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EXTERNAL HAZARDS NEW INSIGHTS INTO OLD ISSUES

- Changing hazards
- Risk assessment
- Protection measures
- New facility design
- Retrofitting

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Winter 1999: A powerful storm named Lothar sweeps through the southwest of France, causing significant flooding at Le Blayais NPP, including some safety-related buildings. *Summer 2007*: The strongest earthquake ever to affect an NPP occurs near Kashiwazaki-Kariwa, the world's largest nuclear power plant, located in western Japan. Though the reactors and their safety-related equipment perform satisfactorily, the quake damages non-safety-related equipment, and four of the seven units are still shut down. *Summer 2010*: An unprecedented heat wave hits several parts of Russia, lighting violent forest fires. Working day and night, the fire squadrons succeed in containing the fire only four kilometres away from the Novovoronezh NPP. The situation was never out of control in any of these three cases, and yet…

This issue of the EUROSAFE Tribune, devoted to external hazards, bears witness to the increasing awareness of the uncertainty associated with phenomena such as floods, earthquakes, tsunamis, extreme heat, dust- and sandstorms, and airplane crashes. It provides an overview of the lessons learned from each event and of the knowledge gained from ongoing studies aimed at making nuclear facilities less vulnerable to external hazards at each stage of the lifecycle, from design through siting, construction and operation. We invite you to draw your own conclusions on these issues, and we wish you pleasant reading. ●

Jacques Repussard and Heinz Liemersdorf

External hazards: Taking up new challenges

Jean-Christophe Gariel and Tiberiu Mateescu, IRSN (France)

Ever since the inception of the nuclear power industry, increased awareness of the risks of low-frequency events, combined with greater consideration of the risks associated with climate change and human activity, have prompted the evolution of safety design and assessments methods with respect to external hazards. How are these methods impacted? How should the design and operation of nuclear facilities be adapted to maintain safety levels? A French perspective.

Risks relating to external hazards, whether natural or man-made, are taken into consideration in the design of nuclear facilities (power reactors, nuclear fuel cycle plants, research reactors, laboratories, etc.) and are regularly reviewed during periodic safety reviews (PSRs). These risks must be studied to guarantee safety functions which, in the case of power reactors, include shutdown, maintaining the reactor in a safe shutdown state, residual heat removal and containment of radioactive products.

Collecting exhaustive, quality data: A challenging prerequisite

With a view to design protection against risks related to external hazards, the hazards to be taken into consideration must first be assessed. The methods used in France to assess external hazards were described in the 1980s in Basic Safety Rules applicable to all nuclear facilities. The methods described in these rules can be either deterministic – as in the case of seismic hazard assessment – or probabilistic, as in studies of the risk of an aircraft crash. Whether probabilistic or deterministic, the method used is always reliant on *observations* (recorded in meteorological records, earthquake catalogues, flood measures) that are processed to define a maximum event for facility design.

The definition of the hazard is therefore highly dependent on the quality and exhaustiveness of available data. The environment around nuclear facilities changes, for multiple reasons: climatic and geomorphological change on a global or local scale (e.g. global warming or coastal erosion), or changes in infrastructure (e.g. increased air traffic or changes in land use). Prospective studies in these areas provide valuable information, but contain even greater uncertainty when we focus on extreme events to be considered in the nuclear field. As is often the case, operating feedback is an essential source of information on the processes involved. In this respect, France benefits from 30 to 40 years of nuclear facility operating experience feedback (OEF), built in particular on 1,500 reactor-years of EDF reactor fleet operations. Combined with international OEF, this can now be applied to assessment of the robustness of methods used to characterise external hazards. Two major questions emerge from this operating experience: have any extreme events occurred in recent years and, if so, have they called hazards definition into question? Has any new technical and scientific knowledge been acquired and, if so, has it led to the need to change methods used to assess external hazards? A couple of cases offering answers to these questions follow.

Flooding: Partial flooding of Le Blayais nuclear power plant in 1999

In December 1999, an exceptionally violent storm struck most of Europe. It led to the partial flooding of Le Blayais nuclear power plant, located along the Gironde estuary in southwestern France, and a partial loss of offsite power. Analysis showed that the exceptionally high water levels observed during the storm were due to the combined effects of high tide, storm surge and waves driven by very strong wind. The partial flooding of the site was due to the fact that the last of these factors was not taken into consideration when the height of the dike that protects the site was calculated. The feedback from this situation led to the re-assessment of flood protection for all nuclear facilities and to improved characterisation of the flood risk by taking additional phenomena and combinations of phenomena into account, such as the impact of wind on wave height and consideration of local rainfall. A new guide incorporating these factors, intended to replace the 1984 Basic Safety Rule, is currently in the public consultation phase. The French Nuclear Safety Authority (ASN) is expected to publish it in 2011.

Heat waves: The summers of 2003 and 2006

During these two summers, mean daily temperatures were well above mean values observed over the previous thirty years. In addition to high air temperatures, these extreme climatic events resulted in a steep rise in river water temperatures. In 2003, in particular, water temperatures in several rivers rose five degrees above the mean historical temperature and exceeded maximum historical values. This led the regulators to issue a temporary discharge permit based exclusively on the relative increase in water temperature rather than on observance of an absolute temperature threshold. Since the 2003 heat wave, forecast calculations based on climatic change models were performed showing that, by 2020-2035, extreme temperatures could largely exceed those recorded in 2003 and 2006. In light of these observations and forecasts, EDF decided to increase the capacity of some of its heat exchangers.

Earthquakes: Lessons learned from Kashiwazaki-Kariwa

The most severe earthquake ever recorded at a nuclear facility occurred at the Kashiwazaki-Kariwa nuclear power plant, located in Niigata Prefecture, 250 km northwest of Tokyo, Japan. The 6.6 magnitude earthquake that struck the seven-reactor power plant occurred along a fault in which the seismogenic potential (i.e. the most powerful earthquake likely to occur at this spot) had been significantly underestimated. Nonetheless, thanks to the very conservative safety criteria of the plant's design and the high quality of construction, this situation had no impact on nuclear safety, although restart is still pending for units 2, 3, 4 and 5 .

This example clearly shows that even in a highly developed country that is accustomed to taking seismic phenom-

ena into consideration, the seismic hazard for sensitive facilities can still be largely underestimated.
In France, the Basic Safety Rule concerning seismic hazard assessment was revised in light of fresh seismological knowledge. The 2001 revision introduced two new concepts. Firstly, consideration was given to paleoseismology, the study of earthquakes with very long return periods (several tens of thousands of years), far longer than the period considered in historical seismology, which is about one thousand years in France. Secondly, the effects of local amplification induced by the presence of 'soft' geological layers at the surface were taken into account, as these layers amplify seismic motion.

Aircraft crash test in the USA.

Aircraft crashes: Factoring in changing aircraft types and air traffic

The method used by French nuclear operators to assess the risk of an aircraft crash for their facility is based on the application of Basic Safety Rules I.1.a and I.2.a, developed by ASN. A *probabilistic approach* is adopted first. For each nuclear site, the annual probability of an unintended aircraft crash is assessed at each target facility. This assessment is performed for each of three aircraft categories: general aviation (aircraft weighing less than 5.7 tonnes), commercial aviation and military aviation. The assessment is based on air traffic statistics and records of accidents involving each category of aircraft in metropolitan France. The probabilistic objective of the Basic Safety Rules is that the overall probability of a facility being the source of an unacceptable release of radioactive substances should not exceed 10^{-6} per year, expressed as an order of magnitude. In practical terms, if the annual probability of a crash impacting a safety function for a given category of aircraft exceeds an order of magnitude of 10^{-7}, the radiological consequences are then assessed using a *deterministic approach*. If those consequences are unacceptable, the target facilities which ensure this safety function must be designed to withstand a crash involving a representative aircraft in each category considered.
The aircraft crash risk is constantly reviewed during the lifecycle of a nuclear facility to ensure that it continues to be consistent with the original structural specifications. Failing this, steps must be taken so that the consequences are acceptable. The methods used to assess the aircraft crash risk must be reviewed periodically to take into account changes in aircraft (the A380 wide-body aircraft, civil defence 'Canadair' water-bombers

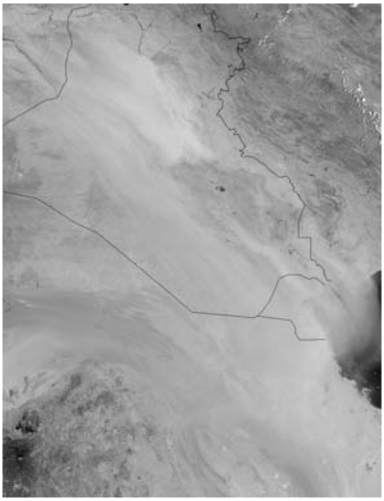
used in fighting forest fires, especially in the south of France) and air traffic in each category, as well as the growing amount of statistical data available to refine approaches.

With regard to intentional aircraft crashes, nuclear facilities are under constant surveillance and a variety of measures were implemented in the wake of the 9/11 terrorist attacks in 2001.

External hazards: 'New' types of phenomena to be factored in

All of the above examples show that close attention must be paid to assessing risks relating to external hazards. There are several situations where the intensity of expected events has been underestimated or inadequately assessed owing to the failure to consider certain phenomena or combinations of phenomena. For existing facilities, particular attention must therefore be paid to the observation of extreme phenomena and to the acquisition of new knowledge. Whatever the case, regulations must be regularly updated on the basis of operating experience feedback and fresh knowledge.

With newcomer countries planning to build nuclear reactors, new issues will have to be addressed when defining the risks relating to external hazards. In some of these countries, for example, the new facilities will be located in regions with conditions – weather conditions in particular – that have never been encountered by the facilities currently in operation around the world. These conditions include the regular occurrence of extremely high air temperatures (above 40°C) and high cooling water temperatures (above 30°C). Such problems will need to be taken into account. Other climatic phenomena, such as sandstorms, which have not previously received much attention, will now have to be considered. ●



Sand storms seen from space and from the ground.

Design load case: From deterministic to probabilistic assessment

Heinz Liemersdorf, GRS (Germany) | Heinz-Peter Berg, BfS (Germany) | Dietmar Hosser, iBMB (Germany)

External hazards have the potential to affect a nuclear power plant (NPP) as a whole, and simultaneously induce initiating events (e.g. loss-of-coolant accidents or transients) and impair the safety systems necessary to limit the consequences of these events. This is why German NPPs have been designed to withstand the impact of external hazards such as aircraft crashes, pressure waves, earthquakes and flooding. This design draws increasingly upon probabilistic safety assessments (PSAs).

The spectrum of hazards to be considered, the different design provisions, and the type and extent of the protection measures required according to the standards and regulations have changed over time. This is reflected most notably in the German NPP fleet, comprising four design generations of pressurised water reactors and two construction lines for boiling water reactors. Despite all the differences in the design, one similarity is noticeable: *all design concepts were based on deterministic considerations.*
Up to now, regulations and standards refer to probabilistic methods, mainly in the context of assessing the safety of *existing* reactors. In Germany, the design of NPPs against external hazards is based on a limited set of nuclear standards and regulations covering five hazards explicitly: earthquakes, flooding, lightning, pressure waves from chemical explosions, and unintended aircraft crashes. For other hazards, such as loads from wind and snow pack, non-nuclear standards and regulations are applied. According to the technical reference document on PSA methods supplementing the German guideline for periodic safety reviews, probabilistic analyses are required for four categories of external hazards: earthquakes, flooding, pressure waves and aircraft crashes.

From *design earthquake* and *safety earthquake* to *design basis earthquake*

Seismic hazards are addressed in the German Nuclear Safety Standard KTA 2201, Design of Nuclear Power Plants against Seismic Events, which consists of six parts covering all the relevant aspects from hazard assessment to foundation soil issues to design and post-earthquake measures. The first requirements to consider seismic hazards were specified in 1975 by KTA 2201, which defines two different earthquake levels: the *design earthquake* (similar to an operation basis earthquake), representing a lower intensity earthquake for which continued plant operation should be feasible, and the *safety earthquake* (similar to a safe shutdown earthquake), which determines the ultimate safety-related design requirements. In the revised version of KTA 2201, published in 1990, the design basis earthquake replaced this two-level concept. Based on scientific knowledge, this designates the most severe earthquake that could potentially affect the plant site. Its determination is essentially based on the definition of seismic source zones and observed historic seismicity. Although a target exceedance probability of 10^{-4} per year together with an 84-percentile design spectrum is applied, this is not specified in the current standard. In the ongoing revision of KTA 2201, an exceedance probability of 10^{-5} per year together with a median design spectrum and the additional application of probabilistic methods will be introduced.

The value of experience feedback in safety standard revisions

Other, more specific KTA safety standards, which have also been revised twice, are dedicated to protection against flooding (KTA 2207) and lightning (KTA 2206). KTA 2207, issued in 1982, was revised in 1992 and 2004. The last amendment of this standard was a direct consequence of operating experience: In 1999, the Le Blayais site in the southwest of France was affected by the winter storm Lothar, causing significant flooding of the plant area and of some safety-related buildings. This led to a revision of KTA 2207 in 2004 to incorporate lessons learned from French operating experience. In addition to the specification of methods to be used for flood hazard assessment at river and coastal sites, the exceedance probability for the design basis flood was set at 10^{-4} per year. As stipulated in the previous version of the standard, permanent protection measures are required for flood events with exceedance probabilities of up to 10^{-2} per year, whereas temporary measures are allowed for probabilities from 10^{-2} to 10^{-4} per year.

The standard on lightning protection, KTA 2206, was first published in 1992 as a consequence of operating experience in the eighties. The revisions in 2000 and 2009 incorporate new scientific and technical findings.

Increasing awareness of man-made hazards

While no KTA standards for man-made hazards exist so far, guidelines are available for protection against pressure waves from chemical explosions and aircraft crashes. A guideline on pressure waves focusing on appropriate site selection and on structural design measures – i.e. on the design against a pre-defined pressure curve – was issued in 1976, whereas a specific section on aircraft crashes supplemented the RSK Guidelines for Pressurised Water Reactors in 1974.

Originally, the aircraft crash hazards covered only military jets, not civil aircraft. Design analyses for German NPPs in the early seventies were already based on the characteristics of Starfighter-type military aircraft (mass and velocity at time of impact). But since the typical NATO jet in operation over Germany at that time was the Phantom, a load function compatible with the impact of that aircraft was defined in the guideline. The specifications of the RSK guidelines are still applicable to current military aircraft – the Tornado and the Eurofighter Typhoon – since their basic characteristics are similar to those of the Phantom. Furthermore, they provide basic protection against unintended crashes of a wide range of civil aircraft.

Views of the damage caused by the 2007 tremor at Kashiwazaki-Kariwa NPP (western Japan).

Subsidence of refilled soil after the 2007 tremor at Kashiwazaki-Kariwa NPP (western Japan).

Incorporating PSAs in international safety documents: A slow but steady trend

Over the last thirty years, probabilistic risk assessment has supplemented deterministic hazard assessment more and more. As operating experience at several NPP sites, mainly in the USA and Japan, revealed non-negligible frequencies of specific hazards such as earthquakes, hurricanes, tornadoes and flooding, it was recognised that nature-induced hazards might impair NPP safety significantly. There were therefore some first attempts to incorporate external hazards in probabilistic assessment. Due to difficulties in determining exceedance probabilities for this type of hazard and in incorporating their impact in the plant model, it took nearly fifteen years until the first complete seismic PSA was performed for a German NPP. Current international documents on PSAs advise that severe weather conditions and seismic events be addressed. In this respect, part of the IAEA Safety Guide is devoted to a long list of external hazards to be considered [1]. However, specific recommendations are provided for selected hazards that usually cannot be screened out: seismic hazards, strong winds, external flooding and human-induced hazards. The latter cover off-site explosions (e.g. by a pipeline accident), off-site toxic substance releases and an unintended aircraft crash.

PSAs: An integral part of new build projects

For new NPP projects[2], the most significant improvements include the requirement for PSAs at the design stage, reduction in the acceptable consequences of external hazards, and crash protection against large-size civil aircraft.

The current revision of the German technical PSA documents in particular will adopt experience in performing PSAs for external hazards resulting from progress in methods and updated data, but also from changes such as the increasing number of flights over Germany, which has lead to a broadening of previously restricted air routes. ●

(1) Development and Application of Level 1 Probabilistic Safety Assessment for Nuclear Power Plants, SSG-3, April 2010.
(2) WENRA Safety Objectives for New Power Reactors, December 2009.

SEISMOLOGY

From earthquakes to seismic hazard

Timo Schmitt, SDA-engineering GmbH (Germany)

Because earthquakes are potentially highly damaging, NPP site studies include assessments of the seismic hazard inherent in each candidate site. Similar studies are performed in Germany for operating NPPs as part of periodic safety reviews. From the observation of earthquakes to the calculation of the seismic hazard, this article provides an overview of scientific advances and limitations.

As we were reminded by the Haiti tremor in January 2010, earthquakes are among the most destructive natural disasters in the world, producing significant accelerations at frequencies to which buildings are vulnerable. To avoid damage, the first step should therefore be evaluation of the seismic hazard based on target safety levels. For standard civil engineering calculations, seismic loads are specified in national building codes by standard response spectra. Usually, the seismic hazard is calculated for a probability of 10% in 50 years, i.e. a return period of 475 years. For facilities with high secondary risk, such as nuclear power plants, radioactive waste deposits or large dams, longer return periods are required. This is the case for nuclear power plants (NPPs), where the probability of exceedance typically ranges from 10^{-4}/year to 10^{-5}/year. Moreover, in this particular case, site-specific studies must be conducted by a multidisciplinary team with state-of-the-art geological, geophysical and engineering knowledge.

These disciplines are needed for seismic hazard assessment, as this type of evaluation is based firstly on historical and recent seismicity data collected in earthquake catalogues, and secondly on knowledge about geology and tectonics, such as source regions and active faults.

Estimating the seismic hazard for different probabilities of exceedance

The first seismic hazard assessments for nuclear power plants were carried out in the late 60s following deterministic procedures. At that time, guidelines were developed to provide a framework and basic requirements for performing seismic hazard assessments (see Table). The deterministic seismic hazard assessment (DSHA) considers case scenarios and evaluates the strongest credible vibrations at the site, based on historical seismicity and tectonics. The probabilistic seismic hazard assessment (PSHA) goes back to the American civil engineer Carl Allin Cornell and the Mexican civil engineer Luis Esteva. In 1968, Cornell published a major theoretical work for a probabilistic seismic hazard assessment that estimates the seismic hazard for different probabilities of exceedance (see box). Part of this work is the *total probability theorem*, where the probability that the expected earthquake parameter at the site will be reached or exceeded is dependent on earthquake strength, distance and the cumulative distribution functions of these two characteristics. Computer programmes were developed in the 70's based on this theory, the best-known being EQRISK, which made it possible to perform a PSHA with numerical procedures. It took a few more years for probabilistic methods to disseminate and be used by NPP owners. Nowadays, the PSHA is the standard procedure for seismic hazard assessment, and PSHA methodologies were made mandatory for NPP codes (although most of the codes still prescribe a deterministic procedure as the basic requirement).

The significance of uncertainties

Deterministic and probabilistic methods are basically the same, except that the PSHA evaluates the earthquakes statistically and provides design accelerations for different probabilities of exceedance, thereby making it possible to define safety or design levels. Over time, the PSHA became more sophisticated and the importance of uncertainties was identified. Uncertainties were divided into mathematical uncertainties (aleatory) and model uncertainties (epistemic). Although all uncertainties are theoretically epistemic, the differentiation is useful for consideration in the hazard calculation. Aleatory uncertainties such as attenuation of ground motion are taken into account by standard deviations, whereas epistemic uncertainties such as the selection of an appropriate attenuation function or the definition of source regions and their maximum magnitudes are usually assessed by a logic tree approach. Although uncertainties are often mentioned in the PSHA, they can apply in the DSHA as well.

The seismic hazard with long return periods

Generally, the greatest uncertainties relate to ground motion attenuation and local soil conditions. Calculations of soil dynamics can be performed to estimate the effects of ground motion on the local site. These calculations are already standard, but it is important to determine input parameters carefully. This is done by measurements of shear wave velocities at the site in addition to borehole data that give the stratigraphic profile and soil density. The trend towards estimating an increasing number of uncertainties leads to hazard results that are not comprehensible anymore. Sensitivity studies are performed to make the results of the PSHA understandable. In these studies, the hazard is de-aggregated to analyse the influence of single hazard parameters. The sensitivity studies consider the effects of seismic source characterisation, maximum magnitudes, attenuation functions etc. on the aggregate hazard at the site. The information that seismic source regions are significant for the overall hazard is of special interest when earthquake scenarios are used in design calculations.
Although there are many tools for seismic hazard assessment, results for a particular site sometimes differ significantly among experts. This is no surprise in the case of earthquakes for which we have only a couple of centuries of observation, whereas required return periods for the design of NPPs are very long.

Considerations for future PSHA development

In the past ten years, some time- and cost-consuming hazard studies were performed to evaluate parameters that are difficult to assess, taking into account differing expert opinions. The basic idea is to combine expert opinions using a logic tree, assuming that different experts represent a community of opinion. Project management plays an important role in this approach. The question then arises as to whether a hazard study designed to factor in all eventualities and include several different expert groups really meets the goal of a more precise hazard assessment, or if it just produces more data and a broader distribution of uncertainty. However, the PSHA is not a standard procedure and it is therefore important to document all input data and to describe and explain all methodologies and decisions in order to make the calculations reproducible.

How will the PSHA evolve in the future? Are we taking a step back to smaller and more efficient expert groups, concentrating on the most significant parameters? Is a scenario-based approach thinkable? In practice, a hazard assessment for the licensing process might be carried out either by setting up workshops with experts, advisors and reviewers, or through a study performed by an expert working group and reviewed by another independent group. However, benchmark tests are often neglected.

Checking the reliability of results

Mathematically, we can calculate the seismic hazard to infinitely small probabilities, resulting in accelerations that are physically impossible due to the implied Gaussian distribution in the hazard formulation. It is therefore essential to have tools aimed at checking the reliability of the results. We must keep in mind that the earthquake catalogue is the fundamental basis of all our calculations. To make the results of a PSHA plausible, especially for low probabilities of exceedance, the DSHA can help, because it is a simple and much more transparent procedure. ●

Principle of a probabilistic seismic hazard calculation

First, it is assumed that earthquakes are Poisson-distributed, i.e. that they are statistically independent events. Therefore, it is important to exclude pre- and aftershocks before calculating the regression parameters of the frequency distribution of the source regions. PSHA programmes calculate the hazard for a site as follows: The area around the site is divided into small regions. For each region, the frequency distribution and the activity rate of earthquakes are known. The hazard at the site can therefore be calculated for a given ground motion attenuation function. The sum of all contributions from all source regions gives a hazard curve for the site. The hazard curve gives the earthquake strength in terms of spectral accelerations, peak ground accelerations or intensities.

Basic Data

Earthquake catalogues, Geology and (Neo-)Tectonics, local soil

Basic Model Parameters

- Seismic source regions
- Ground motion attenuation functions
- Local soil conditions
- For each source region:
  - Depth distribution
  - Maximum credible earthquake strength
  - Frequency distribution of earthquakes (only PSHA)

Hazard Calculation

Deterministic	*Probabilistic*
Maximum credible site intensity response spectra acceleration	Probability of exceedance for different site intensities response spectra acceleration

Soil dynamic calculations

Results

Hazard curve, site-specific response spectra

Table
Basic components of seismic hazard assessment
These include input data (such as earthquake catalogues and tectonics), model parameters (such as seismic source regions) and ground motion attenuation functions, as well as deterministic and probabilistic calculation procedures. The final results are hazard curves and specific response spectra for the site.

SEISMIC DESIGN OF NPP BUILDINGS

Taming the Namazu[1]

Rüdiger Danisch and Peter Rangelow, AREVA NP GmbH (Germany)

It is estimated that 20% of the world's nuclear reactors are operating in areas of significant seismic activity. In all cases, nuclear power plants (NPPs) are designed to withstand much stronger and less probable earthquakes (see box) than ordinary building structures. Moreover, in Germany, seismic events to be considered in the design are combined with other events in operating and accidental conditions by taking into account the probability of simultaneous occurrence. Based on the mathematical models used to analyse the effects of earthquakes on structures, systems and components, mechanical isolation offers major advantages over conventional methods in areas of significant seismic activity.

(1) In Japanese mythology, Namazu is a giant catfish that causes earthquakes. Namazu lives in the mud beneath the earth and is guarded by the god Kashima, who restrains the fish with a stone. When Kashima lets his guard fall, Namazu thrashes about, causing violent earthquakes.

The regulatory basis of seismic design

In Europe, seismic design of civil structures is based on a standard called *Eurocode 8* (EC8), whose main objective is to protect human life, limit damage and ensure that infrastructure important to public safety (e.g. hospitals) remains operational. The EC8 seismic design load for normal and important buildings is based on return periods of 475 years and 2,500 years respectively.

NPPs are designed to withstand much stronger earthquakes, with return periods of 10,000 to 100,000 years (see Fig. 1). The basic approach for ensuring their seismic safety is formulated in national (e.g. KTA-2201 in Germany) as well as international (e.g. IAEA) standards and safety guides, which define the safety objectives, criteria and seismic design requirements and require their implementation in the design. These regulatory requirements are reflected in the European Utility Requirements (EUR), currently the most widely used standard in Europe for new build projects.

Earthquakes: A complex, multifaceted hazard

According to the EUR, a vendor's standard NPP must be designed to withstand the *Design Basis Earthquake* (DBE), defined in EUR by standard design acceleration and a set of seismic spectra reflecting local conditions. Based on the seismicity and geology of the site and its surrounding area, the plant owner determines the parameters of the site-specific *Safe Shutdown Earthquake* (SSE), and the vendor must establish that the standard design is satisfactory when checked against this site-specific SSE.

The plant owner may also define an *Operating Basis Earthquake* (OBE), under which no specific inspection would be required to continue operation. Experience has shown that if structures, systems and components (SSCs) have to be strengthened to meet the requirements of a demanding OBE level, this may be detrimental to their behaviour in normal operation (e.g. due to thermal restraint effects). In addition, an analysis of the site-specific seismic margin of the structures and equipment is carried out to ensure that adequate safety

margins exist in the seismic design of the main structures and components beyond the design basis conditions. According to the EUR, the design must withstand a *Seismic Margin Assessment Review Level Earthquake* (SMA-RLE) with a margin of 40% on the horizontal peak ground acceleration above the design SSE level.
Seismic loads to be considered in the design of the structures and equipment are combined with other loads for operating and accidental conditions. Such combinations are based on the partial load factor approach, which takes into account the probability of simultaneous occurrence of the loads.

Procedure for modelling and analysis

Mathematical models are used to analyse the response of nuclear building structures to seismic action. Several models of the structure are created due to its complexity and the resulting need for division into several subsystems. The response of the primary structure model provides the seismic excitation input to the substructure models for subsequent analysis.
The seismic analysis procedure consists of the following main steps:

- Depending on the type of analysis selected, definition of the SSE by time histories, ground response spectra and/or power spectral density;
- Generation of the structural model, taking into account the effects of soil-structure interaction;
- Response analysis of the model;
- Evaluation of floor time histories and floor response spectra (FRS);
- Dynamic analysis of components with the FRS or with compatible time histories.

Considerable uncertainties in the design arising from different sources – e.g. definition of the hazard, material properties, soil-structure interaction, FRS evaluation, etc. – are addressed by parameter variation and, for example, levelling and broadening the FRS.

The case of the Kashiwazaki-Kariwa NPP

The largest earthquake ever to affect an NPP occurred on July 16, 2007 near the world's largest nuclear power facility in Japan. The Kashiwazaki-Kariwa NPP is a seven-unit facility on the northern Japanese coast. The strength of the quake (moment magnitude, Mw = 6.6) killed a dozen people in neighbouring areas, flattened nearly 350 structures, and its force significantly exceeded the limits for which the NPP was originally designed. It caused the plant, located only 15 km away from the epicentre, to safely shut down. Though the reactors and all their safety-related SSCs performed very well, the quake damaged non-safety related SSCs and four out of the seven units are still shut down.

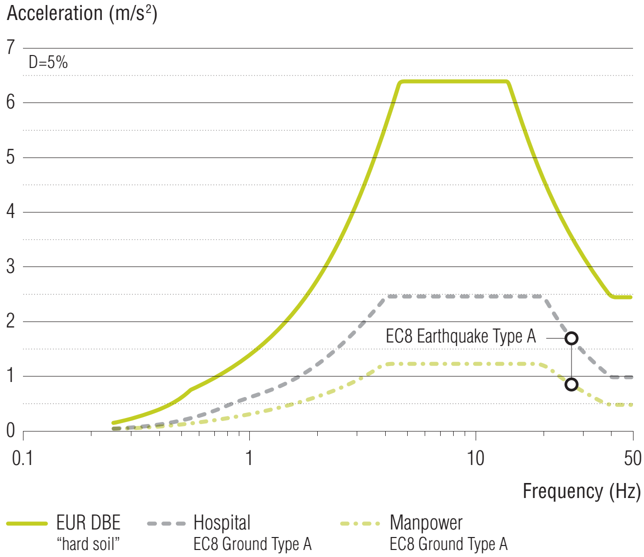


Figure 1
Seismic design loads (product of mass and acceleration) according to European Utility Requirements (EUR) for a potential NPP site in the UK in comparison with the much lower EC8 loads which a normal building or a hospital at the same location must withstand. The maximum horizontal acceleration is defined as a function of the natural frequency of the building vibration for 5% damping. The dominant natural vibrations of buildings are at frequencies of less than 10 Hz. In this frequency range, the accelerations for which the NPP structures must be designed are about six times the values for a normal building or about three times the values for a hospital is designed.

Designing plants for high seismic areas

There are two principal methods to protect a reactor's structural integrity during a strong earthquake: the conventional one is to design the structures and foundations with sufficient strength to cope with the induced seismic forces, while the second one is to reduce the forces transmitted to the structure by isolating the building from its foundation. In order to increase the global stability of the reactor building against a strong earthquake or the crash of a large commercial aircraft, four main options are available: increase the size of the base mat, as shown in Fig. 2; combine several buildings on a common base mat, as shown in Fig. 3; deeply embed the building into the ground; or fix the base mat to the ground with anchors for tall structures.

The smartest protection methods consist of reducing the seismic forces transmitted to the building through isolation, as implemented differently on the four units of the Cruas plant in the south of France and the two units of the Koeberg plant in South Africa.

The main advantages of the base isolation method are the reduction of inertial forces and stresses resulting from the reduction in design-acceleration levels, the reduction in the cost of plant equipment, the guarantee of equal performance regardless of site seismic conditions (enabling standardisation of plant SSCs), and improved plant seismic margins. The main disadvantages of the base isolation method are the need for an additional foundation slab to support the isolation devices, the existence of a gap around the building to allow for seismic movement, the need for expansion joints on piping between the isolated structure and the ground, and increased maintenance costs.

In conclusion, it is clear that seismic isolation is a very effective method for protection against strong ground vibration. In areas of significant seismic activity, it offers major advantages over conventional methods. For this reason, seismic isolation is expected to be broadly instituted in the next generation of NPPs in high seismic areas. ●

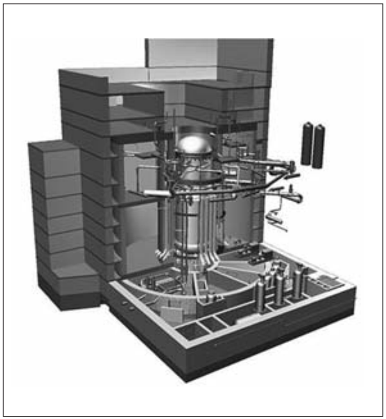


Figure 2
AREVA's KERENA™ boiling water reactor building with a larger base mat (update status: December 2009).

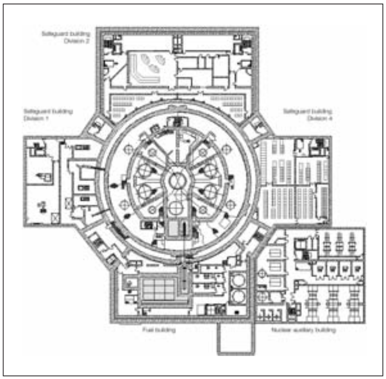


Figure 3
AREVA's EPR™ pressurised water reactor common base concept: reactor, safeguard and fuel buildings.

REASSESSMENT OF FLOOD PROTECTION MEASURES

An overview of Belgian and Dutch experience

Dries Gryffroy, Bel V (Belgium) | **Hans Brinkman**, NRG (Netherlands)

Extreme phenomena, such as storm surges or high river water levels, may endanger the safety of nuclear power plants (NPPs) by flooding the plant site, with subsequent damage to safety-related buildings. Flooding may result in simultaneous failures of safety-related components, such as service water pumps and electrical equipment. In addition, the plant may become inaccessible due to flooding in the plant environment. (Re)assessments of flood risk and flood protection measures should therefore be based on accurate state-of-the-art methods.

In the light of new data and modelling techniques

For the current fleet of Generation-II (Gen-II) NPPs, the initial assessment of external flood risks and the subsequent deterministic design of flood protection measures (including engineered site platform level) have often been executed in a period of limited availability of both statistical data on natural phenomena (storm surges, high river flow rates, etc.) and tools for modelling flood threats. Nowadays, the modelling of flood threats has improved substantially due to progress on several fronts: techniques for obtaining detailed bathymetric and topographic measurements (for the site and surrounding area), advanced hydrodynamic modelling techniques, and powerful computational capabilities. The combination of these data and techniques allows more precise assessments of flood threats and design verifications for existing or additional protection measures. For a Gen-II NPP, a *periodic safety review* (PSR) usually offers an appropriate framework for a reassessment of flood risk and flood protection.

Reassessment of flood protection at Belgian NPPs

In Belgium, a reassessment of flood risk and protection was performed for each NPP site during the most recent PSRs. For Doel, which is an estuary site located along the tidal reach of the river Scheldt, the major incentive for this reassessment was the flooding of the Blayais site in France (December 1999), which was provoked by a storm surge and high wind waves in combination with high tide. For Tihange, which is a river site located along the river Meuse, the original flood risk assessment was mainly based on historically reported floods and had to be revisited after some unexpectedly high water levels exceeding the original estimations.

Starting from a survey of potential flood threats induced by external phenomena, potential hydro-meteorological or geological phenomena and upstream dam breaches were identified and a selection of potential hazard scenarios was made for each site to determine the *design basis flood* (DBF) and its effects on the site and the nuclear installations. The DBF to be taken into account is the worst case among these hazards or concomitant occurrences of hazards having an occurrence frequency exceeding 10^{-4}/year (or a return period of 10,000 years).

Doel NPP: Coping with high tide and storm surge

The flood risk in the Scheldt estuary is dominated by storm surges. To calculate high water levels, wave heights and wave overtopping of the dikes at the Doel site as a function of the return period (up to 10,000 years), a calibrated hydrodynamic model of the Scheldt estuary and its tributaries is used, with downstream inflow from the open coastal side and upstream run-off discharges from the river side as boundary conditions. The main statistical variables for the downstream inflow are extreme tide level, wind speed and wind direction. They are stochastically generated by a Monte Carlo calculation code using extreme value distributions. It can be demonstrated that the upstream inflow from the river Scheldt has a minor effect on the water level at the Doel site in comparison with the combined effect of high tide and storm surge.

Tihange NPP: High flow rates, wind waves or upstream dam failures as major hazards

The flood risk at the Tihange site is largely dominated by extreme precipitation in the Meuse river basin. The flood risk has been verified for maximum river flow rates for different return periods derived from statistical peak-over-threshold (POT) analyses of flow rate data. Combinations of flow rates and wind waves or upstream dam

The Tihange NPP (Belgium).

failures were considered for a frequency of concomitant occurrence up to and including 10^{-4}/year. For these scenarios, flood levels and areas were simulated with high precision using a 2D-hydrodynamic model and detailed bathymetric and topographic data from the Meuse valley. On the river, mobile dams constructed every 15 to 20 km each have several passages that are normally shut with steel locks, which are lifted above the water level in the event of high flow rates. Therefore, a flood level increment ("cliff-edge" effect) caused by the mobile dam downstream of the Tihange site is also simulated for return periods exceeding approximately 1,000 years.

The defence-in-depth logic

The results of these simulations show that, in particular for the Tihange site, a reassessment of the flood protection measures was needed following the logic of defence-in-depth, based on:

- *Adequate flood monitoring and warning* systems;
- *Permanent structural protection measures* (e.g. peripheral flood barriers or dikes where site elevation only is insufficient, water-tight protection of important safety-related areas or buildings or equipment that must be protected);
- *Temporary flood protection* for specific areas if warning time can be assured (e.g. mobile flood barriers);
- *Drainage of flood water* off the plant site;
- *Emergency response management*, including organisational measures, operating instructions, and measures ensuring plant accessibility.

Reassessment of flood protection at the Borssele NPP

Located in the Netherlands, at the same Scheldt estuary as Doel, Borssele is much closer to the sea. The external flooding risk is therefore completely dominated by storm surges. Dutch nuclear regulations require that an NPP withstand all external initiating events with a return period exceeding one million years. For external flooding, this requirement is the basis of the so-called *nuclear design level* (*nucleair ontwerp peil*, NOP), i.e. the water level at which a system – among others, the nuclear island and the ultimate heat sink – should still function properly. For bunkered systems, a higher value for the NOP is applied to exclude cliff-edge effects. In determining the NOP, the mean water level, wave height and wave behaviour during storm surges are taken into account. This concept could also be used to simulate external flooding in a PSA by assuming that floods exceeding NOP levels lead directly to core damage. However, this straightforward modelling approach ignores two important aspects: the first is the mitigative effect of the dike ring protecting the plant; the second aspect is that although water levels lower than NOP will not lead directly to core damage, they could do so indirectly as a result of combinations of system losses by flooding and random failures of required safety systems to transfer the plant to a safe, stable state. Consequently, a more sophisticated PSA approach is needed.

Drawing upon experience gained in safety assessment of the dikes

In the development of such PSAs, the experience of the Netherlands' Department of Water Management (Rijkswaterstaat) is useful. It applies a comparable probabilistic method to evaluating the designs of existing dike rings along the main rivers. Obviously, for a PSA, the water levels of interest are those levels that, for instance, cause an initiating event (e.g. failure of main heat sink and secondary cooling or loss of off-site power due to flooding of the electrical switchyard). A convolution of the hazard function (exceedence frequency of the water level outside the dike ring) and the fragility curve of the dike ring (the conditional probability of failure as a function of the water level) are made to determine the exceedence frequency of those levels inside the dike ring. The fragility curve of the dike ring is obtained from a failure model that includes dike sectioning (according to dike strength, orientation, subsoil, etc.) and possible failure mechanisms such as:

- *(Wave) overtopping*: failure occurs due to water running over the dike crest and eroding the inside slope of the dike;
- *Piping*: water seeps through or under the dike as a result of the difference in water level on the inside and outside of the dike;
- *Instability of the inside slope*, caused for instance by saturation of the dike;
- *Damage of the revetment*, followed by erosion of the dike body by wave attack.

View of the Doel NPP in the Scheldt estuary (Belgium).

Besides a deterministic model describing the failure mechanisms (for example for soil liquefaction and piping) and their corresponding limit states, the new approach requires extensive (statistical) data on hydraulic conditions and failure mechanisms. However, due to the very low frequency of the phenomena involved, the availability of these data remains a challenge.

Time: A critical factor

Finally, time is an important aspect to be included in dike failure models, because:

- most failure mechanisms need time to develop;
- time also determines the amount of water that enters the failed dike ring.

For instance, in case of overtopping of the dike, the duration of overtopping can be too short to reach a dangerous water level inside the dike ring. The failure frequency of the dike ring at a given water level is therefore not by definition equal to the initiating event frequency for that given water level.

An approach similar to that of dike designs

The described approach allows a realistic analysis of the external flooding hazard of NPPs. It requires extensive knowledge of dike behaviour and of the relevant local geotechnical and hydraulics conditions. The development closely resembles a comparable approach followed by the Rijkswaterstaat for probabilistic evaluation of dike designs. ●

Tsunamis: A (not so) new threat

Antonio R. Godoy, Former Head of the International Seismic Safety Centre, IAEA

As a major consequence of the magnitude 9.3 earthquake that occurred at the boundary of the Indian and Burmese tectonic plates on 26 December 2004, an ocean-wide tsunami was generated that resulted in devastation amounting to national disasters in numerous countries on the coastline of the Indian Ocean. This was one of the largest tsunamis ever recorded in historical time. Again, on 27 February 2010, when a magnitude 8.8 earthquake occurred off of Maule, Chile, a tsunami was generated that devastated its coastal areas and islands, producing many fatalities and reaching far into the Pacific basin.

A (not so) new threat that draws increasing attention

Generally speaking, tsunamis are not *new* threats to the safety of nuclear installations and, from the perspective of the IAEA, they should have been considered, properly and in a timely fashion, in their siting, design, construction and operation.

The selection and evaluation of the sites and the design of existing plants were mostly performed following safety requirements, methodologies and well-established criteria for preventing those external hazards, both natural and human induced, which may challenge defence-in-depth and affect the safety of those installations. No nuclear accident was caused by a natural event during the approximately 14,000 years of cumulative operation of nuclear reactors worldwide. Safety re-evaluation programmes were implemented in many countries to take due account of new data, methodologies and criteria as part of periodic safety reviews. All these safety re-evaluation processes led in many cases to significant upgrades of the facilities. But let us explain this in more detail.

All oceanic regions and sea basins of the world and even fjords and large lakes can be affected by tsunamis. Tidal waves propagate outward from the generating area in all directions, with the main direction of energy propagation determined by the dimensions and orientation of the generating source. A tsunami could cause inland flooding because its wavelength is so stretched that a huge mass of water follows behind the wave front (see Figure for tsunami parameters).

A tsunami is called a *local tsunami* when it affects only the region near its source. Less frequent but affecting wider regions are *distant tsunamis* that arrive at places remote from their source after travelling across the ocean or sea basins. Examples of destructive, earthquake-induced, distant tsunamis include the 1960 and 2010 Chilean tsunamis and the 2004 Indian Ocean tsunami.

Increased attention has been paid by nuclear power plant vendors, with the need to consider all the natural hazards due to the occurrence of strong earthquakes, floods, hurricanes and volcanic eruptions in the new

Views of the Sanriku area (Japan) before and after the tsunami provoked by the 1933 earthquake.

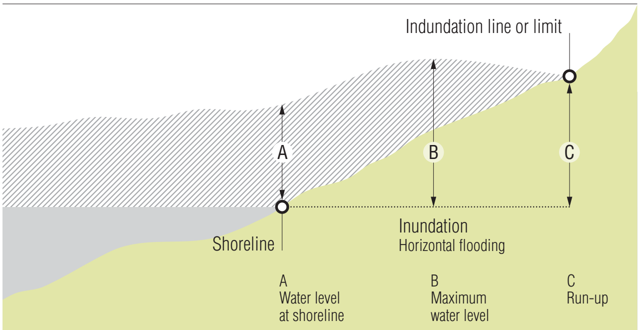


Figure
Parameters derived from tsunami hazard assessment.
When the tsunami waves reach the coastal zone, they produce hazardous effects near and on the shoreline. In this case, for the safety evaluation of a nuclear power plant which may be affected, the main concerns relate to: (1) damage to systems, structures and components (SSCs) important to safety due to flooding induced by the tsunami at the site, (2) temporary lack of cooling water availability because sea water levels may drop due to sea recession, (3) loss of cooling water because the water intake may be plugged by drifting material, and (4) damage from dynamic forces to water intake structures. A tsunami hazard assessment should therefore be performed during the evaluation of the site and duly considered in the design basis of the plant. Basically, it should compare the plant ground level and the potential tsunami heights at the site. To assess the maximum heights that a future tsunami can reach at a given location, documented historical tsunami records are key elements. They are supplemented by computer model simulation of the tsunami's generation and propagation processes, including proper consideration of all uncertainties involved.

designs. Similar attention is received from newcomers in relation to safety issues to be solved, and from the operators and regulatory bodies, due to the potential impact on the safety of operating facilities.

The different steps taken by the IAEA

The safety of nuclear installations with regard to external hazards has received substantial attention at the IAEA through the development of related safety standards. During the past three decades, these standards have matured through a continuous updating process and with the feedback from a large number of safety review and training services provided to Member States. Today, they constitute a well-recognised set of safety requirements and guides. They were revised, taking due account of recent developments and incorporating the lessons learned from these extreme natural events, with significant participation and contribution from Member States.
Regarding past extreme natural events, the IAEA took immediate actions after the 2004 Indian Ocean tsunami through the organisation of international workshops at the Kalpakham NPP site in India and by launching a three-year extra-budgetary project in relation to tsunami hazard assessments and emergency response to nuclear accidents induced by earthquakes and tsunamis. Training courses, dissemination of tsunami hazard assessment and emergency management tools, and experts meetings were part of it.
The International Seismic Safety Centre (ISSC) was established by the IAEA Director General in 2008 as a global focal point to share information and experience, pool expert knowledge and assist nuclear operators and regulators to assure and enhance the safety of nuclear installations in relation to these phenomena; it is operative today as a section of the Nuclear Safety Installations Division.

The importance of public awareness

Finally, it should be mentioned that a critical issue identified from these events is the need to inform the public on the safety level of the nuclear installations as regards these natural events and to provide reliable information without delay. The prompt dissemination to the international nuclear community of all lessons learned from these events together with the revision of the IAEA safety standards can be considered as the most valuable outputs of these efforts. Sharing information on recent technical knowledge and research developments, as well as experience and good practices relating to the occurrence and effects of this type of extreme external event on nuclear power plant sites, are important to maintaining the safe operation of these critical and sensitive facilities in a continuously changing environment. ●

FROM GLOBAL CLIMATE CHANGE TO LOCAL CLIMATE IMPACT

Global warming, a fairly local issue

Jürgen Jensen, Research Institute for Water and Environment, University of Siegen (Germany)

Global climate change is a central issue of political and public interest, but local meteorological conditions may differ significantly from the projected global mean values. Regional or even local climate impact studies must therefore be performed to design appropriate protection measures at individual sites.

Global climate change

Originally used to designate a change in the statistical distribution of weather over periods of time ranging from decades to millions of years, the expression *global climate change* has come to mean, in recent times, changes in modern climate. It is often qualified as *anthropogenic climate change* or *global warming*. The latter pertains to the increase in the average temperature of Earth's near-surface air and oceans since the mid-20th century and to its projected continuation.

According to the 2007 Fourth Assessment Report by the Intergovernmental Panel on Climate Change (IPCC), global surface temperature increased by 0.7 °C (± 0.2 °C) during the 20th century. It can be said that most of the observed temperature increase since the middle of the century has been caused by growing concentrations of greenhouse gases released by human activities. Climate model projections summarised in the latest IPCC report indicate that the global surface temperature is likely to rise a further 1 to 6 °C during the 21st century. The uncertainty in this estimate arises from the use of models with differing sensitivity to greenhouse gas concentrations and the use of differing estimates of future greenhouse gas emissions.

Expected consequences of global warming

An increase in global temperature will cause sea levels to rise and will change the amount and pattern of precipitation. Other likely effects include changes in the frequency and intensity of extreme weather events, although the nature of regional variations is uncertain. It is obvious that a higher sea level influences the heights of storm surges, resulting in a higher risk of flooding for the affected coastal areas. In contrast to many climate model projections, the mean sea level and its variability over the past centuries have not been analysed in detail up to now.

Downscaling global climate change estimates to the regional and local scale

Climate model projections, as in the latest IPCC report, are mainly based on General Circulation Models (GCMs), considered to be the most advanced tools currently available for detecting the impacts of changes in

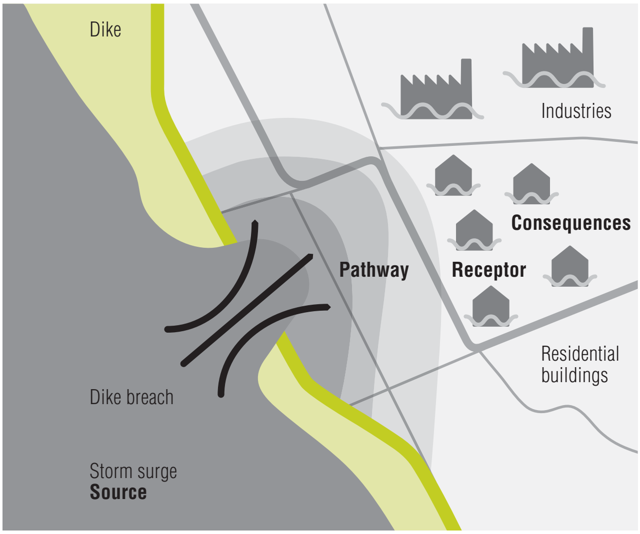


Figure 1
Example of a source-pathway-receptor-consequences model in coastal areas.

the climate system. GCMs depict the natural system by using a three-dimensional grid with a quite coarse horizontal resolution ranging from 200 km to 600 km. As a consequence, many physical processes cannot be modelled properly, meaning that important sub-grid scale features such as clouds and small-scale topography are neglected. GCMs being impractical for regional impact studies, downscaling methods have been developed, which reduce the problem of discordant scales between coupled models and enable the user to obtain regional-scale data from atmospheric variables provided by GCMs.

Consequences for the design of hydraulic structures

Climate change is an important driver for further developments in design methods for hydraulic structures, as these rely on the basic principle that the resistance of a structure is greater than the load. This principle should be valid not only for the present, but for the entire lifetime of the structure as well. Climate changes are expected to lead to changing loads, e.g. increasing discharges and storm surge heights, or more frequent extreme events. Advanced design methods taking these issues into account must therefore be developed. A major field of research currently involves analysing in detail the consequences of failures of hydraulic structures such as dikes and estimating the risk as a product of the probability of failure and the consequences (see Fig. 1). This requires detailed description of loads and resistance and calculation of the flooded area. Whereas the loads on flood protection measures along rivers (inland) are mainly water levels and flood duration, the protection measures along coastlines and in tidal estuaries are also affected by extreme storm surges (peak and intensity) and by wind waves (run-up, overtopping). Since the alteration characteristics of the relevant parameters due to climate change are highly dependent on regional and local conditions, design methods have to be adapted to individual sites. Considering the probable change in loads and resistance, the risk can be estimated both for the present state and for future states, and the hydraulic structures have to be designed accordingly to minimise the risk. ●

NEW DESIGN REQUIREMENTS

New challenges in NPP design due to climate change

Jorma Sandberg, STUK (Finland) | Gabriel Georgescu, IRSN (France)

The debate on climate change has directed attention to how extreme weather conditions may impact the design and safety of nuclear power plants. Work carried out on this issue in France, Finland and Germany, for example, brought to light that the design of new plants against external hazards should be able to accommodate possible future human-induced changes and natural variability. Nonetheless, climate change is not predicted to have severe effects on nuclear power plant safety.

Climate change: Soon an integral part of safety assessment

International agreements to reduce greenhouse gas emissions have enhanced interest in new nuclear power plant projects. At the same time, the debates about the increasing intensities of meteorological phenomena have also drawn attention to the ability of NPPs to withstand extreme conditions, possibly aggravated by climate change, as projections on climate change over the planned life of new NPP units have large uncertainties, especially at the regional level.

Extreme natural phenomena are factored into site assessments based on historical data, but climate change should also be considered, as it could affect, among other things, maximum and minimum air temperature and moisture, precipitation (rain and snow), extreme wind speed and storm frequency, water levels (sea, lake, river, estuaries), and ice (frazil ice, pack ice).

On this subject, the IAEA draft guide entitled *Meteorological and Hydrological Hazards in Site Evaluation for Nuclear Installations* includes a section on climate change. In its work on external event-related PSAs, the NEA/WGRISK issued a recommendation that research on climate change be continued, while in Canada for instance, national regulations require consideration of potential climate change.

If it is required that the core damage frequency (CDF) be less than 10^{-5} per year, the CDF due to any single event should be less than about 10^{-6} per year.

Global warming makes the conditions in the Baltic Sea favourable to eutrophication and to immigrant species such as *Mytilopsis leucophaeta,* which can form dense colonies and cause operational and safety problems in NPP seawater systems.

Finnish NPPs are designed to withstand harsh winter conditions including low temperature, frazil ice formation, pack ice and snowstorm. Due to possible climate change, a wider spectrum of extreme conditions has to be considered and safety margins have to be re-evaluated in the design of new NPPs.

For catastrophic events with a low safety margin, the initiating event frequency should at most be of the same order of magnitude. If the safety margin is higher, the frequency of the design value can be increased correspondingly. As good quality meteorological measurements are typically available only for one hundred years, the uncertainties at these low frequencies are considerable, regardless of possible climate change.

In Finland and Germany: Climate change unlikely to have significant impact on NPP design or siting

In Finland, STUK issued safety assessments for three new NPP projects in 2009 covering two existing and three possible new sites, all located on the Baltic Sea coast. Extreme meteorological and hydrological phenomena were considered as well as climate change, based on research by the Finnish Meteorological Institute. One interesting outcome is the behaviour of seawater levels: an ocean level rise has been estimated in Intergovernmental Panel on Climate Change (IPCC) reports, for example, but the estimates depend on controversial issues such as glacial melting. Since the melting of large ice masses influences the Earth's gravity field, melting of the Greenland glaciers could cause ocean levels to rise mainly in the Southern Hemisphere and Antarctic ice melting in the Northern Hemisphere. Nonetheless, extensive melting is unlikely during this century, though it cannot be excluded.

Baltic Sea water levels are also influenced by long-term wind conditions in the North Sea and by local winds and low-pressure areas. On the Finnish coast, postglacial ground uplifting will probably exceed or at least largely compensate the rise in ocean level. The increase in air temperature is likely to be greater in winter than in summer, and precipitation is expected to rise, especially in winter but also in summer, but the changes in extreme intensities of meteorological phenomena are not predicted to have significant effects on NPP design or siting.

GRS, the German TSO, has studied the effects of climate change on the NPPs operated in Germany. There, the expected climate change includes hotter and dryer summers, more rainfall in winter, stronger gales and more tornadoes. While such changes tend to increase the risk of flooding, they are not expected to pose severe threats to NPPs in the coming decades.

France: Lessons learned from previous events

In France, several off-site external events having the potential to threaten nuclear safety have occurred. The most significant one was the partial flooding that occurred in December 1999 at Le Blayais NPP, in the southwest of the country. This event called into question the design basis used for the protection of nuclear power plants against external flooding and the efficiency of existing measures. In addition to the assessment of the protection measures implemented at

Le Blayais, EDF reassessed the maximum design flood level at all plant sites and has launched a 'review project' with the aim of ensuring the effective protection of is facilities against external flooding. The reassessment of the maximum design flood and the application of the new methodology have brought about many modifications and improvements at the sites. Another significant event was the heat wave in the summer of 2003, which prompted EDF to make several design improvements to its reactors.
For new reactors, the Technical Guidelines document [(1)] specifies that design features must protect against external hazards, consistent with the provisions taken against internal failures and internal hazards. External hazards must not constitute a large part of the risk associated with nuclear power plants of the next generation and, at the same time, a substantial reduction of the overall core-melt frequency must be achieved for those NPPs. Implementation of improvements in the defence-in-depth should lead to a total frequency of core melt of less than 10^{-5} per plant operating year, taking into account uncertainties and all types of failures and hazards. Since external hazards can affect different defence lines of the plants consecutively or simultaneously and are site-dependent, due consideration must be paid to site selection so that excessive requirements are not imposed on the design of the corresponding plants.
For the EPR™, the new generation NPP under construction in France, the initial design makes it possible to adapt the plant during operations if actual climate changes are greater than initial forecasts. This is achieved through additional design margins for climate-related hazards based on an assessment of the feasibility of plant modification and of the acceptability of future operational evolutions. The adaptability of the plant is thus analysed for all climate-related hazards.
The incorporation of climate-related external hazards into the plant PSA, as a supplement to the deterministic framework, would play an important role in meeting the aforementioned targets.

Incorporating climate-related external hazards into the PSA

Climate change is one factor affecting the uncertainty of extreme meteorological and hydrological events. There is presently no evidence that the predicted change would have any serious effects on NPP safety. However, it would be prudent to consider the latest studies on anthropogenic climate change and natural variability in the determination of design values for external events and to include features that allow for future plant evolutions. The incorporation of climate-related external hazards into the PSA may also play an important role in ensuring safety for the next generation of NPPs. ●

(1) Technical guidelines for the design and construction of the next generation of nuclear power plants with pressurised water reactors.

EVOLUTION OF SITING AND RETROFITTING METHODS

Coping with external hazards in the future

Giovanni Bruna, IRSN (France)

As evidenced in the previous articles of this special issue of the EUROSAFE Tribune on external hazards, Mother Nature, man and his activity threaten the safe and secure operation of nuclear power plants in several ways, making both the siting of new nuclear facilities and the retrofitting of existing ones very challenging. Based on the findings of ongoing studies on climate change, earthquakes, sandstorms, etc., and on operating feedback, would environmental data selected forty years ago for the construction of the current generation of nuclear facilities still be considered suitable for building future reactors or nuclear fuel cycle plants? In light of these studies, to what extent can operating facilities be upgraded to continue to operate safely and securely? These are questions for consideration at a time when several countries across the globe are announcing plans to resume – or embark on – new build programmes, and when utilities are seeking to extend the service lives of their existing fleets.

The knowledge gained on external hazards through studies and feedback from nuclear power plant operations allows continuous updating of uncertainty appraisal methods. These, in turn, drive the evolution of the safety requirements issued by regulatory bodies, the design and construction specifications adopted by vendors, as well as the safety assessment procedures used by TSOs.

Such new knowledge impacts the site selection criteria for the construction of new facilities: for instance, the prospect of potential drought in a region where climate change may cause rivers to offer insufficient cooling capacity or even to dry up will disqualify the candidate site, just as would the discovery of a seismic fault in a region considered stable until then. Lesser threats, while not disqualifying the site, could impose even more stringent design requirements.

Depending on the hazards and their intensity and potential contribution to risk, the design of new plants incorporates provisions such as reinforced protection of the facility against the crash of a heavy commercial aircraft and resulting fire propagation, the redesign of air intakes to mitigate the drawbacks of dust and sand build-up and of water inlets to prevent clogging caused by the accretion of debris in the water, the mounting of the reactor building or equipment on silent blocks to accommodate vibrations and oscillations such as those generated by earthquakes, or the step-up of water pump throughput to balance the expected temperature increase of cooling water resulting from climate change.

While the design of new facilities can be fleshed out to anticipate suspected – or established and expected – external hazards, the possibility of economically retrofitting existing plants is far more limited due to the technical

difficulties of the task and the very high costs expected.
For example, huge design modifications, such as the reinforcement of civil works to withstand the crash of wide-body airliners or the mounting of the facility on silent blocks to withstand earthquakes, cannot be regarded as fully realistic options today. If in future such requirements should become mandatory for the safe and secure operation of a plant, the operator might consider closing down the plant for good.

The delicate issue of retrofitting

The knowledge gained from ongoing studies on the different external hazards and plant operating experience does not deeply modify siting and construction rules from a regulatory perspective. However, the lessons learned are progressively being incorporated into the design and siting studies of future facilities and in the retrofitting of existing ones with a view to avoiding malfunctions, preventing the occurrence of severe accidents and, should it be the case, reducing their impact on man and the environment through mitigation. In this respect, whereas all reasonably foreseeable hazards can be considered for a new build, some of them, such as earthquakes, are expected to be very difficult to factor into the retrofitting of operating facilities. In some cases, this limitation can be conducive to early decommissioning of the facility. ●

EPR reactor under construction at Flamanville (France).

VENUES & WEBSITES

Upcoming meetings on nuclear safety assessment

March 13-17, 2011, Wilmington (NC), USA

Topical meetings on probabilistic safety assessment and analysis (PSA) | Organised by the American Nuclear Society (ANS)

Additional information at http://www.psa2011.org or E-mail info@psa2011.org

A few links for reading more about external hazards

- *IAEA activities related to seismic safety of nuclear installations* | The International Seismic Safety Centre | By Antonio R. Godoy, Acting Head, International Seismic Safety Centre (NSNI/IAEA), 12 Aug. 2009
http://www.vtt.fi/proj/smirt20/presentations/pw1b/01_pw1b_ar_godoy.pdf

- *Engineering seismic risk analysis* | By Carl Allin Cornell (1968) | Bulletin of the Seismological Society of America 58(5), pp. 1583-1606.
http://www.ce.memphis.edu/7137/PDFs/Cornell/1583.pdf

- *Issues in probabilistic seismic hazard analysis for nuclear facilities in the US* | By Robin K. McGuire (2009) | Submitted to Nuclear Engineering and Technology, Korea Fugro William Lettis & Assoc.
http://article.nuclear.or.kr/jknsfile/v41/JK0411235.pdf

- *European Utility Requirements for LWR nuclear power plants* | Revision C (2001)
http://www.europeanutilityrequirements.org

- *Eurocode 8: design of structures for earthquake resistance* | CEN–EN1998-1 (2005)
http://www.confinedmasonry.org/wp-content/uploads/2009/09/Eurocode-8-1-Earthquakes-general.pdf

- *BGS–Eurocode 8 seismic hazard zoning maps for the UK* | TR CR/07125 (2007)
http://www.seced.org.uk/news/UK_seismic_hazard_report-issue3.pdf

- *IAEA mission report, preliminary findings and lessons learned from the 16 July 2007 earthquake at Kashiwazaki-Kariwa NPP* | Vol. I & II, Tokyo, August 2007
http://www.iaea.org/NewsCenter/News/2007/kashiwazaki-kariwa_report.html

- *Meteorological and hydrological hazards in site evaluation for nuclear installations* | Draft Safety Guide DS417 | IAEA, Vienna (2009)
http://www-ns.iaea.org/committees/comments/default.asp?fd=942

- *Site evaluation for new nuclear power plants* | RD-346, Canadian Nuclear Safety Commission (2008).
http://www.cnsc-ccsn.gc.ca/eng/lawsregs/regulatorydocuments/published/index.cfm

- *Probabilistic Safety Analysis (PSA) of other external events than earthquake* | Report NEA/CSNI/R(2009)4 | OECD, Paris (2009).
http://www.nea.fr/nsd/docs/2009/csni-r2009-16.pdf

- *Technical Guidelines for the design and construction of the next generation of nuclear power plants with pressurized water reactors* | Adopted during the GPR/German experts plenary meetings held on October 19th and 26th, 2000. http://www.french-nuclear-safety.fr/index.php/content/dowload/15572/100931/technical_guidelines_design_construction.pdf

- *Probabilistic safety analysis of (non-seismic) external hazards* | By J. Sandberg, G. Thuma, G. Georgescu | EUROSAFE Forum 2009, 2-3 November 2009, Brussels.
http://www.eurosafe-forum.org/2009-seminar-1

- *Intergovernmental Panel on Climate Change (IPCC) website*
www.ipcc.ch

- *Finnish Meteorological Institute web pages on climate change*
www.fmi.fi/ilmastonmuutos/

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