Probabilistic safety analysis of non-seismic external hazards

J. Sandberg*, G. Thuma (GRS), G. Georgescu (IRSN)

** Radiation & Nuclear Safety Authority (STUK), P.O.Box 14, 00881 Helsinki, Finland*

Abstract:
External hazards play an important role for the safety of nuclear facilities, because they have the potential to cause initiating events and simultaneously to impair the safety systems necessary to limit the consequences of the initiating events. Owing to the worldwide increasing interest in the assessment of the possible safety threats induced by such hazards, NEA/CSNI set up a task group on *Probabilistic Safety Analysis (PSA) of Other Off-site External Events than Earthquake*. In this paper, we report on the activities and findings of this task group. Additionally, information on the operating experiences related to external events in Finland and France as well as the assessment of the impact of climate change on the safety of German NPPs is provided.

1 OECD/NEA TASK ON PROBABILISTIC SAFETY ANALYSIS OF NON-SEISMIC EXTERNAL HAZARDS

1.1 Background

In 2006 the OECD/NEA Committee on the Safety of Nuclear Installations (CSNI) initiated a task group on *Probabilistic Safety Analysis (PSA) of Other Off-site External Events than Earthquake* under the Working Group on Risk (WGRISK). Its objective was to review the external events analysis methods as well as the results and the insights gained in these analyses in order to present a basis for advances in the area. The following countries took an active part in the task: Finland, France, Germany, USA and the Republic of China (Taiwan; as observer at OECD/NEA). The task report was published by NEA in 2009 [1].

Regarding external events, seismic risk analyses is a well established part of PSA, and the topic has been included in several NEA activities [2,3,4,5]. But in the recent years, also non-seismic external conditions have caused some occurrences at nuclear power plants. For example, storm and high tide have caused nuclear power plant flooding in Europe and high wind and ice storms have damaged main power transmission lines in Europe and Canada. The results of some external events PSAs have also revealed potential risks due to non-seismic external events. In addition, there have been some natural catastrophes and climate change has been widely recognized as an important issue. All these factors have increased the interest in probabilistic safety analysis of non-seismic external events (EE PSA).

The hazards considered in the task include high winds and tornados, extreme temperatures, rain and snowfall, external floods, impurities in seawater, etc.

The work of the task group was based on information collected within a questionnaire. The questionnaire was distributed to national safety authorities of NEA member countries or their

technical safety organizations (TSOs). The questionnaire included approx. twenty questions grouped under four headings:

- Regulatory requirements and status of EE PSA
- Definition of EE PSA scope
- Analysis methods
- Results and practical applications

Answers were received from 12 countries: Belgium, Canada, Finland, France, Germany, Japan, Korea, Mexico, Slovak Republic, Switzerland, Republic of China (Taiwan) and the United States of America. The answers can be considered representative of the situation in OECD member countries. They cover two thirds of the countries with nuclear power plants and an even larger share of nuclear power plants in the OECD countries.

1.2 Regulatory Requirements on External Events PSA

In the regulatory requirements there is a general trend towards full-scope PSA, including external events. However, there are large differences in the national requirements in the NEA countries. Some countries have no legal requirements on PSA. In other countries there are explicit requirements on Level 1 and Level 2 PSA (for operating as well as new units, for all operating states, and for all groups of initiating events) with respect to off-site external events.

The Slovak Republic, Finland and Switzerland reported that they have requirements on full scope Level 1 and Level 2 PSA including external events for all operating states, for both operating units and new units. In Germany, Level 1 EE PSA (for power operation state) is required for operating units. In the USA there is no legal requirement for licensees to perform PSA for operating units. However, a PSA that addresses risk significant contributors is important for supporting risk informed applications at the regulatory and licensee side. Regarding future reactors, design specific PSA have to be included in the application for the design certification and the combined licence. There are no specific regulatory requirements on EE PSA, however guidance for a technically acceptable PSA (including external events) is available. In Korea and Taiwan external events PSA is not explicitly required for the operating units, but for new units Level 1 and 2 external events PSA is required for power operation states. In France, requirements on EE PSA for the operating reactors were recently formulated by the safety authority. For new units, there are no formal requirements on EE PSA, but technical guidelines for new reactors set a target on the overall CDF including all hazards, so a quantification of the external hazards contribution to risk is necessary. In Canada, full scope PSA is required in principle, but external events PSA can be substituted with alternative methods. Three countries reported that they have no regulatory requirements on external events PSA.

The role of external events PSA in the regulatory framework is different in different countries. In some countries external events PSA plays an important role in assessing whether the protection against extreme external events is sufficient, in particular with regard to older plants designed to earlier standards. In other countries the emphasis is on deterministic design requirements.

There are also wide variations in the actual status of external events PSA for operating units. In a few NEA countries external events PSAs covering a fairly wide spectrum of initiating events have been performed or are underway for operating units. In some countries the analysis has been limited to the most severe events, such as hurricanes/typhoons, and in a few countries no external events PSAs have been performed.

1.3 Findings on Methods and Results

The results of the questionnaire do not show a general trend that external events are especially important risk contributors. However, for some individual plants external events have been found to be quite significant. At two plants significant risks due to external hazards have been identified and mainly eliminated by plant modifications. At one of them off-site external events still account for 18 % of the total CDF.

Based on the questionnaire it is not possible to evaluate what are the reasons for the differences in the importance of external events for different plants. The difference may be due to local conditions and differences in technical solutions. However, it is also possible that the differences in the results are due to differences in the analysis methods and the level of detail in modelling.

Depending on design-specific and site-specific details, severe external events may have the potential to simultaneously affect redundant and diverse safety systems and thereby induce common cause failures (CCFs) or common cause initiators (CCIs). The results of external events PSA depend largely on the possibility of common cause failures of safety systems. The results are sensitive to the modelling of dependencies between initiating events and safety system failures as well as between failures of different safety systems. Different approaches to the analysis of potential common cause failures and identification of dependencies may have significant influence on the results. However, well established methods for the treatment of dependencies between extreme weather conditions were not reported. The analysis seems to be done on a case by case basis.

The external events PSA is started by identification of potentially significant events and combinations of correlated events. Usually, a screening analysis is performed to select the events and combinations of events to detailed modelling and quantitative analysis. For some events, e.g. floods and wind speed, the intensity-frequency distribution can be used in the screening analysis. The distribution can be determined either from local observation data or international recommendations can be used. The frequencies of potential extreme weather conditions are difficult to estimate and uncertainties are large. Screening out events in terms of EE PSA seems to be largely based on expert judgement. The screening results may be influenced by the treatment of uncertainties and dependencies between extreme weather conditions.

The answers to the questionnaire indicate that there is a reasonably well established framework for external events PSA. General deficiencies in the methods were observed. However, only a few extensive external events PSAs were reported and detailed comparison of methods was not done. Standards and guides for EE PSA are available. In the United States, ANS and ASME have published a standard on EE PSA [6,7] and, for example, the Swedish regulatory authority SKI (currently SSM) has published a report outlining methods for EE PSA used in Sweden and Finland [8]. Also IAEA has published at least one report on EE PSA [9] and several reports on external events in general [10,11,12].

External events may affect human reliability of human actions either due to increased stress or adverse physical working conditions. In some EE PSAs increased human error probabilities have been used, but so far there are no consensus adjustment factors.

External hazards threaten simultaneously all the units at the site and the assumptions about dependencies may affect the results. The units at a multi-unit site may be able to support each other in emergency situations (loss of electric power supply, etc.). On the other hand, problems at one unit may require resources from other units. Different practices for considering multi-unit sites in varying level of detail were reported. However, well-established comprehensive methods for considering multi-unit sites in EE PSA are not available. There is

a tendency to integrate external events in the general Level 1 PSA model to be used in PSA applications. In some PSAs external events are treated as a separate model.

The questionnaire included a question on examples of significant occurrences due to external events and their effect on the EE PSA. The examples of EEs reported by the participants include conditions related to precipitation, including snow, and low temperatures, wind, ocean level changes, organic material build-up around water intakes, and combinations of issues due to events such as hurricanes or typhoons. Such EEs have led to unavailability of components and systems degradations (both internal and external to the plant), and thus affected plant capabilities and risk levels. Because of EEs, plants have had to address issues such as the loss of offsite power, water intake blockage, reactor scrams, and decisions to shutdown plants in anticipation of and during EEs.

As an example of combined events, some EE PSAs have addressed the potential station black-out due to the loss of off-site power caused by high wind and simultaneous loss of diesel generators due to cooling water blockage caused by wind-related impurities in seawater (algae) or blockage of diesel combustion air intakes by snow.

Regarding the effect of occurrences due to EEs on PSA, some countries have not reported any EE PSA changes, one country is considering incorporating events into its EE PSA at a later time, and some have changed their PSAs. None of the respondents identified any events with significant complications (e.g., dependent failures) that might require a re-examination of the way EE analyses are performed.

1.4 Recommendations of the Task Group

According to the findings of the Task Group, more work, including research, is needed in the following areas:

- Effects of climate change on extreme events and NPP safety;
- Uncertainties related to extreme weather conditions;
- Treatment of dependencies
    - between external events, e.g., extreme weather conditions,
    - between initiating events and safety system failures;
- Criteria for screening phenomena out of EE PSA.

Identification of significant external events requires good knowledge on the specific local conditions. The national regulatory authorities, licensees and PSA consultants should evaluate whether they have sufficient awareness of external events and adequate analysis capabilities. It was also pointed out that international cooperation would be valuable to enlarge the data basis in the analysis of operating events due to harsh weather and other external conditions. Some earlier preliminary studies suggest that external events are significant contributors to certain types of occurrences, such as loss of off-site power, loss of emergency power and loss of ultimate heat sink. Systematic analyses, however, are not publicly available. The possibility to analyse operating events due to external events in co-operation with the CSNI Working Group on Operating Experience (WGOE) and possibly with IAEA and the EU Clearinghouse of NPP Operating Events Feedback in JRC Petten should be considered.

External events issues have been treated on several international forums, for example, in special sessions of the PSAM and PSA conferences. Continuation of the practice was recommended and licensees, regulators and research organizations of the NEA member

countries were encouraged to participate in these activities to exchange information on off-site external events.

In summary, the following general recommendations were proposed by the Task Group to all parties active in the PSA field, including international organizations, utilities, regulatory authorities, PSA consultants and research organizations:

- Follow research on climate change and its effects (including potential effects on nuclear power plants, such as those being studied by IAEA);
- Re-evaluate the situation on external events PSA in a few years;
- Encourage analysis of operating events caused by external hazards;
- Participate in sessions on external events in international conferences, e.g. PSAM and PSA.

2 OPERATING EXPERIENCES RELATED TO EXTERNAL EVENTS IN FINLAND

The following types of occurrences have been caused by harsh weather conditions at the Olkiluoto NPP in Finland [13]:

- Failure of diesel generators to run during testing due to blockage of combustion air filters by snow;
- Partial blockages of seawater intake by frazil ice, algae and mussels.

The problems have been mainly removed with plant modifications, such as alternative air intake routes. An example of an occurrence at a conventional power plant with relevance to nuclear safety is the loss of the external power grid connection due to steel panels torn off from the plant walls and flown to the switchyard.

Plant modifications and procedure development to prevent the risk of seawater intake blockage due to frazil ice formation, algae or oil slick can be mentioned as examples of corrective measures initiated or supported by PSA:

- Pressure difference measurements over band screens to trip main seawater pumps on incipient blockage of seawater intake (Loviisa);
- Alternative service water intake to cope with blockage of normal seawater intake (Loviisa);
- Installation of pipelines to supply warm outlet water to the sea water intake channel during conditions favourable to fast freezing of subcooled water.

In the design of Olkiluoto 3 special care has been taken to remove risks due to external hazards, e.g., protection of diesel generator air intakes and underground cables from a gas turbine plant [14].

3 OPERATING EXPERIENCES RELATED TO EXTERNAL EVENTS IN FRANCE

In France several off-site external events having the potential to threaten nucelar safety occurred. The most significat event was the partial floodig of the Blayais NPP in December 1999. Severe floods affected the Blayais nuclear plant in the Bordeaux region of France. During a severe storm, high waves overtopped a protective dyke installed at the plant partly submerging portions of the plant area. This event called into question the design basis used for the protection of nuclear power plants against external flooding and the efficiency of the

existing measures, especially the warning systems, the site protection measures, the protection of safety-related equipment, the procedures, and the emergency organization.

In addition to the assessment of the protection measures implemented at the Blayais site, EDF has reassessed the maximum design flood level at all plant sites and has launched a 'review project' with the aim to ensure the effective protection of installations against external flooding. The 'review project' principles were submitted for review to the French Safety Authority in December 2001 after being evaluated by IRSN. In general, they were considered satisfactory. Therefore, the analysis of the protection of all French nuclear plants against external flooding should be performed in compliance with both Basic Safety Rule and the methodology developed after the incident occurred at Blayais. In practice, the reassessment of the maximum design flood and the application of the new methodology have brought about many modifications and improvements on the sites.

4 THE IMPACT OF CLIMATE CHANGE ON THE SAFETY SIGNIFICANCE OF HARSH WEATHER CONDITIONS IN GERMANY

Recent scientific findings indicate that globally there is a potential for an increase in the frequency and intensity of harsh weather conditions due to climate change. Against this background, GRS tried to answer the question, whether such impacts should be treated in the framework of probabilistic safety assessments for nuclear power plants in Germany [15].

The assessment was based on the following set of considerations:

- The need for a detailed probabilistic assessment scales with the safety significance of the hazard under consideration.
- The safety significance of a hazard can be deduced from the operating experience.
- Looking at the operating experience of nuclear power plants worldwide also extreme events are covered.
- Even though climate change might cause the meteorological conditions in Germany to change for the worse, we will not face more severe events than covered with the assessment of the worldwide operating experience.
- The design of the German nuclear power plants is comparable to the design of most other nuclear power plants.

These considerations allow applying a three-step approach:

- Assessment of the national-scale (Germany) climate change impact;
- Evaluation of the international operating experience of nuclear power plants with respect to harsh weather conditions;
- Comparison of the operating experience with the expected future meteorological conditions.

4.1 Regional Climate Projections for Germany

Based on the evaluation of the available literature (e. g. [16,17,18]) on regional climate impacts, some general predictions on the future development of the meteorological conditions in Germany can be made:

- During the summer months higher temperatures are to be expected and long-lasting droughts will become more frequent. Consequently, the probability for forest fires will also increase.
- In winter the number of days exhibiting frost will decrease and precipitation will predominantly come as rain instead of snow.
- The total amount of precipitation and the frequency of heavy rainfall events will increase in the winter months.
- Due to the increase of precipitation in winter serious floods will become more probable in winter and spring.
- The frequency of gales will remain more or less unchanged, but the intensity of gales might possibly increase. Additionally, tornadoes might become more frequent.
- Because of the expected increase in the frequency of thunderstorms the probability of lightning strikes will increase as well.

Altogether, in contrast to the global trend, the regional-scale climate projections predict only moderate changes within the next decades. Therefore, the hazard due to harsh weather conditions is not expected to increase significantly on a medium-term scale.

4.2 International Operating Experience with Harsh Weather Conditions

To evaluate the operating experience of nuclear power plants with respect to harsh weather conditions three databases (INES, IRS, BEVOR/VERA) were searched for events related to such types of hazards.

Based on the evaluation of the 125 identified events, there is no indication of an increase in the frequency of weather induced events during the past 30 years.

55 % of all analyzed events are linked to storms. 80 % of these events resulted from local effects such as lightning, high winds, and precipitation and 20 % were due to flooding (of local or distant origin). The dominant impact of local storm effects consists in the disturbance of I&C equipment. Floods can additionally affect the service water system.

The remaining 45 % of the events were provoked by temperature effects. Again, one can distinguish between two sub-groups: Immediate temperature effects (including icing) make up for 85 % of the events, whereas the rest is due to medium term consequences of high temperatures such as draughts and fires. The impacts on nuclear power plants are quite similar to those by storms (disturbance of I&C equipment and the cooling water supply).

For almost all events analyzed, the impacts were covered by the plant design. Only in a few exceptional cases safety margins were utilized.

4.3 Consequences for the Safety of German Nuclear Power Plants

The results of the assessment made by GRS can be summarized as follows:

- Harsh weather conditions have the potential to impair the safety of nuclear power plants. I&C equipment and the cooling water supply (in particular the service water system) are the systems most susceptible to impacts of harsh weather conditions.
- In spite of the global trend towards more extreme weather conditions due to climate change, no significant increase in the contribution of harsh weather

conditions to the overall risk to nuclear power plants in Germany is expected during the next decades.

These findings indicate that there is no urgent need for an extensive probabilistic assessment of the impact of harsh weather conditions on nuclear power plants in Germany. This holds in particular, because the uncertainties regarding the (future) frequency and intensity of such hazards are considerably high and experience shows that the results (core damage frequencies) of probabilistic safety assessments for external hazards are often dominated by the frequency of the initiating events.

5 CONCLUSION

Non-seismic off-site external events, as a group, do not appear to be dominant risk contributors. However, depending upon the specifics of the plant design and location, such events may be significant contributors. The frequency and intensity of extreme weather events, and consequently their risk significance, may be affected by natural climate variability and by human-induced global warming. So far little information is available on the prediction of changes, especially on a regional level, but intensive research is ongoing worldwide. The NEA/CSNI recommends to all parties active in the PSA field to follow research on climate change and its effects (including potential effects on nuclear power plants) and to re-evaluate the situation on external events PSA in a few years.

6 ACKNOWLEDGEMENT

The description of the OECD/NEA task on the PSA of non-seismic external events is based on the task report published by OECD/NEA [1]. The authors wish to acknowledge the work of the NEA secretariat and of all those who participated in the task, especially Dr. Nathan Siu (US NRC).

7 REFERENCES

1. *Probabilistic Safety Analysis (PSA) of other External Events than Earthquake,* Report NEA/CSNI,/R(2009)4, OECD, Paris, France (2009).
2. *Proceedings of the OECD/NEA Workshop on Seismic Risk*, 10-12 August 1999, Tokyo, Japan, Report NEA/CSNI,/R(1999)28, OECD, Paris, France (1999).
3. *Proceedings of a Specialist Meeting on the Seismic Probabilistic Safety Assessment of Nuclear Facilities,* Jeju Island, Korea, 6-8 November 2006, Report NEA/CSNI(2007)14, OECD, Paris, France (2007).
4. *Proceedings of the Workshop on Recent Findings and Developments in Probabilistic Seismic Hazards Analysis (PSHA) Methodologies and Applications*, 7-9 April 2008, Lyon, France, Report NEA/CSNI/R(2008)6, OECD, Paris, France, to be published.
5. *State-of-the-art report on the current status of methodologies for seismic PSA*, Report NEA/CSNI/R(1997)22, OECD, Paris, France (1998).
6. *External-events PRA methodology*, American National Standard, ANSI/ANS-58.21-2007, American Nuclear Society, La Grange Park, IL., USA (2007).
7. *Standard for Level 1/Large Early Release Frequency Probabilistic Risk Assessment for Nuclear Power Plant Applications*, ANSI/ASME/ANS RA-S-2008, (rev. of ANSI/ASME RA-S-2002), American Society of Mechanical Engineers, New York, NY, USA (2008).

8. M.Knochenhauer and P.Louko, *Guidance for External Events Analysis*, SKI Research Report 02:27, Swedish Nuclear Inspectorate, Stockholm, Sweden (2003).
9. *Treatment of External Hazards in Probabilistic Safety Assessment for Nuclear Power Plants*, Safety Reports Series No. 50-P-7, IAEA, Vienna, Austria (1995).
10. *External Events Excluding Earthquakes in the Design of Nuclear Power Plants*, Safety Guide, Safety Standards Series No. NS-G-1.5, IAEA, Vienna, Austria (2004).
11. *Flood Hazard for Nuclear Power Plants on Coastal and River Sites*, Safety Guide, Safety Standards Series No. NS-G-3.5, IAEA, Vienna, Austria (2004).
12. *Extreme External Events in the Design and Assessment of Nuclear Power Plants*, IAEA TECDOC Series No. 1341, IAEA, Vienna, Austria (2003).
13. J. Sandberg, *Weather and Seismic Risk Analyses of the Finnish Nuclear Power Plants - Results and Lessons Learned,* the Proceedings of International Topical Meeting on Probabilistic Safety Assessment, PSA '02, Oct. 6-9, 2002, Detroit, MI, USA, American Nuclear Society, USA (2002).
14. J.V. Sandberg, A.M. Julin, J.J. Marttila, R.K. Virolainen, *Regulatory Review of Internal and External Hazards of EPR 1600 in Finland*, PSAM8, Proceedings of the 8th International Conference on Probabilistic Safety Analysis and Management, held on May 14-19 , 2006, New Orleans, LA, USA.
15. M. Krauß, G. Thuma, *Untersuchungen zu extremen Wetterereignissen und Witterungsbedingungen*, Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) mbH, GRS-A-3426, Cologne, Germany (2008)
16. A. Spekat et al., *Neuentwicklung von regional hoch aufgelösten Wetterlagen für Deutschland und Bereitstellung regionaler Klimaszenarios auf der Basis von globalen Klimasimulationen mit dem Regionalisierungsmodell WETTREG auf der Basis von globalen Klimasimulationen mit ECHAM5/MPI-OM T63L31 2010 bis 2100 für die SRES-Szenarios B1, A1B und A2*, Report on a research project on behalf of the Umweltbundesamt, Germany (2007)
17. Potsdam-Institut für Klimafolgenforschung (PIK), *Klimawandel - Auswirkungen, Risiken, Anpassung (KLARA)*, PIK Report No. 99, Germany (2005)
18. Deutsche Meteorologische Gesellschaft (DMG), *Stellungnahme der Deutschen Meteorologischen Gesellschaft zur Klimaproblematik*, Germany (2007)