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Resilience of nuclear plants in case of hazards

Keywords

resilience, internal hazards, external hazards, combination of events, safety assessment

Abstract

Internal and external hazards analysis methods have been used recently to evaluate operating nuclear power plants (NPP) and to identify the resilience of NPP in case of hazards and potential needs for modification of plant systems and procedures as well as to support design of new plants The external hazards risk contribution has been modeled in many NPP PSA (at least for some external hazards) over the last decade, including events occurring during shutdown and low power operations. Recently, a revision of the German nuclear safety regulations has been successfully completed and these regulations entitled "Safety Requirements for Nuclear Power Plants", also requiring a detailed investigation of internal and external hazards and combinations of different hazards applying deterministic and probabilistic safety assessment methods.

1. Introduction

Lessons learned from the Fukushima Dai-ichi reactor accidents and related actions at national, European and global level have emphasized the importance to identify the resilience of nuclear installations, in particular nuclear power plants (NPP), and to assess risks associated with internal and external hazards (including combinations of these hazards) and their impacts on a plant site (possibly with several different types of nuclear units).

Resilience in that context is a property of a system which measures how the system can still function to a required level by means of its own after the system has experienced partial damage.

Resilience engineering is about modelling, analysis, and design of a system for achieving a desired resilience property of the system. Resilience is in a strong relationship with robustness, reliability, redundancy, sustainability and repairing. More details on this relationship is provided in [1].

Regulators in most countries have already taken actions to include – besides internal hazards like fire and explosion - seismic and flooding risk, and, to some level, some other specific external hazards in national probabilistic safety assessment (PSA) practices and safety regulations [19].

The development of systematic approaches for addressing external hazards completely in PSA practices is still ongoing.

Useful hazard estimates can be determined with current methods and used in applications in the processes of risk oriented decision making.

Development of methods and preparation of studies aiming to obtain realistic risk assessments, neither too optimistic nor too much conservative, is a key issue. These more realistic evaluations would provide a better view on the real problems and also a better view on the interest of safety improvements.

Recently developed methods and guides are available for seismic hazard determination, identification of external hazards and screening of external hazards for detailed consequent analysis. Several lists of screening criteria are available. The methods of Probabilistic Seismic Hazards Assessment have been developed and used in practice.

Internal and external hazards analysis methods have been used recently to evaluate operating NPP units and to identify needs for modification of plant systems and procedures as well as to support design of new plants

The external hazards risk contribution has been modeled in many PSA for NPP (at least for some external hazards) over the last decade, including events occurring during shutdown and low power operation.

In the US risk evaluations follow a process similar to that shown in *Figure 1*; the process would start with risk-informed external hazard scenarios such as seismic, flood, fire, or tsunami, or a combination of these as initiating events [8].

Verified and validated (V&V) models would be used to simulate the external hazard initiators and model results would be used to determine which systems are at risk; decisions will be made on the protective measures needed to minimize risk.

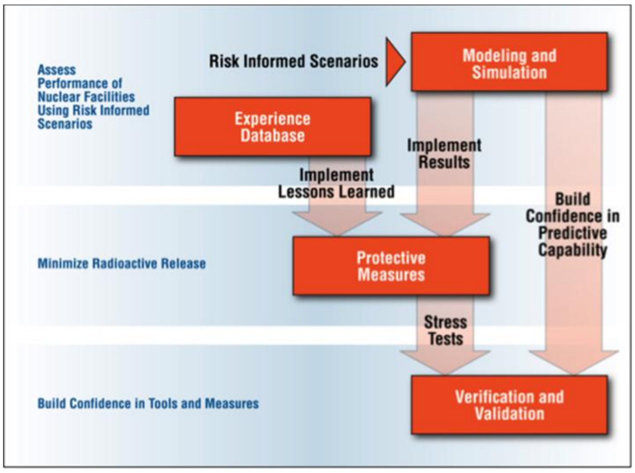

Figure 1. Future risk-informed process to minimize potential external hazard risk according to [8]

A significant challenge is data analysis, particularly estimation of the initiating event frequency. For many hazard estimates, observational data (sometimes including paleo information) data are commonly available, usually for a period of the order of 100 years. However, risk-related screening criteria can be far beyond the range of observation. As a consequence, strong "distant" extrapolations using extreme value distributions are necessary, typical resulting in high uncertainty in the final quantitative results.

Identification of correlations between external hazards is another important point. The combinations of simultaneous or successive external hazards may result in increased loadings on structures, systems and components or they may simultaneously endanger diverse safety systems. Formal mathematical methods to treat the probabilities of correlated hazards are available but the quantification of the model parameters is a big challenge.

A systematic consideration of external hazards as shown in *Table 1* is a necessary precondition to ensure a complete risk assessment.

The Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) initiated in September 2003 a comprehensive program for the revision of the national nuclear safety regulations which has been successfully completed in November 2012 [12].

Table 1. Systematic Consideration of External Hazards

Natural hazards	**Man-made hazards**
Seismo-tectonic	External fire
Hydrological	Aircraft crash
Meteorological	External explosion, blast wave
Extraterrestrial	Ingress of dangerous materials (i.e. gaseous or liquid)
Biological	External electromagnetic interference (EMI)
Geological	

These nuclear regulations take into account the current recommendations of the International Atomic Energy Agency (IAEA) and Western European Nuclear Regulators Association (WENRA).

In this context, the recommendations and guidelines of the German Nuclear Safety Standards Commission (KTA) and the technical documents elaborated by the respective Expert Group on Probabilistic Safety Analysis for Nuclear Power Plants (FAK PSA) are being updated or in the final process of completion. In both cases one main topic of the revision was the issue external hazards.

As part of this process and in the light of the accident at Fukushima and the findings of the related actions resulting in safety reviews of nuclear power plants at national level in Germany [21] and on European level [11], a revision of all relevant standards and documents has been made, especially the recommendations of KTA and FAK PSA. In that context, not only design issues with respect to events such as earthquakes and floods have been discussed, but also methodological issues regarding the implementation of improved probabilistic safety analyses on this topic.

As a result of the revision of the KTA 2201 series [18] "Design of Nuclear Power Plants against Seismic Events" with their parts 1 to 6. Part 1 (Principles) was published as the first standard in November 2011, followed by the revised versions of KTA 2201.2 (Soil) and 2201.4 (Systems and components) in 2012. The modified standard KTA 2201.3 (Structures) has been issued in 2013. In case of part 5 (Seismic instrumentation) and part 6 (Post-seismic actions) a publication is expected in 2015.

The above mentioned expert group on PSA is an advisory body of the Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB). This expert group, led by the Federal Office for Radiation Protection (BfS), has the task to advise the BMUB on all methodological issues for the implementation of probabilistic safety analyses and has elaborated two publications on methods and data for PSA with the aim to support a unified application of the PSA in Germany.

2. Regulatory basis in Germany

The German safety concept for nuclear power plants gives priority to the deterministic approach, i.e. deterministic safety assessment and good engineering judgement, are primary tools of design evaluation.
Probabilistic safety assessment is seen as a supplementary tool to the deterministic approach which provides quantitative information on the occurrence of incidents and thus can be used to check deterministic design assumptions, to evaluate desired plant and system modifications, to optimize corrective measures and to identify existing safety margins, e.g. in the frame of comprehensive (periodic) safety reviews [10].
The hierarchy of the German PSR documents is shown in *Figure 2*.

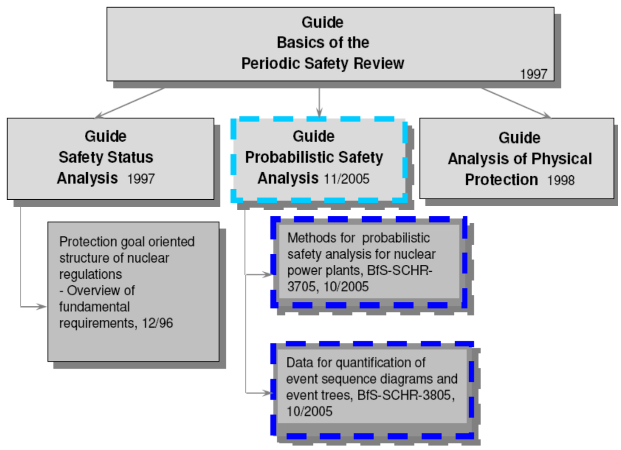

Figure 2. Hierarchy of the German documents for (periodic) safety reviews

As a result of an Integrated Regulatory Review Service (IRRS) mission to Germany in 2008 suggesting to develop a uniform Federal policy document [14], the need for a more stringent approach to risk-informed decision making within the German regulatory framework has been identified.

However, risk-informed decision making in general is still not practice in Germany and is currently not intended to set in force.
In the past, the safety concept of nuclear power plants, the regulatory framework laid down in ordinances, guidelines, recommendations of the Reactor Safety Commission (RSK) and nuclear safety standards (KTA Standards) as well as licensing decisions by the competent authorities and their experts in the Federal Republic of Germany were mainly based on a set of deterministic principles, such as

- safety features to prevent or control abnormal operation conditions and incidents,
- passive barriers against radioactivity releases in case of an incident, and
- redundancy and diversity of safety systems to ensure high reliability.

Safety requirements including acceptance criteria and safety targets are usually defined by the regulatory body. Safety decision making during design, construction and licensing has essentially been based on the verification of compliance with pre-described technical requirements as laid down, e.g., in the German nuclear safety standards. Boundary conditions for the safety analysis, safety margins with regard to the prevention and control of incidents as well as specific, partially very detailed, requirements concerning safety functions are deterministically postulated.
Due to the permanent regulatory oversight of specified normal operation (levels 1 and 2 of the defence in depth concept), it is entirely sufficient to assess the results for these two levels in the frame of a comprehensive periodic safety review in a simplified way.
By assessing operating experience, including safety-relevant areas of operating management, the aim is to show to what extent the respective requirements for these levels are satisfied and how the technical installations and measures have proven to ensure safety during operation so far. Investigations concerning incidents constitute the central point of the PSR, i. e. focusing on whether the enveloping incidents can be controlled by available precautionary measures with sufficient effectiveness and reliability and if the required resilience of the nuclear power plant against internal and external hazards can be shown.
It is the overall requirement in the frame of PSR in Germany to perform a PSA as a supplement to the deterministic safety analysis to get insights which are not revealed by the deterministic approach. The main objectives are to check the overall safety level of the plant and analyze if the engineered safety features designed to cope with safety relevant incidents are

well balanced. The last item does preponderantly contain an evaluation of single contributions (event sequences) from initiating events which should not dominate the overall quantitative safety results and is looked upon as the prior objective. The evaluation has to be performed taking into consideration quantitative as well as qualitative results of the analysis. Interpretation of the results shall include adequate uncertainty, sensitivity and importance analysis.

Deterministic and probabilistic approaches are now jointly being used in evaluating and improving nuclear safety.

For the PSR performed up to now, no probabilistic quantitative safety goals are determined although different proposals were made in the past [3]. On the other hand, the competent authorities and their supporting expert organizations have to assess the results of the probabilistic safety assessments submitted by the licensees and have to decide if the quantitative results of the probabilistic safety assessments, provided in the frame of (periodic) safety reviews, are adequate [7].

The measures to be taken and directives to be given by the responsible supervisory authority in the scope of the overall evaluation of the results have to be established according to the principle of commensurability [2]. Significant modifications of technical systems and components in German nuclear installations are generally assessed by application of the detailed prescriptive German nuclear safety standards.

In case of deviations, e.g. from the original material used and/or its thickness in case of pipe work, it is possible to proof that the design of the new equipment is equivalent to the design of the old equipment and that the existing safety margins are not reduced. This means in practice that in case of significant modifications it has to be shown in Germany that all deterministic boundary conditions are still fulfilled.

Nevertheless, licensees in Germany have submitted in the past – together with their approval for a significant modification – probabilistic considerations in addition to the deterministic assessment as supporting arguments.

Recently, a revision of the national nuclear safety regulations has been successfully completed and these regulations entitled “Safety Requirements for Nuclear Power Plants” [12] require with respect to probabilistic safety assessments:

- For the safety demonstration that the technical safety requirements are met, deterministic as well as probabilistic safety analyses have to be considered.
- Probabilistic safety analyses (PSA) shall supplement deterministic safety analyses for demonstrating the balance of the safety related plant design.
- Furthermore, probabilistic safety analyses (PSA) shall supplement deterministic safety assessments for demonstrating the safety significance:
  - of modifications of measures, equipment or the operating mode of the plant, as well as
  - of findings that have become known from safety-relevant events or phenomena that have occurred and which can be applied to the nuclear power plants in Germany that are referred to in the scope of application of the "Safety Requirements for Nuclear Power Plants" for which a significant influence on the results of the PSA can be expected.
- Compared with the unchanged condition of the plant, modifications of measures, equipment or the operating mode of the plant must not lead to an increase in the average core damage frequency (CDF) and the average frequency of large and early releases (LERF), neither for power operation nor for low-power and shutdown states, considering all plant-internal events as well as all internal and external hazards as well as very rare human induced external hazards.

This means that the new German safety requirements contain an implicit definition of quantitative safety criteria. However, no absolute value is given by which the current risk status of the plant can be judged to be acceptable [22].

The values for CDF have been calculated in the frame of the comprehensive safety reviews and the results of the latest safety review for the respective NPP are the basis for the comparison in case of modifications.

3. Design and assessment of external hazards for nuclear power plants in Germany

Methods to analyze existing plants systematically regarding the adequacy of their existing protection equipment against hazards can be deterministic as well as probabilistic. Typical investigations for German nuclear power plants are provided in [5], [6] and [13].

3.1. Seismic design and flood protection according to KTA

In Germany, nuclear power plants are designed against earthquakes according to the nuclear safety standard series KTA 2201.

A site specific deterministic seismic hazard assessment is required for NPP sites in Germany according to [18]. In the new version of this standard the application of probabilistic methods for the hazard assessment is explicitly required.

Further parts of the KTA 2201 series addressing seismic instrumentation and post-seismic actions are nearly finalized.

The design basis earthquake is the earthquake of maximum intensity at a specific site which, according to scientific knowledge, may occur at the site or within a larger radius of the site (up to approx. 200 km from the site). In the probabilistic determination of the design earthquake, the exceedance probability in the range of 10^{-4} to 10^{-5} per year is to be based. The fractile value of the design spectrum may be assumed to be 50% if the exceedance probability of the design earthquake at 10^{-5} per year is shown, the fractile is assumed at 84%, if an exceedance probability of 10^{-4} per year is assumed. For the design earthquake are in the assessment of seismic intensity, location, indicate the strong-motion duration and site-specific response spectra.

Here also the local and regional geological and tectonic conditions are taken into account. Also in geological areas with low seismicity, the design earthquake for nuclear power plants has to be assumed so that even in those cases the effects of seismic intensity VI according to the European Macroseismic Scale (EMS) have to be calculated.

Combinations of loads resulting from earthquakes and earthquake-induced incidents and consequential incidents shall be taken into consideration. More details on the seismic design of nuclear power plants are provided in [16].

According to KTA 2207 [20], it is necessary to determine statistically the storm-tide water level with an exceeding frequency of 10^{-2} per year plus a site-specific addend. In conclusion, a storm-tide must be covered with an exceeding frequency of 10^{-4} per year. In the context of the analysis, design-basis flood is that particular flood event which is the basis for the flood protection of the respective plant, specifically with regard to meeting the safety objectives.

The permanent flood protection is that flood protection which is effective at all times (e.g. protection by flood-safe enclosure, by structural seals).

The loads due to the design-basis flood must be combined with other loads such as an operational loads, earth thrust, and wind load, static water pressure due to the design water level, streaming water, waves, upswing, flotsam, and ice pressure. More details are provided in [6].

3.2. Probabilistic safety assessment of natural external hazards

The latest revision of the German guideline on Probabilistic Safety Analyses (PSA) in the framework of safety reviews of nuclear power plants requires PSA for natural external hazards like seismic or flood events [10] supported by the corresponding technical document on PSA methods [9]. Recent research results on natural hazard PSA in Germany are described in [24].

The PSA procedure for seismic events consists of three major steps:

1. seismic hazard analysis,
2. determination of failure probabilities of structures, systems and components (SSC),
3. development of seismically induced event trees with subsequent calculation of core damage frequencies.

The seismic PSA is an essential part of the safety review of nuclear power plants worldwide, because at locations with a non-negligible seismic hazard, earthquakes can contribute significantly to the overall core damage frequency.

Therefore, the latest revision of the German PSA technical documents [9] stipulates a complete seismic resistance analysis for those plants, whose seismic hazard assessment exhibits an earthquake intensity greater than VII (according to the EMS-scale). For nuclear power plants with a lower seismic hazard simplified analyses are acceptable (see *Table 2*).

Table 2. Progressive verification records for an “earthquake” event in accordance with the value of the current adequately determined intensity of the design basis earthquake at the location of the facilities.

Intensity I_0	Record verification	Comment
$I_0 \leq$ VI	no analysis necessary	- acc. to KTA 2201.1 (2011) a basic design level exists
VI < $I_0 \leq$ VII	simplified analysis necessary	- verification of sufficient margins for the deduction of earthquake stresses, assessed on basis of a 1E-5/a earthquake with an intensity I_0+1
I_0 > VII	full scope analysis necessary	- earthquake safety analysis applying the safety reserve factor procedure

In general, all seismically induced initiating events which might occur in a nuclear power plant have to be considered in a seismic PSA. But unlike internal initiating events, the seismic induced initiating events and the seismic failure behaviour of the safety systems depend on the actual intensity of the earthquake.

Thus, a set (discrete or continuous) of several earthquake intensities has to be considered (cf. [9] and [23]).
The German regulatory framework for flood events requires a determination of a sufficient water level as design-basis and appropriate structural protection measures against this hazard in the design of the plants to avoid radiological consequences for the environment.
The adequacy of the protection measures have been shown in the past only on a deterministic basis. The probabilistic safety assessment guideline as well as the corresponding technical documents prescribes also probabilistic analyses of external hazards including flooding.
PSA regulations consider extreme events of recurrence intervals of 10,000 years. Beside the frequently occurring extreme storm surges, also other events have to be considered. One example is the possible impact of a tsunami type of event simulating the propagation and development of extreme waves in the North Sea towards the German Bight, initiated by a hypothetical slide at the continental margin off the Norwegian coast. This scenario has been analyzed as a consequence of the tsunami in December 2004 in Indonesia [4].

Table 3. The graded safety assessment approach regarding external flooding.

Criteria	Record verification	Comment
Due to the topography and the plant design, a failure of vital functions can be practically excluded. Temporary measures are not included.	no analysis necessary	Is assumed that the design of the plant complies with the basic level according to RSK SÜ / RSK 11 /. Compare also the understanding of the safety philosophy of the RSK to the interpretation of the term "(practically) excluded" / RSK 13 /
If the analysis of flood-related event sequences shows that the contribution to the core damage frequency of this event is well below 10-6/a, further considerations are not required.	The measures of the plant-specific flood protection concept according to KTA 2207 be probabilistically. It is set out that the conditional probability of an uncontrollable water entry is much smaller than 10-2 to assess. There are potential penetration paths for water-related structures and equipment to identify. For the assessments to the water entry, only the buildings (including subsequent tube and cable channels) of importance, to the emergency power supply and to the subsequent heat dissipation systems are included. The conditional probability of failure of required for the core cooling systems for the design flood is then to estimate. Insights from qualified plant inspections remain here to consider.	Only permanent protective measures are used in the analysis. Plant-internal accident management measures can be taken into account. The shut-down of the plant according to BHB either at a water level, which includes a significant distance to the design flood or occurrence of defined situational plant-specific conditions, such as when a foreseeable failure of the main heat sink.
other design	In-depth event sequence considerations are necessary. Temporary facility-specific safeguards can be considered.	If the simplified procedure does not lead to success, an increased effort is necessary.

A graded approach for the extent of a probabilistic safety assessment in case of external flooding containing deterministic and probabilistic elements has been developed and is described in [22]. This approach takes into account site-specific aspects like the nuclear power plant grounded level compared with surroundings level and plant-specific aspects such as design with permanent protection measures and prescribed shut down of the plant according to the instructions of the operation manual at a specified water level which is significantly below the level of the design flooding. The graded approach for external flooding can be summarized as given in *Table 3* above.

4. Concluding remarks

Resilience attributes to improve understanding of the emergency operation system (EOS) resilience dynamics of complex systems such as nuclear power plants are analysed and characterized in [15]. By improving understanding of resilience attributes, it may provide insights to new resilient strategies that the management can adapt.
The main conclusion is that EOS resilience analysis approach can supplement traditional safety approaches to help in addressing their inherent limitations. This approach focuses on how success is achieved in a dynamic environment such as a nuclear power plant.
With rapid growth in technology, large socio-technical systems such as nuclear power plants have become so complex that the established safety analyses methods have become inadequate. The characterization may help managers and employees to correct or expand their understanding on resilience.
Based on the observations of a recent study [25], external phenomena mostly affected the systems and equipment of heat sink or power supply. Extreme strong wind conditions and lightning strikes in all reported cases affected electrical equipment and grid disturbances. Cold air temperature, external phenomena related to biological reasons, debris and soil related generally impacted on heat sink systems and equipment. One frequent group of consequences was the spurious actuation of safety systems due to the freezing of instrumentation impulse lines or due to lightning strikes.
In some cases, multi-units or even multi-plants consequences of external hazards were not considered as a design basis for plant safety. The consequences of external phenomena to infrastructure and communication means may also cause unforeseen problems in an accident management in the nuclear plant during extreme

external conditions.

With the publication [12], a modern version of a German nuclear safety regulations has been published. In this regulation the broad experience of the application of the periodic safety reviews have been incorporated as a key element of regulatory supervision. Further key findings from the European safety review of nuclear power plants were taken into account after the accident at Fukushima. The revision also paid special attention to the requirements and recommendations of WENRA and IAEA.

In addition, the recommendations and guidelines of the Nuclear Safety Standards Commission (KTA) and the expert group on Probabilistic Safety Analysis (PSA FAK) have also been updated. The activities of the updates have been focused the natural external hazards "earthquake" and "flooding" in the German regulations:

- Probabilistic assessment for retrofit measures in individual cases for all operating modes and the PSA level 1 and level 2 is possible.
- Deterministic and probabilistic site hazard analysis for the events "earthquake" and "flood" are required.
- For the event "earthquake" according to IAEA plants receives a minimum design comparable to 0.1g - concept.
- Furthermore, a seismic instrumentation independent of the location of intensity is required for each installation.
- The importance of quality assured plant walk downs to determine the specified plant conditions was explicitly emphasized and required measures to ensure.
- Furthermore, the existing methods for their applicability verified the associated generic data base for PSA updated.
- The explicit consideration of all natural external hazards is required.

A supplementary document to [9] is in progress and intended to be issued in 2015. *Table 2* and *Table 3* are already reflecting this update of [9] with respect to natural hazards.

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