modes of critical SSCs, with reference to the respective safety function, as a crucial step for calculation of the safety margins was confirmed at the IEM.

10. RESEARCH AND DEVELOPMENT (R&D)

At the International Experts Meeting:

The experts proposed that the following key issues and topics be addressed in future research activities on safety margin assessment for nuclear power plants under the impact of multiple hazards:

— Improve analytical modelling capabilities and further develop tools for assessment of multi-unit sites under the impact of correlated multiple hazards induced by complex natural event scenarios.
— Further develop methodologies and tools for calculating safety margins for multiple correlated hazards using a probabilistic approach to account for the complexity, their development in time and the broad variety of potential consequences.

The experts proposed that the following key issues and topics be addressed in future research activities on tsunami hazard assessment:

(a) Validation and verification of the models used for assessing the tsunami hazard with analytical, experimental and observational benchmark data, including quantitative measures of the difference between the data predicted by the model and the measured data;
(b) Use of spatial and temporal propagation of segmented (heterogeneous) fault ruptures for earthquake generated tsunamis;
(c) Modelling of landslide and volcano generated tsunamis;

(d) Simulation of bathymetry, topography, urban settlement patterns for land use and coastal morphology in very high resolution (less than 5 m grid resolution of the region of nuclear power plant sites);
(e) Use of spatial distribution of friction coefficient according to the land use in the nuclear power plant site near region;
(f) Evidence of past tsunamis along subduction zones for improved modelling of the tsunami hazard;
(g) Further developments for numerical modelling of all phenomena associated with the tsunami coastal impact such as wave dynamic forces, scouring, sedimentation, impact of debris, resonance effects of the basin(s) or bay(s) in site near region, generation and amplification of other types of long waves (e.g. seiches, swells, storm surges);
(h) Capability to compute and output the distribution of maximum values of current velocities, flow depth, discharge flux and momentum of tsunami waves at the site for further analysis of impacts, scouring, sedimentation and debris flow;
(i) Capability to visualize 3-D animation of tsunami inundation at the site using the final plant layout modelled in the highest resolution.

11. CONCLUSIONS

The IEM confirmed that appropriate safety margins should be available in the design of nuclear power plants, taking natural hazards into account in overall plant safety. Many Member States proposed to consider beyond design basis measures and procedures for extreme natural hazards at nuclear power plants. A proper balance between all these measures and procedures should be considered, taking into account overall plant safety.

The experts highlighted the importance of the use of probabilistic assessments in the evaluation of safety margins associated with the protection against natural hazards.

The IEM confirmed that for all nuclear power plants, the deterministic seismic design basis for a seismic level 2 (SL-2) or safe shutdown earthquake should not be less than 0.1g, even for areas of low seismic activity, in line with IAEA safety standards.

The IEM also confirmed the need for a clear identification and understanding of the failure modes of critical SSCs, with reference to their respective safety function, as a crucial step in the calculation of the safety margins against natural hazards.

The experts highlighted the need to have a high level of confidence in the hazard assessments for each site in order to effectively manage the risk to the nuclear power plant from extreme natural hazards.

The importance of periodic re-evaluation of extreme natural hazards and of plant responses to such hazards was also highlighted.

There is a need to ensure that the siting and design of nuclear power plants include sufficient protection against complex combinations of extreme natural hazards and the effects of these hazards on multi-unit nuclear power plant sites.

It is essential to encourage the exchange of information and dissemination of results from ongoing safety assessments and the plant upgrade programmes being carried out by Member States worldwide.

In relation to research activities, consideration should be given to the re-examination of the requirements and guidelines for nuclear power plants in relation to extreme external natural hazards, applying all the lessons learned from recent events and the results from all ongoing evaluation, upgrading and research activities.

The IAEA plays an essential role in supporting Member States in their review of their requirements and guidance in relation to extreme natural hazards by providing assistance in the application of the IAEA safety standards and through the IAEA peer review services.

Annex A

CHAIRPERSON’S SUMMARY

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

BACKGROUND

As part of the implementation of the International Atomic Energy Agency’s Action Plan on Nuclear Safety, which was approved by the IAEA Board of Governors and unanimously endorsed by the IAEA General Conference in 2011, the IAEA Secretariat held a four-day International Experts Meeting on Protection against Extreme Earthquakes and Tsunamis in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant, from 4 to 7 September 2012, at IAEA Headquarters in Vienna, Austria.

During the last years, increasing international concern has been raised about the occurrence of extreme natural hazards (earthquakes, tsunamis, volcanoes, meteorological and hydrological hazards) and their possible impact on the safety of nuclear installations. Although in the past three decades a few nuclear power plants have experienced earthquake ground motions, strong earthquakes have occurred recently that have surpassed the original seismic design or evaluation levels and seriously affected operating nuclear power plants, mainly in Japan. The experience in this regard shows that operating plants were shut down immediately following the event and remained shut down for extended periods while comprehensive studies, investigations and evaluations were conducted to assess their safety. In most cases, no significant damage was identified in these nuclear power plant units. In a limited number of cases, upgrades were implemented to meet new definitions of the design basis or requirements for beyond design basis earthquakes. The Kashiwazaki-Kariwa nuclear power plant, affected by the July 2007 Niigataken Chuetsu-oki Earthquake, is a significant example of such cases.

However, it was the combined effects of the earthquake and tsunami in Japan on 11 March 2011 that produced the most serious consequences, with the subsequent nuclear accident at the Fukushima Daiichi nuclear power plant (the Fukushima Daiichi accident). This is the first time that external hazards have significantly contributed to a nuclear accident, thus confirming that such events may challenge all layers of defence in depth. The overarching lesson to be learned is that an integrated approach is needed to protect nuclear installations against external hazards of similar magnitude. The occurrence of this severe earthquake and subsequent tsunami has opened the gates for a critical re-examination not only of the margins of safety in the design and operation of critical facilities, but also of the equally complex process of decision making. The dialogue between the scientific community and the decision makers must ensure that policies are always guided by risk-informed processes. This way, the management of risk will become consistent.

Valuable experience has been gained and many lessons have been and are being learned by Member States and operators in managing the safety of nuclear power plants under adverse extreme conditions created by external events, as well as in the need to take a number of urgent actions by the nuclear community worldwide in all aspects involved in the Fukushima Daiichi accident.

THE INTERNATIONAL EXPERTS MEETING: OBJECTIVES AND CONDUCT

The objectives of this International Experts Meeting (IEM) were as follows:

- To share lessons learned from recent extreme earthquakes and tsunamis, including the Great East Japan Earthquake and tsunami of 11 March 2011;
- To exchange information on the development of recent technologies and the results of ongoing research programmes relating to site evaluation and nuclear power plant safety that aim to provide protection against earthquakes and tsunamis;
- To identify issues that should be further investigated.

The following two thematic areas and topics were selected for organizing the sessions:

Technical session 1: Seismic and tsunami hazards

- Databases;
- Hazard assessment;
- Characterization of effects of external events.

Technical session 2: Seismic and tsunami safety

— Safety assessment;
— Protective measures;
— Lessons learned;
— Event warning systems.

The four day IEM featured 42 expert presentations from keynote and invited speakers and contributors. Two panel sessions were held at the end of the sessions, providing a forum for open discussion and exchange of views and opinions between panellists and the audience. The topics discussed by the panels were as follows:

Panel session 1

— Assessment of hazards, with scarce or non-existent data and treatment of uncertainties for both earthquakes and tsunamis;
— Tsunami modelling, including associated phenomena;
— Combination of extreme events.

Panel session 2

— Selection of beyond design basis scenarios:
  - How much beyond?
  - How to model the scenario affecting structures, systems and components, plant, site, region?
— Incorporation of nonlinear behaviour of structures and components in margin calculation;
— Challenges of probabilistic safety/risk assessments:
  - Loss of on-site and off-site infrastructure;
  - Breach of defence in depth;
  - Time effect;
  - Risk communication.

The IEM revealed a high level of interest on the part of numerous experts from all scientific and engineering disciplines involved in the assessment of earthquake and tsunami hazards and related design safety aspects, from operating organizations to regulatory authorities, vendors and consultants. A total of 120 participants from 35 countries and one international organization participated in the meeting.

A press conference was held after the closing session on 7 September 2012.

The present summary was produced by the Chairperson and the Co-Chairpersons of the IEM on the basis of the proceedings and discussions of the IEM.

MAIN ISSUES AND LESSONS FROM THE FUKUSHIMA DAIICHI ACCIDENT IN RELATION TO EARTHQUAKES AND TSUNAMIS

General

In general, it was confirmed during the discussions and presentations that in considering external natural hazards, there is a need to ensure the following:

- The selection and evaluation of the sites and the design of nuclear plants should include sufficient protection against infrequent and complex combinations of external events, and these should be considered in the plant safety analysis — specifically those that can cause site flooding and that may have longer term impacts.
- Plant layout should be based on maintaining a ‘dry site’ concept, where practicable, as a defence in depth measure against site flooding as well as physical separation and diversity of critical safety systems.
- Common cause failure should be particularly considered for multiple unit sites and multiple sites, and for independent unit recovery options, utilizing all on-site resources.
- Any changes in external hazards or understanding of them should be periodically reviewed for their impact on the current plant configuration.
- An active tsunami warning system should be established, with the provision for immediate operator action.

Topics and issues

The topics discussed and the issues related to hazard assessments can be grouped into the following broad categories:

- *Recent advances in methods* related to hazard assessment, including deterministic and probabilistic approaches, modelling, data gathering, data analysis, field investigations and other activities.
- *Development of design basis* related to the consideration of criteria to define a design basis, various practices in the Member States and how to account for unknowns, including the need to consider minimum values.

— *Beyond design basis considerations* related to how to define events beyond those adopted for the design basis, what the deterministic and probabilistic considerations are and how to account for unknowns.
— *Uncertainties* related to lack of knowledge and to the intrinsic variability of the phenomena under analysis. How to account for uncertainties associated with defining rare extreme events is a critical issue. The understanding of various types of uncertainties and the available methods to account for them was extensively debated.
— Consideration of *new knowledge* related to the fact that our understanding of natural hazards continues to evolve, and that systematic, predictable and stable approaches are needed to address the new and significant information as it emerges.

Consequently, from the perspectives of safe design of nuclear power plants against natural hazards and evaluation of plant capabilities, the following topics were discussed:

(1) Methods associated with the design and beyond design basis evaluations, including the use of probabilistic and deterministic margin assessment types of approach, understanding of why safety margins exist, advances in modelling, and availability of tests and experience data;
(2) Cliff edge effects and measures to address them, considering the specific differences for each type of external event;
(3) Consideration of selection and evaluation of sites and how to incorporate the lessons learned for countries embarking on nuclear power programmes for the first time;
(4) Consideration of risk-informed approaches, including the need for balance between deterministic and risk-based approaches and the formulation of adequate strategies for unique aspects of defence in depth associated with the natural hazards;
(5) Acceptance criteria associated with establishment of the design basis, beyond design basis events and plant performance.

In discussing the above issues, the participants in this IEM discussed the methods used or planned to be used in the post-Fukushima evaluations, insights obtained from the evaluations that have been completed and the lessons learned from the investigations of recent events as carried out to date.

In addition to discussion of the available methods and enhancement needed, items 4 and 5 above related to risk-informed approaches and related acceptance criteria were extensively debated. There was a recognition that it is necessary to understand the integrated plant response to a combination of natural events, with a thorough knowledge of the potential accident sequences and scenarios, interactions of equipment and human performance, and effectiveness of various defence in depth features.

Integration of the design process needs to be properly considered in order to ensure performance and an adequate safety margin (to guard against the 'unknowns') at the structure and component levels, with the evaluation of integrated plant response as a whole system. It was emphasized that defence in depth considerations must be combined with risk information in order to establish an effective, systematic and comprehensive regulatory framework for adequate protection of nuclear installations against these external natural hazards.

ACTIONS TAKEN BY MEMBER STATES AS A RESPONSE TO THE FUKUSHIMA DAIICHI ACCIDENT IN RELATION TO EXTERNAL NATURAL HAZARDS, MAINLY EARTHQUAKES AND TSUNAMIS

The presentations at this IEM further confirmed the point made in the Chairperson's Summary of the IEM on the reactor and spent fuel safety[1] that there were common elements in the efforts directed at assurance of protection of nuclear installations against the effects from extreme external natural hazards.

Among other things, these elements included:

— Dealing with a long term station blackout and loss of heat sink;
— Developing mitigation strategies for external events beyond the design basis;
— Controlling hydrogen deflagration and detonation;
— Implementing reliable spent fuel pool instrumentation;
— Re-evaluating external hazards specific to the nuclear installation sites, particularly seismic hazards and flooding (which includes tsunami related flood effects);
— Evaluating the plant responses to the re-evaluated hazards as well as assessing the capability and the available safety margins to withstand a potential higher level of hazards, including the communication of the associated risks.

[1] INTENATIONAL ATOMIC ENERGY AGENCY, IAEA Report on Reactor and Spent Fuel Safety in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant, IAEA/IEM/1, IAEA, Vienna, Austria (2012).

The last two items were the topics of this IEM. The presentations by experts from various Member States discussed progress, activities and research related efforts regarding hazard reassessments and capacity evaluation methods. The focus was on identification of the issues and of approaches to be considered to address these issues, not only from the perspective of the two items above, but also going forward in incorporating lessons learned for selection and evaluation of sites, for design and for operation. Thus, the IEM provided a detailed update of the programmes developed by a number of Member States to improve the safety of nuclear installations as a consequence of the Fukushima Daiichi accident.

The evaluation and upgrading programmes have many aspects in common and share a generic structure that can be summarized in the following three main phases:

(1) A set of immediate, short term, evaluation and ‘easy fixes’ measures, of both an engineering and an operational nature, is under deployment, addressing redundancies of additional sources of water and power supply, and improvement of emergency procedures.
(2) A medium term set of measures will be completed in few years, aimed at further detailed reassessment of the external hazards that affect safety and of the effectiveness of implementing ‘not so easy fixes’ measures at the plants.
(3) A long term set of measures will be implemented through programmes of upgrading and operational changes as a consequence of previous assessments.

KEY ISSUES AND TOPICS TO BE FURTHER INVESTIGATED

General

The sheer size of the fault rupture that occurred off the east coast of Japan on 11 March 2011 (the 2011 Great East Japan Earthquake) and the height and breadth of the tsunami waves it hurled against the coastal settlements have rightfully demanded that the nuclear community should re-examine its established guidelines for describing the bounds of the design domain for critical nuclear facilities.

That event has confirmed that the assessment of the effects of natural phenomena is plagued by unknown uncertainties (or unknown unknowns), and that the already available safety margins may fall short of ensuring adequate protection to people and the environment. Experts need to reconsider the abstruse concepts of probability theory to ensure that the correct tools are used correctly to cover the tail ends of probabilistic distributions and the residual risks.

The data from the 2011 Great East Japan Earthquake and tsunami indicate that the criteria used for predicting the seismic ground motion and tsunami generation, propagation and inundation effects at the Fukushima Daiichi nuclear power plant site were not appropriate. While the tsunami hazard assessment has been periodically updated at the Fukushima Daiichi nuclear power plant considering the latest accepted methodology in Japan, the size of the hazard was still underestimated because it was based on historical data from recent events (within the past few hundred years). Extreme events could have been assessed from the persistent occurrence of mega-size subduction zone earthquakes, each generating major tsunamis, during the past fifty years around the Pacific Ocean periphery. Regarding the need to fill the gap between scientific development and the institutional framework, the concept of 'technology governance' as defined in some countries was proposed as a key technology management framework for nuclear safety based on the experience of the Fukushima Daiichi accident as well as on the current situation in Japan in relation to the roles to be played by regulators, operators and academics to ensure that the decision making process properly considers all the critical elements. A definition of technology governance was proposed, and its significance was elaborated on the basis of both reports by the Japanese Government and the National Diet of Japan, and the IAEA safety standards.

During the discussions, it was pointed out that the term 'risk-informed' should be used instead of 'risk-based' to represent holistic frameworks incorporating both deterministic and probabilistic approaches in a comprehensive manner.

Seismic hazard assessment

Key issues

There is a large variability in the ground motion for a given magnitude and distance. Using a bounding value for ground motion is not practical, and a design ground motion less than the bounding value needs to be used.

There is a small but non-zero chance of experiencing ground motions beyond the design basis. The characteristics of the rare ground motions that exceed the design basis may be significantly different from those of more typical ground motions.

There is a large uncertainty in the estimated seismic hazard. The uncertainty that corresponds to the lack of knowledge (i.e. the epistemic uncertainty) in seismic hazard assessment can be greater than a factor of 100 for sites in areas with sparse data and near a factor of about 10 for sites in areas with large amounts of data. Utilities and regulators need to understand and to properly address all uncertainties involved in the decision making process. While epistemic uncertainty can be addressed through the use of increasingly refined ground motion prediction models, the inherent variability in ground motions does not lend itself to easy quantification.

Seismic hazard based on historical data is not sufficient to capture the long term hazards, and investigations to collect prehistoric data are needed. However, the uncertainties that cannot be reduced by means of site investigations do not permit hazard values to decrease below certain threshold values. Simplified approaches such as a minimum seismic loading for design of nuclear installations can be used to address the large uncertainty and potential for unknown faults.

It is common to use the weighted average (mean) estimate of the risk, but this is one value in a very large uncertainty range. The use of the mean value captures some effects of the uncertainty due to the skewed distribution of the uncertainty, but only partly.

Considering that an impressive amount of new ground motion data is being collected and new methods are being developed, it is expected that significant changes will occur over the next 1–2 years in the seismological science. Overall, significant revisions in the earthquake science relevant to seismic hazard assessment are occurring over 5 year time periods. Therefore, considering the fact that seismic hazard evaluations will likely not remain valid over the life of the power plant, periodic updates of the seismic hazard are to be carried out. Setting a schedule for planned updates is needed, to allow long term budgeting so that funding is available.

Topics to be further investigated

— Evaluate the revision of existing criteria regarding minimum seismic loading for design of nuclear installations located in regions with sparse data, to address the large uncertainties and possible unknown blind faults.
— Evaluate the characteristics of the ground motions beyond the design basis (e.g. spectral shape and time history characteristics) for use in evaluating the effects on plant safety.
— As part of risk informed regulation, consider the uncertainty range in the risk and not just the mean risk. Evaluate the confidence that the risk is acceptably low. Similarly, before making plant upgrading (or shutdown) decisions, evaluate the confidence that the risk is unacceptably high.
— There is a need for a full update of the seismic hazard every 10 years, or when new evidence arises, incorporating new seismic information.

— Encourage the use of probabilistic seismic hazard assessment to guide the selection of deterministic events, with an emphasis on the selection of the number of studies for defining the design and beyond design ground motions.
— Each Member State has responded to the challenges posed by the Great East Japan Earthquake in its own way, and in proportion with its own means. This has opened the way for useful data exchange among them, so that experience and data are transferred to the appropriate platforms.
— Variability of the seismic hazard and fragility of the structures, systems and components of the nuclear installation should be properly accounted for, ensuring consistent end designs.

Tsunami hazard assessment

Key issues

The recent improvements in numerical tsunami modelling are recognized for application in assessing the associated hazards at nuclear installation sites. In general, the modelling is more widely applied to earthquake generated tsunamis and, partly, to landslide generated tsunamis. There are no remarkable modelling applications to volcano generated tsunamis. The key aspect that is vital for accurate tsunami modelling is proper determination of the source mechanisms that generate the phenomena.

The generation and coastal amplification of associated phenomena such as (i) seiches due to forcing of continuous energy input to the basins, (ii) amplification and resulting resonance oscillations inside the semi-enclosed basins or (iii) long waves resulting from large scale atmospheric pressure differences in the region should also be taken into account in the assessment of external flooding. Hazard analysis by tsunami numerical modelling for nuclear power plants should also cover these associated phenomena.

The highest resolution of bathymetric and topographic data, covering land use plans at the site and in site vicinity areas and including all morphological details, is essential for high quality tsunami modelling applications.

Modern tsunami hazard evaluations following current guidance are based on numerical simulations for deterministic scenarios, and the key issue is the proper characterization of the potential tsunamigenic sources. Conservative assumptions on the sources are to be used, but aleatory variability of the tsunami wave parameters for a given source scenario is not usually addressed. As seen in ground motion hazard estimates, the aleatory variability can have a large effect on both deterministic and probabilistic evaluations and the computed tsunami waves will not be bounding values.

Topics to be further investigated

For improvement of tsunami modelling

Proof of validity and verification of the model used for assessing the tsunami hazard with analytical, experimental and observational benchmark data, including quantitative measures of the model data misfits:

- Capability to use spatial and temporal propagation of segmented (heterogeneous) fault ruptures for earthquake generated tsunamis;
- Capability to model landslide and volcano generated tsunamis based on estimated parameters;
- Capability to estimate traces of past tsunamis along subduction zones for improved modelling of the tsunami hazard;
- Capability to use the sea level change by tidal wave or topography/bathymetry change due to ground subsidence/uplift by tectonic motion;
- Capability to simulate the bathymetry, topography, urban settlement patterns for land use and coastal morphology at a very high resolution (less than 5 m grid resolution of the near region of nuclear installation sites);
- Capability to use spatial distribution of friction coefficient according to the land use in the near region of the nuclear installation site;
- Capability to compute and output the distribution of maximum values of current velocities, flow depth, discharge flux and momentum of tsunami waves at the site for further analysis of impacts, scouring, sedimentation and debris flow;
- Capability to visualize 3-D animation of tsunami inundation on the site using the final plant layout at the highest resolution.

For consideration of all associated phenomena

- Further developments are required for numerical modelling of all phenomena associated with the tsunami coastal effects, such as wave dynamic forces, scouring, sedimentation, impact of debris, resonance effects of the basin(s) or bay(s) in site near region, and generation and amplification of other types of long waves (such as seiches, swells, storm surges).

Combination of extreme natural hazards

Key issues

The safety goal should be defined considering comparable risk contributions from all sources including different natural hazards and their combination.

The combination should cover all extreme external natural hazards that can potentially affect the site, either as concomitant or physically separated events.

Topics to be further investigated

The proper combination of all potential combined scenarios for external events to be considered in the design and in the re-evaluation of the safety of nuclear installations, including consideration of all associated phenomena.

Safety against earthquakes and tsunamis

Key issues

In the aftermath of the Fukushima Daiichi accident, the Member States carried out extensive analysis of the accident root cause, sequence and consequences, deriving a set of generic lessons learned, which triggered detailed evaluation and upgrading programmes.

This IEM extensively discussed the lessons learned through a number of technical papers and panel discussions, deriving the conclusion that substantial agreement is shared on the analysis and interpretation of the Fukushima Daiichi accident.

In this regard, the following can be summarized:

(1) The design process (and the re-evaluation of the safety of existing nuclear installations) should consider external event scenarios beyond the design basis, in order to account for:
   - Residual risk from events with intensities beyond the design basis (i.e. the ‘tail’ of the probabilistic hazard distribution);
   - Inaccurate or incomplete modelling of the hazard due to insufficient data availability or knowledge of the scenario development (e.g. undetected faults in the seismic hazard);
   - Unforeseen scenarios, not included in the design process (i.e. scenarios from unforeseen sources).

(2) Guidelines should be developed providing sustainable selection criteria for scenarios beyond the design basis to be considered in the site selection, site evaluation and design processes for new nuclear installations. The current IAEA Safety Guides already offer insights and suggestions in this regard. Improvement in current screening criteria may be recommended. Some scenarios may offer physical bounding criteria, while in other cases (e.g. seismic) the associated risk to the people and environment is probably the only approach to bound the scenario intensity. Communication strategies for the acceptable risk that is intrinsically present in the assessment of natural hazards should also be developed in this regard.

(3) A supplemental effort should be put in place to improve the modelling capabilities for complex scenarios, extending the analysis to the effects on the site and in the surrounding region. Safety related issues should be addressed (such as site access and evacuation, contamination of personnel and the public, etc.), but also social consequences (such as mass evacuation).

(4) With reference to those complex scenarios, methodologies for the calculation of the available safety margins should be developed. Available methods (probabilistic risk assessment, seismic margin assessment, etc.) should be further developed to account for the complexity of the scenarios, their development in time and the broad variety of potential consequences. At the same time, appropriate measures for risk reduction effectiveness should be developed and agreed.

(5) Strategies for deployment of preventive and mitigation measures should be developed, with reference to beyond design basis scenarios. Their nature may be either engineering or operational and they should specifically address the applicability of emergency measures and procedures.

Topics to be further investigated

Specific issues were discussed at the IEM to be used to fine-tune future research tasks, namely:

— On the basis of an appropriate design approach, but also on the basis of recent evidence worldwide from cases where design basis values were exceeded (without major damage to the plants in some cases), the IEM confirmed that the design of nuclear power plants should incorporate external events beyond the design basis. IAEA fact finding mission reports and assessment reports, now publicly available after recent events, are very useful to drive this process, avoiding excessive conservatism and properly addressing the issue. Many Member States have proposed to add beyond design basis measures and procedures to their operating units and to improve the capacity of emergency centres in order to accommodate unprecedented external scenarios. A proper balance between all adopted measures may be optimized, with guidance on the scenarios to be considered for their deployment.

— Despite the availability of guidelines in many Member States and at the IAEA in the area of probabilistic studies applied to external event scenarios, few Member States have developed practical experience on that subject for some challenging combined scenarios such as tsunami, aircraft crash, flooding, etc., and in a few cases rely on deterministic safety margins applied to the design basis, without reference to potential cliff edge effects associated with some scenarios (typically flooding). The IEM confirmed the preference for probabilistic and site specific approaches as the tool for any evaluation of the safety margins.

— In the framework of the evaluation of safety margins, the failure modes are not always easy to select. For example, in the case of containment, reference is usually made to concrete failure, but also to liner tearing or to generic loss of leaktightness. The IEM confirmed the need for clear identification and understanding of the failure modes of critical structures, systems and components, with reference to the respective safety function, as a crucial step for calculation of the safety margins.

— The need for periodic reassessment of the external hazard at nuclear plants was stated at the IEM, and many Member States are taking urgent action in order to update their baseline in view of that periodic safety review process. This is considered a generic trend, and all Member States have been invited to join the approach, which is already well stated in the current related IAEA safety standards.

— Plant walkdowns have been conducted at many sites in relation to protection against external events, particularly seismic and seismic induced fires and flooding. Guidelines are available, and the use of IAEA Safety Guides is encouraged to support this safety evaluation process.

— Seismic isolation is a technique for protection against design basis and beyond design basis scenarios that needs to be further considered. Guidelines are being developed in some Member States, although these are not always in agreement. This technology seems to be a promising solution for nuclear installations in high seismicity sites. The IAEA already addresses this technology in the safety standards programme. More efforts on testing and performance comparisons have to be carried out for broader application, and a clear and well established regulatory framework, not defined yet, should be established in the technology supplier and receiving countries.

— Pre- and post-event inspections have been undertaken in many reactor units preceding and following major events. The IAEA guidelines, with particular emphasis on Safety Report Series No. 66[2], which was taken as a model for some countries, have been recognized as valuable in this regard. Extension of their scope to scenarios other than seismic scenarios may be encouraged.

NEXT STEPS

— The valuable information and the detailed description of the key issues identified during this IEM, as well as the topics defined to be further investigated in relation to external extreme hazards affecting the safety of nuclear installations, should be incorporated in the programme of implementation of the IAEA Action Plan on Nuclear Safety.

— Further lessons need to be drawn from the ongoing safety evaluation processes and plant upgrades implementation programmes. Therefore, it is essential to encourage the exchange of information and dissemination of results from the studies and programmes being carried out by Member States to the nuclear community worldwide and to the public at large. They are key elements for learning from past events, for enhancing the safety of nuclear installations, and for preventing and/or mitigating the consequences of future events. The IAEA should play a key role in this direction with activities like this IEM.

— The nuclear community should re-examine its established requirements and guidelines in relation to the external extreme hazards for nuclear facilities using all the lessons learned from recent events and the results from all ongoing evaluation, upgrading and research activities. The IAEA may play an essential role in this regard, by assisting Member States in the application of the international safety standards through the existing IAEA safety services.

Chairperson: Antonio R. Godoy
Co-Chairpersons: Nilesh Chokshi
Paolo Contri
Polat Gulkan
Kenji Satake
7 September 2012

[2] INTERNATIONAL ATOMIC ENERGY AGENCY, Earthquake Preparedness and Response for Nuclear Power Plants, Safety Reports Series No. 66, IAEA, Vienna (2011).

Annex B

CONTENTS OF THE ATTACHED CD-ROM

The following papers and presentations from the International Experts Meeting on Protection against Extreme Earthquakes and Tsunamis in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant are available on the attached CD-ROM.

RELATED DOCUMENTS

Programme of International Experts Meeting on Protection against Extreme Earthquakes and Tsunamis in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant

Opening Remarks
A.R. Godoy
Independent Consultant, Managing Director of James J. Johnson and Associates, USA

Measures against Earthquakes and Tsunamis in View of the Accident at Fukushima Daiichi Nuclear Power Station
Y. Moriyama
Deputy Director-General for Nuclear Accident Measures, Nuclear and Industrial Safety Agency, JAPAN

Status Report on Tohoku EPCO's Onagawa NPS Seismic Experience Data Collection
S. Samaddar
Head, International Seismic Safety Centre, International Atomic Energy Agency (IAEA)

Chairperson's Summary
A.R. Godoy
Independent Consultant, Managing Director of James J. Johnson and Associates, USA

PRESENTATIONS

Plenary Session

Role of PRA in Enhancing External Events Safety — The Past, Present, and Future
G. Apostolakis
US Nuclear Regulatory Commission, USA

Advances in Tsunami Numerical Modeling with Examples Related to Safety of NPPs
A.C. Yalciner
Middle East Technical University, TURKEY

Seismic Hazard Evaluation and Beyond Design Basis Events Considering New Earthquake Science Information
N. Abrahamson
University of California, Berkeley, USA

Technology Governance for Nuclear Safety under Earthquake-Tsunami Environments — Engineering Mission to Overcome the 3.11 Fukushima Disaster
H. Kameda
Kyoto University, JAPAN

Robustness of Russian Design NPPs against Extreme Earthquakes and Tsunami
V. Kostarev
'CKTI-Vibroseism', RUSSIAN FEDERATION

Initiatives of the NEA in Response to the TEPCO Fukushima Daiichi NPP Accident
A. Huerta
OECD Nuclear Energy Agency (OECD/NEA)

Invited Speaker Presentations

Source of Margins Available for Dealing with Beyond Design Basis Earthquakes
P. Labbé
EDF, FRANCE

The Outlook for Nuclear in Canada after Fukushima
A. Blahoianu
Canadian Nuclear Safety Commission, CANADA

What We Learned from the 2012 Megathrust Earthquake (M9.0) Along the Japan Trench — Paleoseismological Perspectives
K. Okumura
Hiroshima University, JAPAN

Improvement Measures for NPPs in China in light of Fukushima Accident
G. Chai
Nuclear and Radiation Safety Center, CHINA

Safety Margin Assessment of Bulgarian NPPs for External Events
M. Kostov
Risk Engineering Ltd., BULGARIA

Technical Session 1: Seismic and Tsunami Hazards

Current Issues and Front Line of Strong Motion Research after the 3.11 Tohoku Earthquake and Future Perspective for Nuclear Safety
K. Irikura
Aichi Institute of Technology, JAPAN

Checking of Seismic and Tsunami Hazard for Coastal NPP of Chinese Continent
Chang Xiangdong
Nuclear and Radiation Safety Center, CHINA

Strong Ground Motion Observed at Fukushima Daiichi NPS during the 2011 Great East Japan Earthquake
H. Mizutani
Tokyo Electric Power Company, JAPAN

Tsunami Generating Potential of Makran Subduction Zone
J. Hussain
Pakistan Atomic Energy Commission, PAKISTAN

Past Tsunami Evaluation and Tsunami of March 11th in 2011 at Fukushima Daiichi NPS
M. Takao
Tokyo Electric Power Company, JAPAN

Tsunami Evaluation of Coastal Nuclear Power Plants in India
R.K. Singh
Bhabha Atomic Research Centre, INDIA

Lessons to be Learned from the Fukushima NPP Accident with Particular Focus on New Build Projects
A. Gürpinar
James J. Johnson and Associates, USA

Research and Development Programme on Seismic Ground Motion Assessment: SIGMA
G. Senfaute
EDF, FRANCE

The Consideration of Chinese Nuclear Power Plant Safety Technology Research Program after Fukushima Accident
R. Pan
Nuclear and Radiation Safety Center, CHINA

Safety Requirements in France for the Protection against Extreme Earthquakes
R. Pierre
French Nuclear Safety Authority (ASN), FRANCE

Expecting the Unexpected: Recurrence, Fat Tails, and Tsunami PRA
W. Epstein
Scandpower Risk Management, USA

Recipe for Assessing Design Tsunami Height in Light of the 2011 Tohoku Earthquake and Tsunami
Y. Iwabuchi
Japan Nuclear Energy Safety Organization, JAPAN

Fukushima Daini Independent Review and Walkdown
J. Richards
Electric Power Research Institute, USA

Elaboration of Tunisian Earthquake Catalogue
W. Limam
Tunisian Company of Electricity and Gas, TUNISIA

Technical Session 2: Seismic and Tsunami Safety

Post Fukushima Actions Related to Seismic Risk/Margin in the United States
G. Hardy
Simpson Gumpertz and Heger, USA

Safety Re-evaluation and Related Research Activity against Extreme External Events for Korean Nuclear Power Plants
I.-K. Choi
Korea Atomic Energy Research Institute, REPUBLIC OF KOREA

Perspectives of SPRA and SMA to Enhance Seismic Safety for New Reactors in United States
N. Chokshi
U.S. Nuclear Regulatory Commission, USA

Developing New Regulatory Guideline on Seismic Isolation of Japan and the US
H. Abe
Japan Nuclear Energy Safety Organization, JAPAN

Structural Integrity of Fukushima-Daiichi SSCs after the 2011 Great East Japan Earthquake
K. Nagasawa
Tokyo Electric Power Company, JAPAN

Way for Establishing Tsunami Resistant Technology for Nuclear Facility in Japan
N. Takamatsu
Japan Nuclear Energy Safety Organization, JAPAN

Early Warning and Communication Systems for Earthquakes and Tsunami in Kenya
E.K. Kiema
National Disaster Operation Centre, KENYA

EU Stress Tests: Spanish Results on Seismic Events
J. Sanchez Cabanero
CSN, SPAIN

Protection of Russian NPPs against Extreme Earthquakes and Tsunamis: Results and Findings from the Implementation of Russian NPP Evaluation Procedures
D. Sviridov
Rostechnadzor, RUSSIAN FEDERATION

Post-Earthquake Investigations at North Anna Nuclear Power Plant
Yong Li
U.S. Nuclear Regulatory Commission, USA

“TiPEEZ System” for Information Management against Earthquake, Tsunami and Nuclear Disaster, Considering Nuclear Risk Communication
K. Ebisawa
Japan Nuclear Energy Safety Organization, JAPAN

The Seismic Safety Evaluation Programme of the Atucha I (CNA-I) NPP-Argentina at the Light of Lessons Learned from Fukushima Daiichi NPP Accident
A.R. Godoy and J.J. Johnson
James J. Johnson and Associates, USA

Code and Guide for the Society Experienced 3.11 Event: How to Advise Our Friends to Establish Their Own Code and Guide for Newcomers
H. Shibata
University of Tokyo, JAPAN

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