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SEVENTH FRAMEWORK PROGRAMME

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Abstract

The Work Package 2 of the project STREST summarizes the state-of-the-art as a basis for the development of a framework for the future testing of critical infrastructures (CIs).

This report addresses Task 2.1 "Lessons learned from stress tests of nuclear facilities". It provides a review of the methodologies and findings from post-Fukushima stress tests and advanced plant safety assessment studies for nuclear power plants (NPPs). Findings and lessons learned are extracted from the specification and the summary reports of the European stress-test project for NPPs and from a selection of relevant guidelines and reports on plant safety assessments elaborated by the International Atomic Energy Agency IAEA.

Keywords: Stress test, nuclear power plant, natural hazard, risk assessment

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1 Introduction

The Work Package 2 of the project STREST summarizes the state-of-the-art as a basis for the development of a framework for the future testing of critical infrastructures (CIs). It provides a review and comparison of the methodologies and findings from:

- Post-Fukushima stress-tests and advanced plant safety assessment studies for nuclear power plants (NPPs, Task 2.1);
- National standards for hazard and risk assessment and for stress-tests for different classes of CIs (Task 2.2);
- Recent catastrophic events (Task 2.3);
- Relevant on-going and completed EU projects (Task 2.4).

This report (Deliverable 2.1) addresses Task 2.1. It is based on the specification and the summary reports of the European stress-test project for NPPs and on a selection of relevant guidelines and reports on plant safety assessments elaborated by the International Atomic Energy Agency IAEA (see "References").

2 ENSREG: EU Stress-Tests for European Nuclear Power Plants

2.1 OBJECTIVE

In the light of the Fukushima reactor accident in March 2011 the European Council of 24/25 March, 2011, requested that the safety of all EU nuclear plants should be reviewed, on the basis of a comprehensive and transparent risk and safety assessment ("stress-tests"). These “stress-tests” are defined as targeted reassessments of the safety margins of nuclear power plants, developed by the European Nuclear Safety Regulators group ENSREG, including the European Commission.

The assessments are based on the specifications largely prepared by the Western European Nuclear Regulators Association WENRA and submitted by ENSREG (ENSREG, 2011). They cover extraordinary triggering events like earthquakes and flooding, and the consequences of any other initiating events potentially leading to multiple loss of safety functions requiring severe accident management. Human and organisational factors are part of these assessments.

For each plant the assessment reports on the response of the plant and on the effectiveness of the preventive measures, noting any potential weak point and cliff-edge effect, for each of the considered extreme situations. This is to evaluate the robustness of the defence-in-depth.

The safety assessment covers extraordinary triggering events like earthquakes and floods and the consequences of any other initiating events (e.g. transport accidents, such as airplane crashes) potentially leading to multiple loss of safety functions requiring severe accident management. All the operators of nuclear power plants in the EU had to review the response of their nuclear plants to those extreme situations.

2.2 SCOPE

The technical scope of the stress-tests has been defined in (ENSREG, 2011) considering the issues that have been highlighted by the events that occurred at Fukushima, including combination of initiating events and failures. It covers the structures, systems and components (SSCs) which are essential for the safety of the nuclear power plants, providing the following basic functions:

- Control and cooling of the reactor;
- Cooling of the spent fuel facilities;
- Containment of the radioactivity.

The focus was placed on the following issues:

a. Initiating events

   Earthquake, Flooding, Extreme weather conditions;

b. Consequence of loss of safety functions from any initiating event conceivable at the plant site;
c. Severe accident management issues.

Points b and c are not limited to earthquake, tsunami and extreme weather conditions, flooding is included regardless of its origin.

Furthermore, the assessment of consequences of loss of safety functions is relevant also if the situation is provoked by indirect initiating events, for instance large disturbance from the electrical power grid impacting power distribution systems, forest fire or airplane crash.

The review of the severe accident management issues focuses on the licensee's provisions but it may also comprise relevant planned off-site support for maintaining the safety functions of the plant. Although the experience feedback from the Fukushima accident may include the emergency preparedness measures managed by the relevant off-site services for public protection (e.g. fire-fighters, police, health services) this topic is out of the scope of these stress-tests.

2.3 METHODOLOGY

2.3.1 Assessment Areas

The European Commission communicated in (EC, 2012a) that three main areas had to be assessed, according to the specifications:

1. For the extreme natural events earthquake, flooding, extreme weather conditions:
   Hazard assessment,
   design basis events,
   protection measures,
   vulnerabilities,
   evaluation of design and beyond design events,
   safety margins for beyond design events, with special emphasis on cliff edge effects,
   recommended upgrades and safety enhancements.

   The quantification of safety margins was based on „success path concept“, which identified scenarios for safe plant conditions in case of emergency and the corresponding system components needed to remain available.
2. Response of the plants to prolonged loss of electric power including station blackout (SBO) and/or loss of the ultimate heat sink (UHS), irrespective of the initiating cause.
3. Severe accident management
   Means to protect from and to manage loss of core cooling function, loss of cooling function in the fuel storage pools and loss of containment integrity.

These areas were systematically structured with a checklist, consisting of a series of questions or issues to be evaluated. The table of contents in Appendix A follows in principle this checklist and questions.

The evaluation was based in most cases on existing documentation and available studies, such as system specifications, hazard studies, design analyses and safety analysis reports. In special cases complementing investigations had to be undertaken, in order to provide updated data or analyses.

2.3.2 Project Phases

The safety assessments were organised in three phases:

- Phase 1
  Self-assessments by nuclear operators

  The results of the evaluations are documented in plant specific technical reports. The nuclear licensees were asked to submit their reports to the national regulators by 31 October 2011.

- Phase 2
  Review of the self-assessments by national regulators

  The national regulators reviewed the information supplied by the licensees. They asked for complementary information and for revisions and they prepared the national reports by 31 December 2011 (see References "EU Stress-Test Country Reports").
  For one representative example of a country report, Appendix A shows the table of content, which follows the structured questions and checklist established with the ENSREG specification.
  All national reports were submitted to the Commission within the agreed deadline.

- Phase 3
  Peer reviews of the national reports, conducted in the period January – April 2012 (ENSREG Stress Test Peer Review Board, 2012a, 2012b)

As soon as the peer review process started, the public and stakeholders were provided with the opportunity to engage in the “stress-tests”. The project encouraged for active public involvement, by establishing platforms for questions and comments. In phases 2 and 3, the final reports were published on the websites of ENSREG and the national regulators.

2.3.3 Peer Review Process

In order to provide an objective assessment of the work done at national level and to maximise coherence and comparability, the national reports were subjected to a peer review process, organised in three phases (ENSREG, 2012a):

- A desktop review phase where the 17 national reports were analysed by all the peer reviewers, who posed more than 2'000 written questions on the reports. The EU Stress-Test secretariat run by the Joint Research Centre of the Commission opened a dedicated website to gather questions from the public for the peer reviews.
- A peer review related to horizontal topics, comparing the consistency of the national approaches and findings in three key areas: extreme natural events, loss of safety functions and severe accident management. The topical review meetings were organised at the Commission premises in February 2012, and involved around 90

experts. National teams were called in and asked to answer the questions posed in the desktop review phase. The result is documented in a summarizing peer review report (ENSREG Stress Test Peer Review Board, 2012a) and in 17 country specific reports (ENSREG Stress Test Peer Review Board, 2012b) for the participating countries, with a list of remaining open questions for the ensuing country peer reviews.

- A vertical, individual review of each of the 17 country reports.
  The country peer reviews took place in March 2012 and included one NPP site visit in each country. The total number of reactor units on the sites visited during the originally scheduled visits in March 2012 was 43 (approximately 30% of all the units in operation). Additional visits were performed to eight reactor sites by the peer review teams in September 2012, in order to gain additional insight on different reactor types, to discuss implementation of the identified improvements and in order to alleviate concerns relating to installations in areas bordering other Member States. Thus, all operating reactor types in Europe have been visited by peer reviewers.

  The plant visits confirmed the prior analyses and in some cases have led to additional recommendations.

The peer review teams were composed of nuclear safety experts from EU Member States, Switzerland, Ukraine and from the Commission, with observers from third countries (Croatia, USA, Japan) and the IAEA.

2.4 FINDINGS AND LESSONS LEARNED

This chapter presents a selection of key findings and lessons learned, as documented in more detail in (EC, 2012a) and (ENSREG Stress Test Peer Review Board, 2012a). A further selection of representative country specific findings is collected in Appendix B. A case study is presented for the Krško Nuclear Power Plant (Slovenia) in Appendix C.

2.4.1 Generic Results of the Safety Assessments

Initiating Events

Stress-test results clearly indicate that particular attention needs to be paid to periodic safety reviews (PSR) as a powerful tool to regularly reassess plant safety. The stress-tests have confirmed that all the 17 participating countries perform periodic safety reviews at least every 10 years, including a reassessment of the external hazards. External hazards (e.g. earthquake[1], flooding and extreme weather) and robustness of the plants against them should be reassessed as often as appropriate but at least every 10 years.

Generally the approach to demonstrate an appropriate design basis is sound. All plants need to be reviewed with respect to external hazard safety cases corresponding to an exceedance probability of 10^{-4}/year (with a minimum peak ground acceleration of 0.1 g for the seismic hazard). Setting up an international benchmark exercise to evaluate the relative strengths

[1] State-of-the-art European seismic hazard studies have been developed in the projects PEGASOS, PEGASOS Refinement Project PRP (Swissnuclear, 2013) and (SHARE, 2013)

and weaknesses of probabilistic and deterministic hazard assessment methods for external events is recommended.

Almost all countries consider for Design Basis Earthquakes DBE and for the Design Basis Flood DBF an event with an exceedance probability of 10^{-4}/year as a minimum. The stress-test results point out nevertheless alternative approaches for DBE in two of the participating countries (France, Romania) and for DBF in three of the participating countries (Belgium, France, Netherlands) (EC, 2012b).

The evaluation of beyond design basis margins for earthquakes and flooding is not consistent in participating countries. A few countries have quantified the inherent robustness of the plants' beyond the design basis up to cliff edge effects, whereas the majority have made only a general claim that sufficient safety margins exist and therefore there is no verifiable information on the basis of which to consider effective potential improvements.

A number of possible means to increase the robustness of NPPs against external hazards has been identified during the stress-tests. Among these is the installation of a bunkered or ‘hardened core’ of safety-related systems, structures and components capable of withstanding earthquakes and flooding significantly beyond design basis.

Additional guidance on natural hazards assessments, including earthquake, flooding and extreme weather conditions should be developed, as well as corresponding guidance on the assessment of margins beyond the design basis and cliff-edge effects.

Regulators and operators should consider developing standards to address qualified plant walk-downs with regards to earthquake, flooding and extreme weather to provide a more systematic search for non-conformities and correct them.

The design for storage of mobile equipment to perform necessary safety functions should take account of external events at the design and beyond design levels, to ensure appropriate availability in the event of being required following a significant external event.

Advance warning of deteriorating weather is often available in sufficient time to provide the operators with useful advice and national regulators should ensure that appropriate communications and procedures are developed by all operators.

Loss of Safety Functions

All the countries estimated the cliff-edge effects related to various combinations of losses of electrical power and/or cooling water, and the time available before safety functions need to be restored. In terms of safety margins, Station Black-Out (SBO, i.e. total loss of AC power) is the limiting case for most reactors.

Numerous improvements related to hardware and procedures have been identified; some have been implemented and others are still at the planning stage. NPPs typically have several redundant and diverse cooling options to ensure a minimum heat sink for 72 hours, provided that electrical power supply is available. The volume of cooling water available on site that ensures heat removal from essential consumers is not less than 6-8 days.

For multi-unit sites, robustness could be enhanced if additional equipment and trained staff are available to effectively deal with events affecting all the units on one site. At most multi-unit sites, an accident simultaneously occurring at several units was not considered in the original design.

Fire-fighting equipment, including fire trucks, diesel pumps, generators, emergency lighting, etc. is normally readily available at the plants. All plants confirmed that they already possess or are in advanced process of acquiring a variety of mobile devices including skid/trailer based diesel generators and diesel-driven pumps, dedicated fire trucks, etc. including the connection points and procedures on how to engage mobile units. Nevertheless, a systematic selection of and acquisition of the equipment that would provide a variety of power and pressure levels and that is safely stored on-site and/or offsite still needs to be done.

Operational or preparatory actions such as ensuring the supply of fuel and lubrication oil, battery load-shedding to extend battery life are examples of measures that are small (in many cases procedural) but that could make a considerable difference in response to initiators. All in all, most of the plants have already considered these measures and might be adding to them in the future.

The value of bunkered systems has been evaluated within the stress-tests. They are qualified to anticipated external events and equipped with independent diesel driven pumps and water storage to ensure heat sink, and electrical power supply to vital consumers via standby small emergency diesel generators, batteries, and diesel-driven pumps for at least 24 hours. Bunkered systems are already installed as a standard design feature in only a few nuclear power plants. They proved its worth in ensuring an additional level of protection after the external events, able to cope with a variety of initiators, including those beyond the design basis. The concept is taken even further in the form of the "hardened safety core" where in addition to equipment, trained staff and procedures designed to cope with a wide variety of extreme events will be available.

Severe Accident Management (SAM)

Periodic safety reviews (PSR) should continue to be maintained as a powerful regulatory instrument for the continuous enhancement of defence-in-depth in general, and the provisions of SAM. The lessons learned from the Fukushima accident and from the stress-tests should be reflected in the scope of future PSRs.

In response to their previous commitments, regulators should incorporate the WENRA reference levels (WENRA, 2008) related to SAM into their national legal frameworks, and ensure their implementation.

Effective implementation of SAM requires that adequate hardware provisions are in place to perform the selected strategies.

On top of the key nuclear safety systems several other hardware provisions are already installed or will be installed in the different NPPs:

- Additional Diesel Generators (or Combustion Turbines) physically separated from the normal DGs and devoted to cope with SBO, external events or severe accident situations;
- Mobile equipment especially Diesels Generators;
- Centralised storage of emergency equipment, shared among several NPP sites

- Instrumentation and communication means which are qualified for Design Basis Accidents.

Training and exercises aimed at checking the adequacy of SAM procedures and organizational measures should include testing of extended aspects such as the need for corporate and national level coordinated arrangements and long-duration events. All countries that have implemented the SAMG carry out periodic training and exercises to check the adequacy of SAM procedures and the adequate co-ordination among the involved organizations.

On-site emergency centres should be available and designed against impacts from extreme natural and radiological hazards.

Main Control Rooms (MCR) of the plants have been designed against Design Basis Accidents. Most of the countries have proposed additional measures to improve MCR and Emergency Control Rooms (ECR) habitability in case of severe accidents.

2.4.2 Key Recommendations

Specific Recommendations on External Hazards

The technical design and operation of each plant must be able to deal with unforeseen external hazards (e.g. earthquake, flooding, extreme weather and accidents) and unexpected external events, which were not planned for in the original design (beyond design margins).

External hazard safety cases corresponding to an exceedance probability of not more than 10^{-4} per year should be used for earthquakes as well as for flooding. For all sites in Europe, the Design Basis Earthquake should correspond to a peak ground acceleration of not less than 0.1 g.

Seismic monitoring systems should be installed and associated procedures and training developed for those NPPs that currently do not have such systems. On-site seismic instrumentation should be in operation at each NPP. A study to investigate the overall cost-benefit and usefulness of automatic reactor shutdown induced by seismic instrumentation is recommended.

As a good practice, the use of a 'hardened core' of safety-related systems, structures and components capable of withstanding earthquakes and flooding significantly beyond design basis should be considered.

Specific Recommendations on Loss of Safety Functions

Depending strongly on the specific reactor design, the key risk in terms of safety margins has been identified to be controlled by Station Black-Out (SBO, i.e. total loss of AC power), which can lead to core heat-up within 30-40 minutes. Therefore, the following should be readily available under even the most extreme conditions:

- A variety of mobile devices, such as mobile generators, mobile pumps, mobile battery chargers or mobile DC power sources, fire-fighting equipment and emergency lighting;

- Specialised equipment and fully trained staff to deal effectively with events affecting all the units on one site.

To increase the robustness of the ultimate heat sink (UHS) function, it is strongly recommended to identify and implement also alternative means of cooling.

Specific Recommendations on Severe Accident Management (SAM)

Recognized measures to protect containment integrity should be urgently implemented.

Comprehensive Severe Accident Management Guidelines (SAMG's) should be developed. Periodic validation of SAMG's is essential for ensuring their practicability, robustness and reliability.

SAM arrangements need to be enhanced, including the methods and tools for SAM training, and exercises should include the suitability of equipment, instrumentation and communication means.

On-site emergency centres should be available and designed against impacts from extreme natural hazards.

Radiation protection of all staff involved in severe accident management and emergency response must be ensured.

Where emergency equipment is stored centrally, it must be stored in locations that are safe even in the event of general devastation, and where it can be quickly supplied to the relevant NPP site.

Time available to the operator for restoration of the safety functions in case of loss of all electrical power and/or ultimate heat sink should be more than 1 hour (without human intervention).

2.5 FOLLOW-UP ACTIONS

2.5.1 WENRA Actions

Overall, the compliance of the European stress-tests with the ENSREG specification was found to be good with regard to compliance of the installations with their design basis for earthquake and flooding (ENSREG, 2012a). However there was a lack of consistency identified with respect to natural hazards assessments where significant differences exist in national approaches and where difficulties were encountered with beyond design margins and cliff-edge effects assessments. Therefore the peer review Board recommended that the Western Europe Nuclear Regulators Association (WENRA), involving the best available expertise from Europe, develop guidance on natural hazards assessments, including earthquake, flooding and extreme weather conditions, as well as corresponding guidance on the assessment of margins beyond the design basis and cliff-edge effects.

Such guidance shall contribute to harmonization of the design requirements among European countries, considering lessons learned from the EU stress-test experience:

- *Hazard Frequency*
  Specify a return frequency of 10^{-4} per annum for plant reviews/back-fittings with respect to external hazards safety cases

- *Secondary Effects of Earthquakes*
  Consider possible secondary effects of seismic events, such as flood or fire arising as a result of the event
- *Protected Volume Approach*
  Follow a protected volume approach to demonstrate flood protection for identified rooms or spaces
- *Early Warning Notifications*
  Implement advanced warning systems for deteriorating weather, and provide appropriate procedures to be followed by operators when warnings are made
- *Seismic Monitoring*
  Install seismic monitoring systems with related procedures and training
- *Qualified Walkdowns*
  Develop standards to address qualified plant walkdowns with regard to earthquake, flooding and extreme weather – to provide a more systematic search for non-conformities and correct them (e.g. appropriate storage of equipment, particularly for temporary and mobile plant and tools used to mitigate beyond design basis (BDB) external events)
- *External Hazard Margins*
  Assess the margins for all external hazards including seismic, flooding and severe weather, and identify potential improvements

WENRA took immediate action by forming the following working groups for harmonization of the safety requirements within Europe (ENSREG, 2012b):

- T.1 External Hazards
- T.2 Containment in Severe Accidents
- T.3 Accident Management

These working groups started in summer 2012 with the goal to develop safety reference levels and guidance documents to be followed by all WENRA countries.

2.5.2 National Action Plans (NAcP)

As a key result of the EU stress-test each of the participating countries has developped a national action plan (NAcP, see references "National Action Plans Resulting from EU Stress-tests"). The action plans contain a detailed list and schedule for all decided measures. They provide an implementation tool for the utilities and the national regulators.

On the European level ENSREG is watching the progress of implementation of the NAcPs. A first workshop with the objectives of mutual information and discussion was held in Brussels on 22-26 April 2013 (ENSREG, 2013).

3 IAEA: Advanced safety assessment studies for NPP's

3.1 IAEA SAFETY STANDARDS

The International Atomic Energy Agency IAEA provides technical guidance on nuclear safety issues. Safety standards related to the protection against natural hazards are listed in the References of this report D2.1 (see "Selected IAEA guidelines and reports"). These safety standards provide a common basis for the worldwide nuclear community.

3.2 POST-FUKUSHIMA EXPERT MEETING

In order to develop lessons learned from the reactor accident at the Fukushima (Japan) Daiichi Nuclear Power Plant in March 2011, IAEA organized an international experts meeting in September 2012 (IAEA, 2012a). This meeting was devoted to the following objectives:

- 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 on-going 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.

Key issues and lessons learned from this meeting may be considered to represent the current state-of-the-art for the related safety issues, as developed by the IAEA.

3.2.1 General Findings

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.

An active tsunami warning system should be established, with the provision for immediate operator action.

3.2.2 Seismic Hazard Assessment

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[2] for sites in areas with sparse data[3] 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.

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 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.

All IAEA Member States are 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.

3.2.3 Tsunami Hazard Assessment and Flooding Issues

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.

Tsunami waves and associated phenomena may produce severe damage to nuclear power plants located in coastal areas. The current IAEA safety standards (IAEA, 2003b) 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.

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.

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 considered in the nuclear power plant design has to be periodically confirmed by reviewing the site flood

[2] These factors refer to the yearly exceedance probability for a specified ground motion value.

[3] earthquake catalogue data and records in the relevant region

protection measures such as sea walls and watertight doors, all of which will require periodic inspection and maintenance.

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. Adequate safety margins for flood hazards beyond the design basis should be demonstrated and the provision of additional external barriers (e.g. breakwaters, dykes) to prevent flooding of a nuclear power plant site should be evaluated.

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).

3.2.4 Combination of Extreme Natural Hazards

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.

3.2.5 Approaches to Establishing Design Values and Beyond Design Events

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.

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.

3.2.6 Safety Against Earthquakes and Tsunamis

The design process and the re-evaluation of the safety of existing nuclear installations should consider external event scenarios beyond the design basis.

With reference to those challenging scenarios, methodologies for the calculation of the available safety margins should be developed. Preference is confirmed for probabilistic and site specific approaches as the tool for any evaluation of the safety margins. As a crucial step for calculation of the safety margins the failure modes of critical structures, systems and components need to be clearly identified and understood.

The external hazards need to be for periodically reassessed within the periodic safety review process.

Plant walkdowns have been conducted at many sites in relation to protection against external events, particularly seismic and seismic induced fires and flooding.

Seismic isolation is a technique for protection against design basis and beyond design basis scenarios that needs to be further considered.

Early tsunami detection systems and response programmes need to be considered.

3.2.7 IAEA Action Plan on Nuclear Safety

As a conclusion of the meeting it was stated that the lessons learned and the topics defined to be further investigated should be incorporated in the programme of implementation of the IAEA Action Plan on Nuclear Safety (IAEA, 2011a).

4 Conclusions

This state-of-the art report summarizes the lessons learned from stress-tests of nuclear facilities. It provides a review of the methodologies and findings from post-Fukushima stress-tests and from advanced plant safety assessment studies for nuclear power plants (NPPs). Most of the key findings from stress-tests of nuclear facilities are applicable also for non-nuclear critical infrastructures (CIs), though risk informed modifications may be appropriate.

Stress-test results clearly indicate that particular attention needs to be paid to **periodic safety reviews (PSR)**, including a reassessment of the external hazards, as a powerful tool to regularly reassess plant safety.

The applied methods for assessing natural hazards at nuclear power plant sites are currently not harmonized among the European countries. The Western European Nuclear Regulators Association WENRA and the International Atomic Energy Agency IAEA encourage their Member States to use probabilistic methods for seismic and flooding hazard assessments in order to define the ground motions (Design Basis Earthquake DBE) and the flooding levels (Design Basis Flood DBF) for an exceedance probability of 10^{-4}/year. This value may be specified differently for non-nuclear CIs, considering the potential risks to the public and environment. WENRA took immediate action for **harmonizing the safety requirements in Europe**.
Note: For future developments it should be considered to move from the probability at the hazard level to the probability at the structural level, i.e. to the ***probability of failure****.*

The technical design and operation of each plant must be able to deal with unforeseen external hazards (e.g. earthquake, flooding, extreme weather and accidents) and unexpected external events, which were not planned for in the original design (beyond design margins). The evaluation of **beyond design basis margins** for earthquakes and flooding is not consistent in participating countries. A few countries have quantified the inherent robustness of the plants' beyond the design basis up to cliff edge effects, whereas the majority has made only a general claim that sufficient safety margins exist.

On top of the key nuclear safety systems several other hardware provisions are already installed or will be installed in the different NPPs. As a good practice the installation of a bunkered system ("**hardened safety core**"), qualified to anticipated external events and equipped with all components for providing power and cooling capacities in case of failure of the primary safety systems, should be considered.

The plant layout should be based on maintaining a **'dry site' concept**, where practicable, as a defence in depth measure against site flooding. An active tsunami warning system should be established at coastal sites, with the provision for immediate operator action.

Seismic monitoring systems should be installed and associated procedures and training developed for those NPPs that currently do not have such systems.

Common cause failures should be particularly considered for **multiple unit sites** and multiple sites.

Discussion of additional seismic lessons learned

Increasing seismic hazard

Many nuclear power plants (NPP) have witnessed a steadily increasing seismic hazard due to a better evaluation of both aleatory and epistemic uncertainties in modern probabilistic seismic hazard analyses.

Acceleration as the ground motion parameter

In the past, peak ground acceleration (PGA) was the ground motion parameter which controlled the ground motion. It was used in combination with a standard spectral shape, which is intended to represent a uniform hazard spectrum (UHS). It has been recognized for a long time that PGA has not a good correlation with the damage potential of the ground motion. More recently, it is usual to predict site specific spectral accelerations. Nevertheless, PGA is still used in the case of many NPPs. Acceleration is only one of the parameters which determine the structural response in the case of seismic ground motion. Several other measures, which have a better correlation with damage, e.g. measures based on energy, have been proposed in the literature. However, so far, they have not been widely used for three reasons. First, there is a lack of consensus on the most appropriate measures. Second, there is a lack of ground motion prediction equations other than for spectral accelerations (with some exception of peak ground velocity). Third, there is a lack of methods for analysis and design approaches based on parameters different from accelerations. Regarding the spectral shape, the UHS spectrum is considered as being conservative.

Elastic versus inelastic methods of analyses

Typically, it is assumed that structures, systems and most components of NPPs should not be damaged during the Safe Shutdown Earthquake (SSE) ground motion. Consequently, they are analysed and designed by assuming elastic response. Such an approach is very conservative. Small or even moderate damage usually does not jeopardize the function of the structures and components in the case of SSE, which is an event with very low probability. In the case of SSE it is required to assure the capability to shut down the reactor and maintain it in a safe-shutdown condition, and to assure the integrity of the reactor coolant pressure boundary. If some inelastic structural response is tolerated, which is related to some damage, forces and stresses in ductile structures and components are reduced. Moreover, the acceleration floor spectra, which represent the seismic input for systems and components, are reduced. With increasing seismic hazard, i.e. with increasing intensity of design ground motion, sometimes witnessed in recent years, it will be necessary to reduce the conservatism in analysis and design approaches, otherwise it would be difficult to design new NPPs in seismic areas and to demonstrate the capability of existing plants to resist seismic design ground motion.

Deterministic versus probabilistic analysis and uncertainty

In principle, the problem of seismic safety of NPPs is probabilistic. Both aleatory and epistemic uncertainties are involved. For the determination of seismic hazard usually a probabilistic approach is used. Fragility curves are also presented in probabilistic terms. For the analysis (determination of seismic demand) of structures, systems and components, however, usually a deterministic approach is used. Ground motion characteristics, determined for a selected return period (for SSE typically 10'000 years) by a probabilistic seismic hazard analysis, are used as input for deterministic analysis. Epistemic uncertainties related to the structural model are typically taken into account by analysing a few structural models with different characteristics.

The aim of the post-Fukushima stress tests was to assess whether the nuclear power plants can withstand the effects of unexpected events (beyond the design basis), among them strong earthquakes and large floods. The deterministic approach using safety margins was required. In (ENSREG, 2011) it was stated: “In these extreme situations, sequential loss of the lines of defence is assumed, in a deterministic approach, irrespective of the probability of this loss.” In the application of the seismic margin approach a problem occurred, because in the deterministic analysis it is usually necessary to determine capacity of structures and components as deterministic values from the fragility curves which, by definition, represent the conditional probability of the failure of a structure or equipment at a given value of ground motion value. Usually, the HCLPF (High-Confidence-Low-Probability-of-Failure) values are used as the capacity. The HCLPF capacity corresponds to about 95% confidence of less than about a 5% probability of failure. For some applications, an alternative definition of the HCLPF capacity is used: 1% conditional probability of failure. Both definitions clearly indicate that the HCLPF capacity is a very conservative measure. By definition, there is a low probability that the actual capacity of the plant is lower than the HCLPF capacity and there is a large probability that the actual seismic capacity of a building or a component is larger than the HCLPF capacity. This is in conflict with the guidelines for the evaluation of margins, provided in (ENSREG, 2011, page 7): “Based on available information (which could include seismic PSA, seismic margin assessment or other seismic engineering studies to support engineering judgement), give an evaluation of the range of earthquake severity above which loss of fundamental safety functions or severe damage to the fuel (in vessel or in fuel storage) becomes unavoidable.” If the HCLPF capacity of the plant is exceeded, it does not necessarily mean that severe damage is unavoidable. There is a lack of quantitative definitions, which opens the room to subjective engineering judgement and makes the evaluation of results difficult.

For the time being, not enough attention is paid to epistemic uncertainties related to the structural model, which contribute a significant part of the overall uncertainty. There is a need to develop appropriate methods which would take into account these uncertainties along with some other uncertainties which are already included in analysis. On the other hand, the methods should not be excessively complex and/or computationally demanding, so that their application would be feasible in practice.

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Appendix A

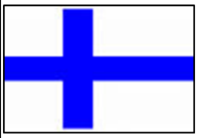
A Table of Contents for a Representative EU Stress Test Report

Appendix B

B Representative Findings from the EU Stresstest Project for Selected Countries

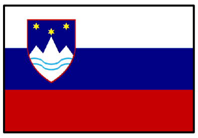
The tables in Appendix B present representative findings extracted from the reference documents listed as "EU Stress Test Country Reports" and "EU Stress Test Peer Review Reports".

Country	Selected Findings
 **Belgium** 7 operating reactors	**Earthquake Safety**[1] – The updated Probabilistic Seismic Hazard Assessment (PSHA) shall be completed and reviewed, as a basis to update the assessment of safety margins and to implement consequential measures. These updates may benefit from a harmonization of the seismic hazard assessment on an international level. Experience exchange, namely among the neighbouring countries is recommended, in order to avoid discrepancies for sites with comparable seismic activity. – It is recommended to update the seismic instrumentation at the plants, in order facilitate and to accelerate the measures to be initiated after a seismic event.
	Flooding Safety[1] – The issue of flood protection is more relevant for the Tihange site. This site is currently protected by its design against a reference flood with a statistical return period up to 400 years. The reference flood with a statistical return period up to 10'000 years will be implemented as a new design basis flood (DBF). Several upgrade measures are identified by the licensee and the regulator in order to provide adequate safety margins for a 10'000 year flood.
	Loss of Safety Systems (Electric Power or/and Ultimate Heat Sink) – It is recommended to take into consideration the benefits of increasing the autonomy of emergency diesel generators at Tihange 1 for seismic events, possibly by enhancing the seismic robustness of a poorly qualified fuel tank.
	Severe Accident Management (SAM) – Various mprovements to further increase the robustness of the concept for severe accident management at the plants have been found by the licensee and the regulatory body; e.g. the consistency of the emergency training and refresher training programs between Tihange NPP and Doel NPP will be increased.
	[1] hazard assessment, design basis earthquake, protection measures, robustness beyond design basis

Country	Selected Findings
 **Finland** 4 operating reactors	**Earthquake Safety**[1] – The Design Basis Earthquake DBE is considered to be acceptable in comparison with international standards. – The additional assessment of critical structures, systems and components (SSCs) with respect to a minimum peak ground acceleration PGA = 0.1g, as recommended in the IAEA Safety Guide NS-G-3.3 should be considered.
	Flooding Safety[1] – The Design Basis Flood DBF is considered to be acceptable in comparison with international standards. Margins above DBF are demonstrated. Measures for flood safety improvement have been proposed for both plant sites.
	Loss of Safety Systems (Electric Power or/and Ultimate Heat Sink) – It is noted that the reactors Olkiluoto 1 & 2 are vulnerable to station black out SBO, particularly if it occurs at the time of reactor scram. There are plans to improve the existing design, as well as to install independent means to provide for the core cooling function. – Currently a heat sink completely independent of seawater does not exist at Olkiluoto 1 & 2; corresponding corrective measures are recommended.
	Severe Accident Management (SAM) – Reassessment of the emergency preparedness should address events that occur at the all units on site at the same time. – The availability of dedicated systems and components to be used during severe accidents scenarios must be verified. – General suggestion is to perform special tests of several equipments, among them DC batteries, endurance tests of diesel generators, under extreme conditions and training of some activities such as the installation of hoses.
	[1] hazard assessment, design basis earthquake, protection measures, robustness beyond design basis

Country	Selected Findings
France 58 operating reactors	**Predominant safety upgrade measure** – The licensee proposed to define and deploy a "Hardened Safety Core" of reinforced equipment at each plant, such as to minimize the potential for severe accidents and avoid significant radioactive releases into the environment, over and above the current safety requirements.
	Earthquake Safety[1] – The implementation of Probabilistic Seismic Hazard Assessment (PSHA) is encouraged, as a tool for the further improvement of the Design Basis Earthquake DBE. – The deployment of a "Hardened Safety Core" will provide a significant increase of overall robustness. – The seismic instrumentation at the plants could be improved to a state of the art concept. – The safety margins for seismic events above the DBE could be evaluated in a more systematic manner, either by performing Probabilistic Safety assessments (PSA) or Seismic Margin Assessments (SMA).
	Flooding Safety[1] – It is recommended to perform a comparative evaluation between the Design Basis Flood DBF defined according to the national requirements with the methodologies used in other European countries. – Numerous actions have been identified in order to verify the compliance of the plants with the current design basis and to improve flooding safety.
	Loss of Safety Systems (Electric Power or/and Ultimate Heat Sink) – The licensee developped plans to increase the system robustness to cope with station blackout and loss of the ultimate heat sink, e.g. by increasing the battery discharge time or by recharging the batteries for emergency power.
	Severe Accident Management (SAM) – The licensee proposed to create a “Nuclear Rapid Response Force" (FARN). It will be composed of specialized crews and equipment. These crews will be made up of the licensee's employees based on 4 NPPs distributed in France. Near to these 4 NPPs, the FARN equipment will be stored in a regional basis.
	[1] hazard assessment, design basis earthquake/flood, protection measures, robustness beyond design basis

Country	Selected Findings
 **Germany** 17 operating reactors	**Earthquake Safety**[1] _ For German NPP sites the PGA values for the Design Basis earthquake DBE are in some cases lower than 0.1g. This deviates from the approach recommended by the IAEA. _ A strong feature is the robustness of the construction of safety relevant buildings that is achieved by the design requirement to assure the resistance to aircraft crashes. _ The margins as well as the cliff edge effects for seismic events have not been determined.
	Flooding Safety[1] _ All the plants in Germany are in compliance with the design requirements regarding flooding. _ For flooding beyond the DBF, the margins have been assessed, by estimating the difference between the water level of the DBF and the height of openings that could lead to flooding of safety related buildings. Sufficient margins have been determined for safety related buildings and structures. _ Nevertheless, additional measures that would increase the robustness even further are envisaged for the tide-influenced plants. Additionally the German reactor safety commission (RSK) is considering eventually needed improvements for the accessibility of specific buildings in a case of flooding of long duration.
	Loss of Safety Systems (Electric Power or/and Ultimate Heat Sink) _ The peer review team accepted the conclusions of the German regulator that no weaknesses have been found related to this topic of the stress test.
	Severe Accident Management (SAM) _ Although guidance exists in the Accident Management Manuals, Severe Accident Management Guidelines (SAMGs) have been developed for one plant only. It is expected that SAMGs will be available at all plants. _ The operability of instrumentation essential to severe accident management should be systematically evaluated for severe accident conditions. This should be achieved in the course of SAMG development.
	[1] hazard assessment, design basis earthquake, protection measures, robustness beyond design basis

Country	Selected Findings
 **Slovenia** 1 operating reactor (see also Appendix C)	**Predominant safety upgrade measure** – The plant owner decided to build and install a third seismically classified emergency diesel generator.
	Earthquake Safety[1] – The results of the recent probabilistic seismic hazard assessment demonstrate an increase of the hazard, by a factor of nearly 2 in terms of peak ground accelerations. – The seismic design basis should be updated accordingly and implemented for future plant modifications (e.g. the third diesel generator).
	Flooding Safety[1] – An additional flood-protection measure (increasing the dike height upstream from the plant) is in progress.
	Loss of Safety Systems (Electric Power or/and Ultimate Heat Sink) – Various additional equipment acquired and installed, with the purpose to maintain the plant in a safe state; e.g. third independent diesel generator, mobile emergency power generators, additional onsite pumping station, additional fire protection pumps, additional quick connection points for mobile equipment, additional seismic strengthening of emergency equipment
	Severe Accident Management (SAM) – Upgrading measures identified to improve SAM capabilities; e.g. filtered venting system, new emergency control room, third engineered safety features train
	[1] hazard assessment, design basis earthquake, protection measures, robustness beyond design basis

Country	Selected Findings
 **Spain** 8 operating reactors	**Predominant safety upgrade measure** _ The seismic capacity of all safety significant structures, systems and components (SSCs) will be upgraded up to 0.3 g. _ The regulator considers it necessary that all plants have a filtered venting system for the containment building.
	Earthquake Safety[1] _ Within the framework of the seismic hazard update claimed by the regulator, it is suggested to consider to include geological and paleoseismological data characterizing the relevant active faults. _ The analysis of seismic margins above the design basis conclude with specific actions for improvement. Special attention shall be devoted to possible combinations of extreme natural events.
	Flooding Safety[1] _ The peer review team notes that current good practices in Europe consider the Design Basis Flood (DBF) corresponding to exceedance probabilities of 10-4/year or lower. _ The most critical events correspond to the potential failure of upstream dams. Further analysis of dam failures is considered to be necessary. _ It has been concluded to consider improving the external flood volumetric protection of buildings containing safety related SSCs.
	Loss of Safety Systems (Electric Power or/and Ultimate Heat Sink) _ Some measures (e.g., linked to manual operation of steam driven pumps and relief valves for heat removal), were decided to be applied. _ The licensees propose several measures for improvements which would allow all plants to be self-sufficient for the first 24 hours.
	Severe Accident Management (SAM) Proposals for improvement have been developed and are considered to be applicable to all the installations, e.g.: _ Availability on site of autonomous electricity generating groups and of autonomous motor-driven pumps for the injection of water to the primary and/or secondary cooling circuit _ Additional portable instrumentation for performance of the manual control manoeuvers required in the event of complete loss of the batteries
	[1] hazard assessment, design basis earthquake, protection measures, robustness beyond design basis

Country	Selected Findings
 **Sweden** 10 operating reactors	**Earthquake Safety**[1] – It has been concluded to reconsider the existing approach for seismic hazard assessment by taking into account the geodetic and paleoseismologic data. – There is a need for a more accurate estimation of the seismic safety margins and for implementation of improvements to be identified in the updated safety evaluations.
	Flooding Safety[1] – The reviewers judge to consider carrying out more detailed flooding risk analysis including cliff edge analysis. In order to identify plant vulnerability against flooding, implementation of a refined external flooding PSA could be suggested to be introduced for Swedish NPPs. – Combination effects of waves and high water levels are not included in the stress tests for all facilities. More investigations are needed for these kinds of combination effects, including dynamic effects.
	Loss of Safety Systems (Electric Power or/and Ultimate Heat Sink) Proposed improvement measures: – Increasing the number of mobile diesel generators at the sites: each facility should get its own mobile diesel unit with prepared connection points – Increasing the discharge time of the batteries by disconnecting of less important loads – Installation of pipelines to provide fire water to spent fuel pools – Verification of the spent fuel pools integrity for boiling conditions.
	Severe Accident Management (SAM) The assessments indicated several areas for safety improvements at the Swedish NNPs: – Consideration of multiple unit events including long term effects – Long term performance of the filtered venting system (> 24 hours) – Consideration of natural disasters leading to loss of infrastructure – Concepts to manage large volumes of contaminated water
	[1] hazard assessment, design basis earthquake, protection measures, robustness beyond design basis

Country	Selected Findings
Switzerland 5 operating reactors	**Predominant safety upgrade measures** _ A new central external storage facility was set up, where emergency resources are stored which can be made available by helicopter in addition to the equipment already available at the NPPs to deal with severe accidents. _ The spent fuel pools of all plants will be back-fitted in order to ensure adequate cooling in case of severe accidents.
	Earthquake Safety[1] _ The results of the on-going state-of-the-art Probabilistic Seismic Hazard Assessment (PEGASOS Refinement Project PRP; Swissnuclear, 2013) shall be implemented within a systematic reassessment of the seismic safety for all plants. PEGASOS and PRP represent the first and only application in Europe of the study level 4 of the PSHA methodology recommended by (SSHAC, 1997). _ A seismic monitoring system is installed at all NPPs. The regulator requires a feasibility study for the need of installing an automatic scram system triggered by the seismic instrumentation.
	Flooding Safety[1] _ All Licensees demonstrated a margin of at least 20% river flow beyond the Design Basis Flood DBF. Nevertheless two plants have identified and implemented a number of improvements of the robustness against external flooding.
	Loss of Safety Systems (Electric Power or/and Ultimate Heat Sink) _ The regulator required a seismically qualified alternative cooling source for the Mühleberg NPP (KKM). _ For two plants, backup cooling of the spent fuel pool will be provided.
	Severe Accident Management (SAM) _ It is recommended that the regulator assesses the opportunity of requiring more reliance on passive systems for hydrogen management for severe accident conditions. It is also recommended that the regulator considers further studies on the hydrogen management for the containment venting systems.
	[1] hazard assessment, design basis earthquake, protection measures, robustness beyond design basis

Country	Selected Findings
 **United Kingdom** 18 operating reactors	**Representative safety upgrade measure** _ Licensees should further review the margins for all safety significant structures, systems and components (SSC), including cooling ponds, in a structured manner to understand the beyond design basis sequence of failure and any cliff edges that apply for all external hazards.
	Earthquake Safety[1] _ A beyond design basis capability is inferred from the stress test studies, but not systematically quantified. The regulator has identified the assessment of safety margins to cliff edges and the potential specific upgrades to be an area for improvement.
	Flooding Safety[1] _ The licensees should undertake a more detailed analysis of the potential for floodwater entry into the buildings containing safety systems. _ A more comprehensive cliff-edge analysis should be undertaken. _ The ability of operators to perform safety-related tasks during and following a flood event should be analyzed in more detail.
	Loss of Safety Systems (Electric Power or/and Ultimate Heat Sink) Further potential improvements are identified and suggested, e.g.: _ injection of water into the reactor core as an ultimate means to provide residual heat removal from the core without use of the boilers, _ increasing the stocks of fuel for at least 72 hours, _ increasing the battery capacity or providing recharge capacities by additional generators.
	Severe Accident Management (SAM) _ In accordance with the existing plans, the on-site emergency facilities should be strengthened in order to be resistant against external hazards and ensure safe working conditions in case of a severe accident. _ A more comprehensive assessment is needed regarding the occurrence of a severe accident at multiple units and the conditions of severely damaged infrastructures. _ The need for a backup control room for shutdown and cooldown to safe condition of the plant should be considered.
	[1] hazard assessment, design basis earthquake, protection measures, robustness beyond design basis

Appendix C

C Case Study Krško Nuclear Power Plant, Slovenia

C.1 INTRODUCTION

Task 2.1 of the STREST project deals with lessons learned from stress tests of nuclear facilities. The scope of this task is a review of the methodologies and findings from (i) advanced Plant Safety Assessment studies for NPPs carried out by the International Atomic Energy Agency (IAEA) and by national industry and regulators, with a specific focus on the hazard estimation for earthquake and flooding initiators, and from (ii) post-Fukushima stress tests for NPP conducted by the European Commission, by the IAEA and by national nuclear regulatory agencies. In this annex the seismic and flooding issues related to the Slovenian Nuclear Power Plant Krško are summarized and discussed.

C.2 BASIC DATA ON THE KRŠKO NUCLEAR POWER PLANT (NEK)

Slovenia, as the smallest nuclear country in the world, has one nuclear power plant with only one unit. The Krško Nuclear Power Plant (In Slovenian: Jedrska elektrarna Krško, JEK, or Nuklearna elektrarna Krško, NEK) is located in Krško. The construction began in 1975. The plant was connected to the power grid on October 2, 1981 and went into commercial operation on January 15, 1983. It was built as a joint venture by Slovenia and Croatia which were at the time both part of former Yugoslavia.

The plant is a 2-loop Westinghouse pressurized water reactor of 2.000 MW thermal power, with the net electrical output of up to 696 megawatts-electric (MWe). It runs on enriched uranium. Its sister power plant is Angra I in Brazil. The operating company Nuklearna elektrarna Krško (NEK) is co-owned by a Slovenian state-owned company and a Croatian state-owned company. The power plant provides more than one-quarter of Slovenia's and 15 percent of Croatia's electric power. It is connected to the 400kV grid supplying power to consumer centres in Slovenia and Croatia.

The high level nuclear waste from the plant is stored in the spent fuel pool, as is the usual practice for nuclear power stations. The spent fuel pool at Krško has the capacity to store all high level waste (spent nuclear fuel assemblies) until the originally planned end of plant life (2023). Low level waste is stored at the power station and secondary repositories. The planned retirement date was January 14, 2023. A request for lifetime extension for 20 years, extending the plant lifetime till January 14, 2043 has been made to the Slovenian regulatory body (URSJV). The NPP Krško Preliminary Decommissioning Plan with Plant Specific Inventory Database Development has been prepared in the variants of 2023 and 2043 reactor shut-down. A deep geological repository consisting of underground facilities and a number of above ground facilities, which are indispensable for normal underground repository operation, is planned.

During almost 30 years of operation various safety reviews and improvements, upgrades and modernizations were performed. The most important examples from the past are plant modernization with power up-rate and steam generator replacement, Probabilistic Safety Analysis (PSA) related studies and upgrades (e.g. fire protection upgrade), adoption of Severe Accident Management Guidelines (SAMG), seismic reviews, analyses and upgrades (e.g. installation of the 3rd emergency diesel generator), wet reactor cavity, plant specific full scope simulator, etc. After the Fukushima accident the operator of Krško NPP has performed its first and quick review trying to identify possible short-term improvements. In June 2011, based on the Krško NPP application, the Slovenian Nuclear Safety Administration (SNSA) licensed a series of minor modifications in the plant which add alternate possibilities for electrical power supply and cooling of reactor and spent fuel pool (SFP) in case of beyond design basis accidents (BDBA). The Krško NPP is in the process of upgrading its existing flood protection by raising the flood protection dikes.

C.3 ORIGINAL DESIGN RELATED TO NATURAL HAZARDS AND STUDIES PERFORMED UNTIL 2011

Earthquakes

The Krško NPP is located in a seismically active region. At the time when the Krško NPP was designed and constructed, the US NRC nuclear regulation and standards were used. Regional geologic investigations for site selection began in the sixties. The location was later explored in detail with geomechanical, hydrogeological, geophysical and seismological investigations. These were performed in several stages. In the seventies the investigations included refractional measurements, soil survey, microseismical ground noise measurements, laboratory tests, gamma-gamma measurements, geoelectrical sounding of terrain, and density determination, all aimed at the estimation of the seismic hazard.

In the original design, peak ground acceleration of the Safe Shutdown Earthquake (SSE) and Operating Basis Earthquake (OBE) ground motion amounted to PGA = 0.3 g and 0.15 g, respectively. The acceleration design spectrum from the Regulatory Guide (RG) 1.60 »Design Response Spectra for Seismic Design of Nuclear Power Plants, revision 1« was used. The vertical component was equal to the horizontal component in all frequency regions. The ground motion was applied without any reduction at the level of foundation. For the NPP Krško Seismic Category I structures (e.g. containment vessel, shield building, interior concrete structures, control building, auxiliary building, intermediate building, essential service water intake and pump-house structure, diesel generator building and component cooling building) an elastic time history analysis was performed by using three components of an accelerogram compatible with the design spectrum. A three-dimensional lumped mass stick model was used. The soil – structure interaction in the original structural model was modeled by using spring elements representing soil. Piping, components and component supports of safety related systems complied with NRC Regulatory Guides, American Society of Mechanical Engineers (ASME), and the American Nuclear Society (ANS) codes.

Several analyses, aimed at the reevaluation of the seismic safety, have been performed until 2011. The most important studies are briefly summarized below.

According to the PSHA study, completed in 1994 (PSHA, 1994), a peak ground acceleration (PGA = 0.42 g) could be expected at the surface for 10000 year return period. This value was larger than the design value. A more recent PSHA study of the NPP Krško site performed in 2004 (PSHA, 2004), has further increased the seismic hazard at the surface to PGA = 0.56 g. According to the present (2014) hazard map of Slovenia for 10000 year return period (http://www.arso.gov.si/potresi/podatki/pospesek_10000.html), PGA for Krško amounts to 0.45 g for soil type A. Taking into account the soil coefficient for soil type B, S=1.2 (Eurocode 8), the value PGA = 0.54 g is obtained for NEK site. On the other hand, a probabilistic analysis, using the new seismic hazard data and a more advanced and realistic model for soil structure interaction for the reactor building**Error! Reference source not found.**, performed in 1995 (EQE, 1995), suggested that the peaks in floor response spectra corresponding to PGA = 0.6 g, i.e. twice the original design value, were similar to those obtained in the original design. This finding suggested that the reactor building in Krško NPP could accommodate a ground motion of much higher intensity than it was designed for. This conclusion, however, does not necessarily hold true for the buildings where the embedment is much smaller than in the case of the reactor building.

As part of the seismic PSA investigation, Individual Plant Examination for External Events (IPEEE) analysis for the seismic part was performed in the nineties (besides an Individual Plant Evaluation, IPE). That included a detailed walk-down of the plant to identify seismic vulnerabilities. The conclusion was that the plant had been well designed and constructed for a seismic event and no serious seismic issues were observed in the containment. Also in the nineties a walk-down outside the containment was performed, covering all components which were identified in the IPE as essential components for accident mitigation and safe shutdown of the plant. For all identified observations the Krško NPP performed appropriate corrective actions or design changes and resolved all deviations. In May and December 2003, a walk-down was conducted to assess new equipment added or replaced since 1996.

In the 1995 Seismic Probabilistic Safety Assessment (SPSA), a fragility screening target of 2.0 g median capacity was set up to assure that any components screened out would have a probability of a seismically induced failure of at least two orders of magnitude less than the final predicted Core Damage Frequency (CDF). In such a way it was assured that the elimination of these components does not influence the results of the assessment. In the updated SPSA performed in 2004 (SPSA, 2004)**Error! Reference source not found.**, a new screening target has been set at 2.75 g median capacity with an associated High Confidence of Low Probability of Failure (HCLPF) value of about 1.0 g in order to assure the same probability of failure of screened out components relative to the expected final CDF. The updated SPSA is the most important existing document relevant for seismic problems. It contains, inter alia, important input data for the seismic part of the stress test (which was performed after the Fukushima event in 2011). The objective of the updated SPSA of Krško NPP was to conduct a risk informed evaluation of all seismic issues that have an effect on the safety of the plant. A SPSA involves the integration of three separate engineering disciplines, (1) the development of the seismic hazard, (2) the development of event tree/fault tree risk models of the plant response to earthquake induced transients and failures, and (3) development of seismic fragilities of structures, systems and components. The SPSA Methodology consists of a fault tree/event tree modeling to quantify the plant response to transients resulting from an earthquake. Event trees and fault trees are used to model the plant functions and their response to initiating events. Input to the SPSA model consists of the probabilistic seismic hazard description and fragilities of essential structures, systems and components in the model. The conditional probabilities of seismic induced failure defined by the fragility curves are propagated through the model and combined with random and human error failures. The result of the analysis is the conditional core damage probability (CDP), which is conditional on the seismic hazard acceleration and frequency for different peak ground acceleration intervals. This CDP must then be multiplied by the seismic hazard frequency for that seismic hazard interval. The sum over all intervals provides the seismic CDF. Liquefaction is assumed to lead directly to core damage and that contribution was evaluated separately and added to the results.

The seismic fragility of a structure or equipment is defined as the conditional probability of its failure at a given value of ground motion value (i.e., peak ground acceleration PGA or peak spectral acceleration at different structural or equipment frequencies). The objective of a fragility evaluation is to estimate the capacity of a given component in terms of the selected ground motion parameter. In the past, typically, the seismic hazard for a plant site was defined by PGA. This was the case also in all calculations related to Krško NPP, hence all fragility estimates were referenced to PGA. Nowadays, spectral acceleration is considered as a better indicator of structural damage and is sometimes preferred as the ground motion parameter for fragility analysis. In spite of its shortcomings as a damage measure, PGA is a familiar term for all analysts involved in SPSA (i.e., systems analysts, hazard analysts and fragility analysts) and it enables a proper interface between the analysts (i.e., hazard, fragility and systems). Note that the fragility data, i.e. the median and HCLPF values for seismic capacities of essential structures, systems and components in the model, provided in (SPSA, 2004) and used in the SPSA analysis, were used also in the post-Fukushima stress test in 2011.

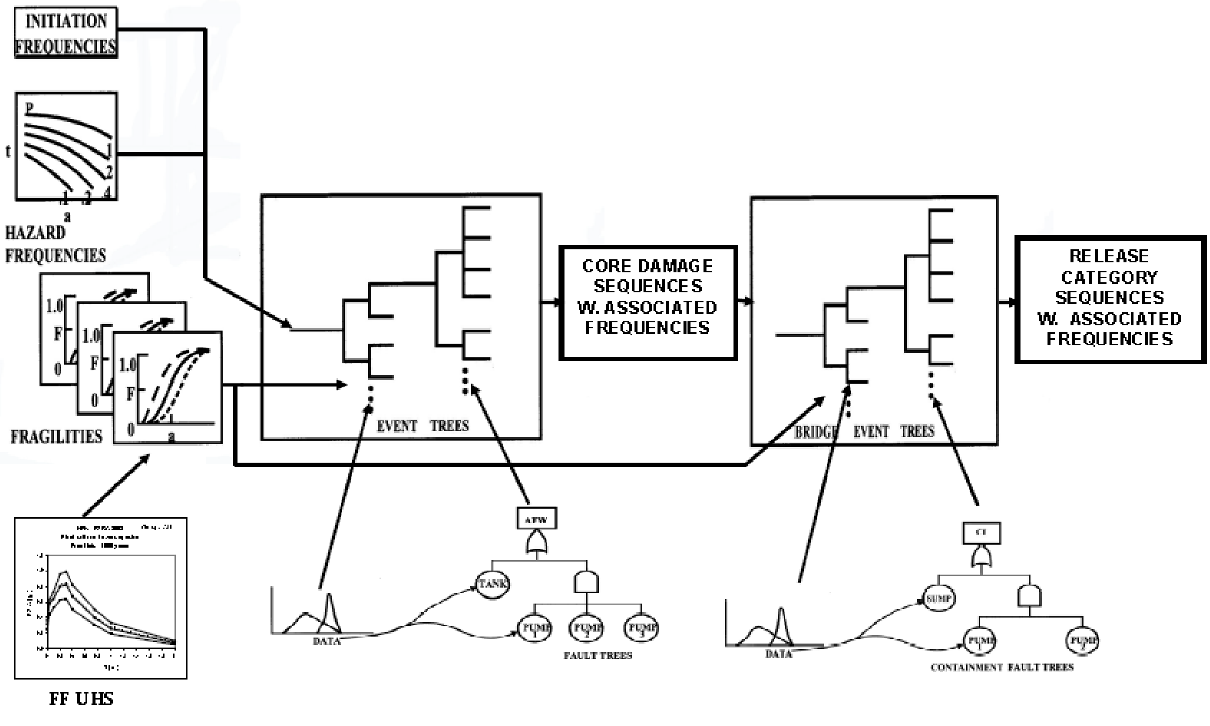


Figure C.1 Seismic Probabilistic Safety Analysis Process used for Krško NPP (taken from SPSA, 2004, Figure 1-1)

A periodic safety review was performed recently, which represented a significant review process, where seismic issues were identified, evaluated, and new actions were set up for plant seismic improvements. One of the most important improvements was the installation of a third seismically classified emergency diesel generator, which was completed in 2012.

Seismically induced floods

The hydro power plant dams at the Sava River are relevant for the consideration of seismically induced floods. There are a number of studies and analyses related to the flooding hazard induced by failures of hydro power plant dams at Sava River. However, studies on the seismic capacities of dams beyond the design level have not been performed and relevant quantitative data are not available. In the studies related to seismically induced floods, it was conservatively assumed that the dams fail during a strong earthquake. Additionally to the HPP dam failures, the risk from the formation of a natural dam (and its subsequent failure) after a catastrophic landslide or large rock fall, following an earthquake, is also an issue which has been investigated.

Flooding

The Krško NPP site is located in the Krško-Brežice Basin, on the left bank of the Sava river, i.e. in an area prone to flooding. The right bank of the Sava river above the Krško NPP and the left bank of the Sava river below the Krško NPP are extensive inundation areas that are flooded in events with high river flow. The design requirements for NEK regarding the flooding from Sava River were defined in the Final Safety Analysis Report (FSAR), based on the information on the past registered floods, high waters and applicable requirements regarding the NPP design. The design was based on the flood (river flow) with 10000 year return period. The FSAR also provided the estimate of Probable Maximum Flood (PMF). The flooding protection was accomplished by the plant design and construction of the flood protection dikes along left banks of the Sava river and the Potocnica creek upstream and downstream of the plant. Plant building entrances and openings are constructed above the elevation of the 10000-year flood. The plant is protected also against the probable maximum flood with the appropriate design of the Sava river interface structures and with the flood protection dikes, provided that the greater quantities of water will flood the inundation on the right bank of the Sava river. Flash floods due to local heavy rainstorms have been also considered. Considered is also the flood due to upstream dam's failure (seismic origin) and the effects of high wind on the raising of the water level. Due to floods in 1990, 1998 and 2007 and a hydropower plant chain being planned and built recently, a lot of studies and analyses of hydrology and flood risk for NPP Krško and surrounding area have been done recently.

C.4 POST-FUKUSHIMA STRESS TEST IN 2011

Considering the accident at the Fukushima nuclear power plant in Japan, the European Council declared that the safety of all EU nuclear plants should be reviewed, on the basis of a comprehensive and transparent risk assessment ("stress tests"). A stress test is defined as a targeted reassessment of the safety margins of nuclear power plants in the light of the events which occurred at Fukushima: extreme natural events challenging the plant safety functions and leading to a severe accident. The technical scope of the stress tests has been defined considering the issues that have been highlighted by the events that occurred at Fukushima, including combination of initiating events and failures. The focus should be placed on the two initiating events: earthquake and flooding. Stress tests should be undertaken by the operators of the facilities under the supervision of the national regulatory authorities.

The scope and the general methodology used in the stress tests are described in sections 2.2 and 2.3 of this report. In this Appendix the specific features used in the Krško NPP stress test are briefly described. The main results are also summarized. More detailed data are provided in the Slovenian National Report prepared by the Slovenian Nuclear Safety Administration (SNSA, 2011).

The aim of the stress tests is to assess whether the nuclear power plants can withstand the effects of unexpected events (beyond the design basis), among them strong earthquakes and large floods. This can be done by determining the safety margins. “The reassessment of the safety margins should consist in an evaluation of the response of a nuclear power plant when facing a set of extreme situations, and in a verification of the preventive and mitigatory measures chosen following a defence-in-depth logic: initiating events, consequential loss of safety functions, severe accident management” (ENSREG, 2011).

Earthquakes

Evaluation of the margins was the key part of the stress test. It was required that, based on available information (which could include seismic PSA, seismic margin assessment or other seismic engineering studies to support engineering judgement), an evaluation of the range of earthquake severity is given above which loss of fundamental safety functions or severe damage to the fuel (in vessel or in fuel storage) becomes unavoidable. The weak points should be indicated and any cliff edge effects according to earthquake severity should by specified. If any provisions to prevent these cliff edge effects or to increase robustness of the plant (modifications of hardware, modification of procedures, organisational provisions…) can be envisaged, they should be indicated. Similarly, it was required to determine the range of earthquake severity the plant can withstand without losing confinement integrity.

It was also required to check if a situation of an earthquake exceeding DBE and consequent flooding exceeding DBF is physically possible.

The NPP Krško site has witnessed a steadily increasing seismic hazard. At the time of original design (in early seventies) the knowledge on seismic ground motion was limited and very high accelerations were not expected in regions with moderate earthquakes. Fortunately, the analysis methods were very conservative. Later on, two probabilistic seismic hazard analyses increased the seismic hazard considerably. The second analysis, performed in 2002-2004, increased the PGA for the SSE (10000 year return period) ground motion for about 30% compared to the first analysis performed in 1992-1994. The reasons for this increase were partly new seismotectonic and seismological data and their interpretation, and new ground motion prediction equations with larger dispersion, which strongly influence the results at larger return periods.

The method for the evaluation of seismic margins started with the identification of success paths for a range of seismic events. The success paths represent the success scenarios obtained from the event trees developed within seismic probabilistic safety assessment. The required critical safety functions are identified for each success path. Each critical safety function is then connected with required systems, structures and components, which are needed in order that the safety function succeeds. The highest earthquake ground motion is determined for which the relevant set of systems, structures and components has a low probability of failure to perform the respective safety function. The seismic margin for a critical safety function is determined from safety margins of required systems, structures and components. The seismic margin for a critical safety function equals the lowest seismic margin of any of the representative systems, structures and components. But if the critical safety function can be provided by several sets of systems, structures and components, the highest seismic margin of either set may be considered.

The availability of success paths after a postulated seismic event was evaluated by increasing the severity of earthquake ground motion starting with the lowest seismic events and increasing the severity in terms of increasing the peak ground acceleration (PGA). PGA was assumed as a measure of the severity of the earthquake. HCLPFs for all relevant SSCs were identified.

If the severity of a certain earthquake is such that the required equipment for a corresponding critical safety function can not stand it, the corresponding seismic margin is exceeded and the critical safety function is assumed as failed. The corresponding success path is assumed failed if any of the required critical safety functions fail. The number of success paths decreases with increasing seismic severity. The point at which the last success path is disabled can be considered a seismic margin for the whole plant.

The approach for analysis of events leading to loss of containment integrity was similar as for events that may lead to core damage:

- mapping of critical safety functions,
- determining safety margins considering the required systems, structures and components to ensure the safety functions
- determining safety margins for safety functions,
- evaluating the availability of success paths for earthquakes with increasing severity.

The main results related to seismic margins are as follows (SNSA, 2011): Seismic levels at which core damage would occur are considered to be at the PGA range of 0.8 g or higher. Seismic events at which early radioactivity releases to the environment would be likely to occur are considered to be at PGA significantly exceeding 1 g and late radioactivity releases in the range of 0.8 g to 0.9 g or higher. The spent fuel pool integrity would not be challenged for PGA’s up to approximately 0.9 g. For earthquake ground motions exceeding the PGA of 0.9 g, gross structural failures of SFP cannot be excluded and fuel uncovers are considered likely to occur. It should be noted that, according to the PSHA analyses, seismic events with PGA higher than 0.8 g were estimated to be very rare at the NEK site, with the return period of the order of 50000 years or more.

Flooding

In the evaluation of the margins, it was required that the level of flooding that the plant can withstand without severe damage to the fuel (core or fuel storage) was estimated. It should be indicated if, based on time between warning and flooding, additional protective measures can be envisaged/implemented. The weak points and cliff edge effects should be indicated. In the evaluation of the margins, buildings and equipment that will be flooded first should be indicated, as well as envisaged provisions to prevent these cliff edge effects. Provisions that increase robustness of the plant such as modifications of hardware, modification of procedures, organization provisions and others, should also be indicated.

Evaluation of external flooding margins at NEK was performed using a similar approach as for earthquake evaluation. Success paths for a range of flooding events are determined. A success path was defined as a minimum set of functions required for avoiding reactor core damage state following a flooding event. Each identified success path was specified in terms of required critical safety functions, which have to be accomplished in order that the success path leads to a safe state. Each critical safety function in every success path was mapped to the specific plant systems, structures and components. The location of relevant systems, structures and components was determined by buildings and by elevations. The availability of all success paths following a postulated flooding event was evaluated considering the flooding levels with increasing severity starting with the lowest flooding events and gradually increasing them in terms of a maximum river flow. The point where the maximum river flow disables the last success path can be considered as an external flooding margin for the whole plant.

The main results related to the safety against flooding are as follows (SNSA, 2011): The cliff edge effect occurs when a flood with a river flow 2.3 times larger than the design basis flood and 1.7 times larger than the existing probable maximum flood would flood the plant plain. Such a flood would have a return period of 1 million years. The challenges considered at probable maximum flood are loss of offsite power (due to overall conditions in the territory of Slovenia) or clogging of intake structures of the essential service water system (ESW). However, even in an extreme case with possible loss of emergency diesel generators, the Krško NPP provides strategies, personnel and equipment to be used with appropriate emergency operating procedures (EOP) and severe accident management guidelines (SAMG) that would prevent core damage and prevent or limit late releases. The Krško NPP is in the process of upgrading its existing flood protection by raising the flood protection dikes upstream of the Krško NPP along the left bank of the Sava river and the Potocnica creek. After implementation of that modification the Krško NPP would not become isolated on an island even during the probable maximum flood. The Krško NPP has also identified additional measures to increase robustness to external events and implemented them.

C.5 DISCUSSION OF THE METHODOLOGY USED IN THE STRESS TEST

In this section the methodology used in the stress tests is discussed. Please note that the discussion applies to the methodology prescribed in (ENSREG, 2011). It was basically used for the stress tests of all units and it is not specific for NEK. However, some details of the methodology discussed in this section apply specifically to the stress test performed for NEK.

Typically, the seismic capacity of nuclear power plants is much higher than the design basis. For evaluations beyond the design basis, two types of methods can be applied. The first one is the Seismic Probabilistic Safety Assessment (SPSA) and the second one is the Seismic Margin Assessment (SMA). SPSA for the Krško NPP was performed in 2004 (SPSA, 2004). It is summarized in the section "Original design related to natural hazards and studies performed until 2011". The seismic analysis, required for the "stress test", is basically based on the seismic margin methodology.

According to (ENSREG, 2011) the reassessment of the safety margins should include an evaluation of the response of a nuclear power plant when facing a set of extreme situations. In (ENSREG, 2011), it is also stated "In these extreme situations, sequential loss of the lines of defence is assumed, in a **deterministic** approach, **irrespective of the probability** of this loss."

Here, it is very important to note that, in order to perform a **deterministic** analysis, fixed (deterministic) values have to be assigned to the seismic capacities of buildings and components. However, the seismic capacities of the systems and components of NEK were determined in previous studies in probabilistic terms (median values and HCLPF values). The HCLPF capacity is a very conservative measure. By definition, there is a **low probability** that the actual capacity of the plant is lower than the HCLPF capacity. This is in conflict with the guidelines for the evaluation of margins, provided in (ENSREG, 2011) (page 7): "Based on available information (which could include seismic PSA, seismic margin assessment or other seismic engineering studies to support engineering judgement), give an evaluation of the range of earthquake severity above which loss of fundamental safety functions or severe damage to the fuel (in vessel or in fuel storage) becomes **unavoidable**." If the HCLPF capacity of the plant is exceeded, it does not necessarily means that severe damage is unavoidable. There is a lack of quantitative definitions, which opens the room to subjective engineering judgement and makes the evaluation of results difficult.

In the evaluation of seismic margins, performed in the "stress test" for NEK, the problem explained above was resolved, after extensive discussion between the authors and the evaluators, by defining the seismic capacity of a structure or a component at a level corresponding to 10% probability of failure. This level, which is between 1% probability corresponding to the HCLPF value, and 50% probability corresponding to the median value, has been chosen arbitrarily, based on engineering judgement. The selected level of probability seems to be reasonable for this "stress test". Such a clearly defined limit state allows a transparent procedure.

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