Committee on the Safety of Nuclear Installations

Working Group on External Events (WGEV)

Technical Note on Riverine Flooding - Hazard Assessment and Protection of Nuclear Installations

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EXECUTIVE SUMMARY

The NEA's Committee on the Safety of Nuclear Installations (CSNI) has been following up on opportunities to address lessons learned from the accident at the Fukushima Daiichi nuclear power plant in Japan. One of the clear areas for concern was natural external events, which can lead to multiple failures and pose a significant threat to a nuclear installation. At its June 2013 meeting, the CSNI decided to create a Task Group on Natural External Events (TGNEV) to review events that are low-frequency, but high-consequence, and determine if there are activities that would benefit from international cooperative work.

At the end of 2014 the CSNI decided to reorganize the TGNEV in the Working Group on External Events (WGEV) to ensure continuity in addressing issues related to external hazards and to provide for a better coverage of the spectrum of hazards to be considered. One of the priorities identified by WGEV was to share regulatory practices and technical approaches for riverine flood hazard assessment (both deterministic and probabilistic) and flood protection of nuclear power plants (NPPs). To address this, the group identified two tasks. The first task was to develop a comprehensive survey which could be used to gain insights into the current state of knowledge. The second task would then use the outcomes and insights from the survey and conduct a workshop to assist with the identification of knowledge gaps and /or identify collaborative activities for filling gaps.

Accordingly, a survey of practices for riverine flood hazard assessment and flood protection was prepared and circulated to CSNI members in the summer of 2016. The purpose of this document is to provide a summary of the main insights from the survey as an indication of potential areas for further collaboration, and as input for the follow-on workshop planned for spring 2018.

The questionnaire provided beneficial insights into how the contributing countries are assessing and reviewing the adequacy of protection against riverine floods. Based on the evaluation of the answers several areas have been identified where the approaches differ significantly between the responding countries or where the applied methods have not yet reached the same level of maturity. With respect to riverine flood hazard assessment methodologies, data, and protection measures, benefits could be gained by:

1. Gaining an in-depth understanding of best-practice methodologies for application of specific types of models to improve the modelling of various flood characteristics, including the range of associated effects and flood event durations;
2. Gaining an in-depth understanding of probabilistic riverine flood hazard assessment, including the human factors and capabilities, use of paleo-information, flooding fragilities of components, combination of different flooding sources, and extrapolation to rare events;
3. Understanding the limitations of the historical record / data for a particular nuclear power plant site (both in time and number of events), and how methods are used to combine the outcomes and insights from deterministic and probabilistic approaches; and
4. Understanding the benefits and limitations of specific flood protection concepts and means with regard to floods from different sources taking also into account the given site characteristics.

It is recommended that the follow-on workshop be used to explore these four items.

1. INTRODUCTION

Background

The NEA's Committee on the Safety of Nuclear Installations (CSNI) identified opportunities to document lessons learned from the accident at the Fukushima Daiichi nuclear power station in Japan. One opportunity was in the area of natural external events, which can lead to multiple potential threats against the safe operation of a nuclear facility. Already previous to the accident at Fukushima Daiichi nuclear plant, the CSNI work programme considered seismic hazards in its Working Group on Integrity and Aging of Components and Structures (WGIAGE). However, following events at Fukushima Daiichi, CSNI recognized that flooding and other external hazard may also be of interest. Consequently, at its June 2013 meeting, the CSNI decided to create a Task Group on Natural External Events (TGNEV) to review natural hazards that are low-frequency, but high-consequence, and determine if there are activities that would benefit from international cooperative work.

At the end of 2014 the CSNI decided to replace the TGNEV by a Working Group (Working Group on External Events, WGEV) to ensure continuity in addressing issues related to external hazards and to provide for a better coverage of the spectrum of hazards to be considered. The main mission of this Working Group is to improve the understanding and treatment of external hazards that would support the continued safety performance of nuclear installations (NIs), and improve the effectiveness of regulatory practices, in NEA member countries. The focus for the Working Group's activities is external hazards (except seismic hazards) that are of sufficient common interest to allow sharing of approaches for analysis and oversight. For these hazards, experience, lessons-learned and regulatory approaches are shared, and research activities and initiatives are identified to address knowledge gaps that lead to major uncertainties.

In 2014 the TGNEV conducted a survey on current regulatory practices and technical approaches used to confirm adequacy of protection for coastal storm effects (high winds and water levels, and wind waves). Based on the evaluation of the responses to this survey, current challenges and knowledge gaps were identified and discussed during the Workshop on Severe Weather and Storm Surge held in February 2016 at the OECD headquarters. The current survey on riverine flooding is a continuation of the work initiated by the TGNEV expanding the scope from coastal to riverine flood hazards and plant responses.

Purpose of the survey on riverine flooding

The purpose of this survey on riverine flooding is the collection of information from CSNI member states with respect to current regulatory practices and technical approaches used to confirm the adequacy of protection of nuclear installations against riverine floods, and the identification of key issues regarding riverine flood hazard assessment (both deterministic and probabilistic) and flood protection.

The questionnaire that had been distributed to the CSNI member states was intended to lead to an informed understanding of the regulatory requirements as well as the scientific and technical approaches to deal with riverine floods. Besides the pertinent regulatory requirements the questionnaire addressed all relevant aspects of hazard assessment and flood control measures at NPP sites (e.g. availability of data, assessment methods, and protection measures).

Structure of the report

To facilitate comparison between the results of this survey and the survey on coastal storms, the structure of this report largely follows that of the coastal storms survey performed in 2014.

The following five sections summarize the input received with respect to

- Regulatory Approaches - Riverine Flooding Hazard Estimation and Flood Protection,
- Technical Methods - Estimating River Flood Hazards and Their Consequences,
- Design Basis - Riverine Flood Protection Measures,
- Beyond Design Basis – Riverine Flood Protection and Mitigation Methods, and
- Ongoing and Planned Research Activities.

As the aim of this survey is not to evaluate specific approaches used in individual countries, but to draw generic conclusions, the compiled information has largely been anonymised. An exception to this rule is the section on regulatory approaches, because regulatory documents are typically publically available making an anonymization meaningless.

Based on an evaluation of the findings from the survey, the last section identifies the topical areas in which benefits could be gained from additional collaboration by the Working Group on External Events.

2. REGULATORY APPROACHES
- RIVERINE FLOODING HAZARD ESTIMATION AND FLOOD PROTECTION

Regulatory approaches vary from country to country. The following are highlights of the survey results.

River flood scenarios considered in member countries' regulations

The methodologies and tools available to hydrologists and hydraulic engineers for siting new nuclear facilities have evolved dramatically since the first reactors were sited more than half a century ago. For example, in Belgium river run-off was the only scenario considered in the 1970's. With the advent of the modern-day computer, the use of simplistic and bounding approaches has given way to realistic scenarios for evaluating floods from rivers, including also local intense precipitation, on-site drainage, and failures of man-made structures.

While some countries do not have specific regulations on how to evaluate river flooding scenarios, some countries do. For example, France has ASN guide n°13 "Protection of Basic Nuclear Installations Against External Flooding" that defines six river flood related scenarios to consider when assessing the flood hazard for a NPP site:

- large/small watershed run-off,
- failure of a water-retaining structure,
- mechanically induced waves due to malfunctioning of hydraulic structures,
- deterioration or malfunctioning of, e.g., dykes between a NPP site and watercourses and canals and the associated hydraulic structures,
- local wind waves.

Germany also has nuclear safety standard KTA 2207 (Flood Protection for Nuclear Power Plants) that requires considering:

- precipitation,
- snow and glacier melts,
- condition and characteristics of the drainage area,
- water retention on-site and in the drainage area,
- backwater,
- ice jam,
- overflow and failure of dikes/embankments,
- dams,
- wind effects and wave run-up,
- duration and development of the flood event over time.

Swiss Federal Nuclear Inspectorate (ENSI) also requires consideration of heavy rainfall, snow melt and failure of hydrological facilities.

Some regulators do not identify specific river flooding scenarios that should be examined but instead request that applicants and licensees evaluate site-specific flood hazard mechanisms that could challenge their site.

River flood hazard assessment approaches

The river flood hazard assessment approaches adopted by member countries are evolving. For example, Belgium started with a deterministic approach earlier but now adopts a mainly probabilistic approach (except for dam failures).

Some countries rely on deterministic approaches (Korea), whereas others use probabilistic (e.g., Germany), or both deterministic and probabilistic approaches (e.g., Switzerland, France, and the Netherlands). Guidance from the US regulator is currently deterministic, based on the so-called probable maximum flood (PMF) driven by the probable maximum precipitation (PMP; maximum rainfall expected to occur over a watershed area and duration of time), but frequency insights are recommended to assess the potential for flooding from combined mechanisms, such as the river discharge coincident with the peak storm surge at an estuary location.

Acceptance frequency criteria for design-basis flooding event

The acceptance frequency criterion for design-basis flooding events at river sites in countries that use probabilistic (or statistical) approaches is 10^{-4}/year.

Riverine flooding assessment intervals

Most countries require a re-assessment of external hazards (including riverine flooding) every 10 years (Belgium, France, Germany, Korea, the Netherlands, Switzerland), with more frequent re-assessment if needed (France, the Netherlands) or less frequent re-assessment if no change has been observed (Germany).

In the USA, riverine flooding hazards are initially assessed as part of licensing the construction for a new reactor. Although there is no regulatory requirement to reassess the potential for flooding at the site on a fixed schedule, the US regulator or their licensees may choose to re-evaluate the flooding hazard should new information come to light that challenges key assumptions made during the initial hazard assessment.

Guidance documents used to establish the design-basis for river floods and for estimating the corresponding water levels

Whereas most countries with NPPs at river sites have developed their own national standards and guidance for assessing flood hazards, some countries also apply IAEA Safety Guides or standards of neighbouring countries.

The following guidance documents were cited by member countries in the survey:

- IAEA Guide SSG-18 (or NS-G-3.5 that has been superseded by SSG-18): Meteorological and. Hydrological Hazards in Site Evaluation for Nuclear Installations,
- French RFS I.2.e: external flooding risk,
- German KTA 2207: Flood Protection for Nuclear Power Plants (2004),
- German KTA 2501: Structural waterproofing of Nuclear Power Plants (2004),
- France ASN guide n°13: Protection of Basic Nuclear Installations Against External Flooding,
- Korean NSSC Notice No. 2014-26: Technical Standards for Investigation and Evaluation of Hydrological and Oceanographic Characteristics of Nuclear Reactor Facility Sites,
- Korean KINS/RG-N01.04: Investigation and Evaluation of Flooding at the NPP Site and Availability of Cooling Water,
- Dutch NVR NS-G-3.5, derived from IAEA-guide NS-G-3.5,
- Dutch NVR NS-G-1.5; External Events excluding earthquakes in the design of NPPs,
- Belgian FANC: Guideline on the evaluation of external flooding hazard for new class I nuclear installations (2015),
- IAEA TECDOC 1341, Extreme External Events in the NPP design and assessment of NPPs (2003),
- IAEA TECDOC 1487, Advanced NPP design options to cope with external events (2006),
- Swiss Ordinance SR 732.112.2: DETEC Ordinance on Hazard Assumptions and the Assessment of the Protection against Accidents in Nuclear Installations,
- Swiss Guideline ENSI-A05: Probabilistic Safety Analysis (PSA): Quality and Scope,
- USA Regulatory Guide 1.59: Design Basis Floods for Nuclear Power Plants,
- USA Regulatory Guide 1.102, Flood Protection for Nuclear Power Plants,
- US NUREG-0800: Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants: Light Water Reactor Edition, Section 2.4,
- US NUREG/CR-7046: Design-Basis Flood Estimation for Site Characterization at Nuclear Power Plants,
- US JLD-ISG-2013-01: Guidance For Assessment of Flooding Hazards Due to Dam Failure.

Regulatory approaches to reviewing applicant's submitted design bases for riverine flooding

The USA documented its regulatory review process for light water reactors in US NUREG-0800, Standard River Plan. In Section 2.4, several sub-sections are devoted to subjects associated with riverine flooding mechanisms (e.g., Section 2.4.3 discusses Stream and Rivers, Section 2.4.4 discusses dam failures, etc.). Each subsection (i.e., each hazard mechanism) discusses the area of review, the acceptance criteria, the review procedures, and the conclusion staff from the US regulator may reach (i.e., evaluation findings). A list of references for each hazard mechanism is provided at the end of each subsection. Although the latest publically-released version of the SRP for Section 2.4 is from 2007, the SRP is continually being updated by the US regulator and new version is expected to be released before 2020.

Other countries do not seem to have documented review guidance, but all have a similar review process:

- Regulatory review of submitted analyses for determining design bases (data, models and parameters, validation of models, etc.), then discussion with licensees and consultants until consensus is reached (Belgium).

- Review by following the regulations on external hazards (Finland).
- A typical review of design bases addresses the data and methods used by the licensee. In some cases, the licensee is requested to perform supplementary calculations in order to check additional hypothesis. If necessary counter calculations are implemented by the reviewer using mainly statistical tools. (France).
- The review is performed either by checking step-by-step the hazard assessment submitted by the applicant or by doing an independent hazard assessment and comparing the results. This review is performed by an expert organization or a research institute (with experience in flood hazard assessments) on behalf of the regulatory authority. (Germany).
- The validity of the input parameters, appropriateness of the statistical and numerical model, and resulting flooding levels are checked by the document review and the audit. If necessary, the audit and third party review were performed during license process. (Korea).
- An assessment framework is agreed upon between licensee and regulator. When necessary, experts can be consulted. (The Netherlands).
- By checking completeness of data used, adequacy of the method used, and cross-checking against hazard results of upstream and / or downstream facilities / gauges / official hazard mappings. (Switzerland).

Models used to characterize the hazard reviewed, tested and used for estimating riverine flooding

Most regulators do not use or test the models, but perform a review of the studies applying such models. The USA, however, has regulatory requirements to verify that software used to model riverine flood hazards to design safety-related structures meets software quality-assurance standards, such as ASME NQA-1.

Regulatory Review of flood protection and flood mitigation associated with riverine flooding

The following types of reviews of flood protection and flood mitigation associated with riverine flooding are noticed among the submitted surveys:

- Conformity demonstration, made by the licensee, is assessed through inspections and periodic safety reviews. In case of changes in the hazard characterization, a safety review on flood protection is developed, not only to maintain the level of safety, but also to increase it. (France).
- Conduct review of submitted analyses on flood protection, then discuss with licensees and consultants to reach consensus (Belgium).
- Check to see whether they meet regulation on external hazards (Finland).
- The appropriateness of flood protection measures is reviewed by expert organizations on behalf of the regulatory authority as part of the normal supervising procedure. The review includes reviews of the plant documentation, dedicated plant walkdowns, and supervision of periodic inspections (Germany).
- By inspections (Switzerland).
- The USA has a documented regulatory review process (SRP 2.4.10 Flooding Protection Requirements). The specific areas of review include (1) Safety-related Facilities Exposed to Flooding, (2) Type of Flood Protection, (3) Emergency Procedures, (4) Consideration of Other Site-Related Evaluation Criteria, and (5) Additional Information for 10 CFR Part 52.

Consideration of historical data and operating experiences in assessing riverine flooding hazards and flood protection for relicensing or re-assessing operating plants

Both historical data and most recent data would be used in assessing riverine flooding hazards and flood protection for relicensing or re-assessing operating plants in almost all responding countries. In the Netherlands, it is up to the licensee to use the adequate historical data and operating experiences. The Regulatory Body reviews whether the approach chosen by the licensee is appropriate. Every twelve years the calculations are updated by the Dutch Water Authority as part of the general review of primary dyke structures in the country. By this mechanism changes in water level (e.g. due to climatologic changes) are taken into account.

Regulatory approach and guidance used to characterize the severity and frequency for river floods for the siting and licensing of new nuclear power plants

In Belgium, the regulatory body has issued a “Guideline on the evaluation of external flooding hazard for new class I nuclear installations” (applicable to new NPPs and new other nuclear facilities).

In France, site selection is not regulated as such. For licensing of new NPP, the applicant shall justify that the design of the NPP is compliant with the specific hazards of the site and that the impacts of the NPP are acceptable via an Environmental Assessment. Flood hazard shall be defined in compliance to the ASN guide n°13.

In Finland, for external hazards for which measured time series are available, a hazard curve needs to be constructed and justified. From the curve exceedance frequencies can be determined.

In the Netherlands, requirements for new nuclear installations are formulated in the Dutch Safety Requirements (DSR). These requirements act as guidance. Within the requirements a probabilistic and deterministic hazard assessment is required. An exceedance frequency of 10^{-4}/year is used. Further ANVS is working on the implementation of IAEA guidance (e.g. SSG-18) with respect to this subject.

Riverine flooding considered in siting, operation and risk assessment for nuclear facilities other than nuclear power plants

Regulatory approaches for riverine flooding considered in siting, operation and risk assessment for nuclear facilities other than nuclear power plants are essentially the same for most countries, such as Belgium, France, Germany, Korea, and the Netherlands. The same with Swiss nuclear facilities that are categorized as posing more than a minor risk potential - cumulative frequency of all hazardous incidents with resulting dose of more than 1 mSv less than 10^{-6} per year.

In the USA, the requirements vary:

- For fuel cycle facilities (e.g., milling, conversion, enrichment), deterministically-defined and bounding events without a specified recurrence interval, such as the probable maximum flood (PMF) which are used as reactor design bases, may be developed and used for siting of the facility,–but is not required if justification is provided. At a minimum, the 100-year flood should be calculated and used as part of the siting process.

- For Fuel Processing Facilities, the flood hazard estimation process for siting is identical to those for a NPP site.

- For High-Level Waste Disposal Facilities, the siting regulations require consideration of flooding hazard at two recurrence periods: 1) flood events that are expected to occur during the lifetime of the facility's operations, and 2) events that are expected to have at least a one in 10,000 chance of occurring.

- For Low-Level Waste Disposal Facilities, facilities may not be sited within a 100-year floodplain, coastal high-hazard area or wetland, and they must be designed to minimize to the extent practicable the contact of percolating or standing water with wastes after disposal. In choosing a disposal site, site characteristics should be considered in terms of the indefinite future and evaluated for at least a 500–year timeframe.

Examples of river floods that dramatically changed the regulatory approach and guidance

The flooding accident at the Blayais site (1999), as well as operational experience at Belgian sites in the nineties (in particular, high flood levels at riverine sites exceeding the original design basis flood), have been at the origin of the periodical review of the flood protection of all Belgian NPP sites.

3. TECHNICAL METHODS
- ESTIMATING RIVER FLOOD HAZARDS AND THEIR CONSEQUENCES

This section focuses on data and methods used to evaluate riverine hazards, including potential effects associated with flooding and combined events. Specifically, the questions in this section of the questionnaire explored the following:

- Types of flooding scenarios, important parameters, and event combinations (e.g., river flood plus severe precipitation and/or wind waves),
- Climatological and hydrological databases; the length of record and scale for these databases; technical advances made in these databases; and surveys (e.g., bathymetric, topographic mapping, land-use),
- Hydrological and hydraulic models, and how physical processes are considered in these models,
- Consideration of river engineering (dams, embankments) and river regulation (e.g., management of water retaining structures) in the flood hazard assessment,
- Combination of discharges from tributaries at confluences,
- Duration and extent of the flooding event,
- Changes of the hazards over time (climate change-related shifts, changes in land use, river regulation, riverbank erosion and subsidence),
- Approach to assessment of potential consequences of riverine flooding to nuclear facilities (core damage, fuel damage, releases, etc.).

The following summarizes technical methods for hazard assessment specific to riverine sites. Countries that do not have nuclear installation on river sites, and consequently did not develop corresponding technical methods, are not included. The phrase “responding countries” is therefore used below to identify this difference between respondent and non-respondent members of CSNI.

Types of flooding scenarios, important parameters, and event combinations (e.g., river flood plus severe precipitation and/or wind waves)

All of the responding countries indicate that they consider scenarios of flooding due to precipitation and/or snowmelt within the catchment basin of the river. One country mentions separate approaches for addressing two different sizes of catchment basins; the scenarios resulting from the assessments of streams with small and with large catchment basins have to be considered separately in the design / reassessment of a nuclear installation.

All except one of the responding countries indicate that they consider a scenario of flooding due to dam failures. Some of the countries mention scenarios based on failure, faulty operation or malfunction of other structures for water control (weir, levee, dyke, hydraulic installation).

Some countries mention specific recommendations for flood routing regarding failure of embankments, the functioning and behaviour of installed equipment along the river, backwater due to landslide or confluence, and ice effect/jam.

The majority of the responding countries indicate that they also consider a scenario of flooding due to local intense precipitation and the associated need for appropriate drainage.

The majority of the responding countries indicate that they consider combinations of river flooding due to precipitation in the catchment basin of the river with other phenomena. Three countries mention combinations with wind-waves, two countries mention combinations with swell or mechanically induced waves. One country mentions combination with local intense precipitation and one country mentions the combination with a dam failure.

Climatological and hydrological databases; the length of record and scale for these databases; technical advances made in these databases; and surveys (e.g., bathymetric, topographic mapping, land-use)

Most of the responding countries specify that national agencies/organizations (for meteorology, environment, construction, hydrology etc.) provide climatological and hydrological data. In many cases, databases specific to meteorological or hydrological parameters are available; one country mentions more than 10 databases. For all responding countries, the length of the time data was recorded near the site is somewhere between decades to about 150 years. One country indicates that, based on about 100 years of meteorological records, a set of 50,000 years was compiled by statistical means in order to perform stochastic simulation of the weather and hydrological\hydrodynamic modelling. One other country indicates that the national hydrological database based on data measured at gauging stations is supplemented by analysis of historical flood, extending the length of record up to 400 to 600 years.

The majority of the responding countries mention national databases for topography, bathymetry and land use. Among these countries, one also mentions soil characteristic database, another mentions a European database for land use (Corine land cover database). A limited number of countries indicate that local (around NPP sites) surveys are available.

Hydrological and hydraulic models and how physical processes are considered in these models

The majority of the responding countries indicate that hydrological models of the catchment area of the river are used. These models are rain-fall-runoff transformation models that simulate hydrologic processes such as precipitation, snowmelt, evaporation, infiltration, and run-off. Some other countries indicate that hydrological models are not used, because the analysis of flood is based on river discharge data.

All of the responding countries indicate that hydraulic models are used to derive water levels and design basis flood level from the run-off data. One country mentions only 1D models, while the other survey respondents discuss the use and application of multidimensional models.

Physical models are mentioned by one country as being occasionally used to represent complex configuration, e.g. local wind waves in estuarine.

A few countries detail the physical processes that are considered in the numerical models. Notably, the modelling systems mentioned are currently being used in standard engineering practice in river flooding domain. The majority of the responding countries mention the use of Manning's or Strickler's coefficients to characterize the roughness of river beds and floodplains.

Consideration of river engineering (dams, embankments) and river regulation (e.g., management of water retaining structures) in the flood hazard assessment

There is a great heterogeneity in the responses; this is probably related to the variability from one country to another on the river engineering (dams, embankments etc.) and regulation.

Two countries indicate that river engineering is modelled in hydraulic models and mention weirs, culverts and dykes as examples. One of these countries also indicates that pumping stations, hydroelectric plants and other structures that could induce hydraulic waves (due to sudden change in the river discharge) are addressed in a specific flooding scenario. Another country indicates that river engineering and river regulation are only considered if they influence the statistics of water discharge measurement.

Scenarios for dyke breaches or failures are mentioned by two countries. In one case overflow of the dyke is mentioned as a specific failure mode, in the other case about 9 failure mechanisms (e.g. piping, overflow and overtopping, erosion, shearing of the backside slope, structural damage) are listed.

Dam failures are mentioned by three countries. One among these countries indicates scenarios related to displacement of dam segments (for gravity dam), breach of dam (for arch dam, weir), erosion of bedrock or erosion of abutment. One other mentions overflow (adapted to the type of dams) and earthquake. Three other countries indicate that a dam failure is postulated.

The majority of the responding countries indicate that consequential dam failures due to domino effects are considered. One country mentions a flooding scenario considering the complete obstruction of the downstream dam combined with the rupture of the upstream dam.

Combination of discharges from tributaries at confluences, duration and extent of the flooding event

Two countries indicate that discharges from tributaries are inherently included in the measured discharges downstream of the confluence. Two countries indicate that hydraulic models combine tributary discharges. One country indicates that hydrographs for each tributary are merged for estimating the flood level. One country presents an approach where a confluence has to be taken into account to evaluate the flood plain in the vicinity of the site: the flow rates are characterized for each of the three branches (two upstream and one downstream); for the downstream branch, the downstream flow rate Q is the reference flow rate (10-4/y). The flow rate adopted for the upstream branches is the distribution of the worst-case flow rates, without exceeding the reference flow rate in each branch, and ensuring that the sum of the two flow rates equals the downstream flow rate Q.

Duration of the flooding event is, for the majority of the responding countries, determined based on the flood hydrograph which is derived for measured or historical floods. These durations are then site specific. Some countries indicate that flood duration is generally not considered or credited. Some countries mention extent of the flooding event, and indicate that it is an outcome of the site specific hydraulic model or that it is considered for demonstration that the NPP can cope with it.

Change of the hazards over time (climate change-related shifts, changes in land use, river regulation, riverbank erosion and subsidence)

All except one of the responding countries indicate that climate change is not currently considered in design basis riverine flood hazard assessments. Some countries justify this position by the lack of significant trends related to climate change in river discharge records. Another country mentions that climate model projections do not provide actionable information about the possible changes in the very rare events that form the design basis. One country indicates that climate change is addressed in development of hazard curve (with no more details).

The majority of the responding countries indicate that changes of the hazard over time are accounted for by the periodic safety review process because the basis for the review is updated measured discharges and figures (land use, river regulation, riverbank erosion and subsidence). One country mentions that these changes are considered to the extent that they are known, or can be reasonably anticipated. Another country indicates that these changes are not considered in a predictive way.

Approach to assess potential consequences of riverine flooding to nuclear facilities (e.g., core damage, fuel damage, releases)

The majority of the responding countries indicate that such consequences are avoided for the design basis flood scenarios. One of these countries specifies that consideration of beyond design flood scenarios led to additional protections to prevent core and spent fuel damages and releases. Several countries indicate that flooding (design basis and beyond-design-basis) is considered in a probabilistic risk / safety assessment (PRA / PSA) framework. One country indicates that PRA/PSA developments in the domain are ongoing.

4. DESIGN BASIS
- RIVERINE FLOOD PROTECTION MEASURES

This section is focused on summarizing how protective measures are used to minimize potential riverine flood and the effects these events may have on plant safety. Specifically, the questionnaire explores the following:

- Description of riverine flood protection measures (temporary and permanent barriers) and their limitations,
- Description of active means of protection (e.g. pumps) used to mitigate flooding events, their reliability, implementation of operational limitations as opposed to passive means of protection
- Human performance, response time, and environmental conditions associated with the installation of temporary barriers and the lead time needed to implement,
- Insights into how reliability is evaluated for protection structures and procedures,
- Insights into how the duration of the event is considered in the reliability evaluations for protection structures and procedures,
- Insights into how hydrologic and debris loadings are considered in the protection evaluations,
- Quality assurance and quality control guidance for flood protection measures,
- Insights into how hydrological and meteorological warning systems are used to inform the decision to implement flood protection measures,
- Whether the regulatory body has established requirements for demonstrating the timely implementation of flood protection measures.

Description of riverine flood protection measures (temporary and permanent barriers) and their limitations

Most countries rely on permanent flood protections external to the NPP sites (such as levees, dykes, dams, drainage systems, external pump stations) and internal to the NPP site (waterproofing of buildings, watertight doors, watertight design of penetration, pumps, thresholds at building access points, etc.).

Temporary flood protection features such as stop-logs, sand bags and flood barriers are usually available but sometimes not credited in the flooding analyses. There are in general operational limitations to the use of temporary barriers. Mostly cited in the questionnaire responses is the available lead time, i.e. the time required to mobilize personnel and materials. Other limitations of temporary flood protection measures include the limitation in size of the temporary barriers and therefore, the limitation in the ability of the barrier to withstand large hydrostatic and hydrodynamic forces.

In a number of countries, the dry site concept is applied for the design basis flood. The dry site concept means that SSCs important to safety are built above the level of the design basis flood, so that ingress of water into rooms containing safety-related and important-to-safety components is avoided. However, this approach is not possible for all sites. In addition, the term can be misleading since local-intense precipitation impacts all nuclear power sites and must be assessed.

In one country, the NPP site can be isolated by a seismically qualified peripheral flood protection system (consisting of peripheral wall, a water intake isolation system at the entrance of the water channel, and a dedicated discharge system for each unit) insuring protection of the NPP site against the maximum water level. In normal situation the flood protection system is inactive. It will be activated in case of flood.

Description of active means of protection (e.g. pumps) used to mitigate flooding events, their reliability, implementation of operational limitations as opposed to passive means of protection

Active means for protecting or mitigating flooding events are not in place on every site. One country notes that there is no specific requirement for active temporary flood protection measures in its regulation.

Another country mentions that the definition and design of measures requiring human intervention or energy inputs take into account the possibilities of anticipating the flood events and their kinetics.

Another country indicates that active protection equipment such as pumps tend to be commercial grade equipment for which there is little rigorous reliability estimates and that this situation can be addressed to some degree by redundancy.

Human performance, response time, and environmental conditions associated with the installation of temporary barriers and the lead time needed to implement

For the implementation of temporary barriers, important factors for success of the human action include the availability of sufficient lead time (cited by three countries). In one country the availability of sufficient lead time has to be demonstrated during the licensing process. If administrative measures and related operator actions are part of precautionary measures, regulatory requirements ask for a demonstration of their effectiveness and reliability by methods such as failure mode and effect analysis or hazard analysis. In these assessments the following conditions have to be considered: availability of distinct procedures and instructions, ergonomic conditions, and environmental/boundary conditions under which the persons in charge carry out / conduct precautionary measures. Potential errors and their consequences have to be considered in the training of the personnel. Another important human performance condition for success cited by one country is accessibility.

In another country, it is assumed that operators should be able to perform the necessary actions, as they will have about 12 hours to shutdown all units and realize complete isolation of the site while maintaining a minimal flow rate to ensure the ultimate heat sink for each unit.

Another country indicates that human performance is enhanced by training, in situ exercises, formalized procedures etc.

Insights into how reliability is evaluated for protection structures and procedures

There are different approaches with respect to ensuring and evaluating the reliability of flood protection measures:

- One country indicates that the reliability of protection structures is evaluated by taking as much margin as reasonably achievable on loads corresponding to the design basis situation. The licensee verifies the effectiveness of procedures.
- Another country states that flood protection measures, which belong to the so called “precautionary measures”, the quality assurance (e.g. for penetrations and similar flood protection measures), follow procedures and standards equal/similar to those for safety systems.
- In another country, for deterministic analyses, protection barriers are considered passive devices of good quality and therefore assumed completely reliable. For PSA, human error probability is determined based on available procedures. No reliability is evaluated for protection structures, because they are either very robust (concrete walls) or only challenged in case of events with very low frequency or only protect equipment with low PSA importance (and failure probability is deemed lower than corresponding operator action to install the protective wall).
- One country mentions that reliability of protection structures is typically evaluated by walkdowns (visual inspections) and engineering assessments. The reliability of procedures is addressed by reasonable simulation. Reasonable simulation is a walk-through of a procedure or activity to verify the procedure or activity can be executed as specified/written.

Insights into how the duration of the event is considered in the reliability evaluations for protection structures and procedures

For the evaluation of the reliability of protection structures and procedures, a flood event duration is explicitly considered in some of the participating countries. The duration of the flood event may be a function of the location specifics and of the site vulnerability. Some countries indicate that the duration of the flood is taken into account for the evaluation of protection structures and procedures but do not indicate the assumed duration. Furthermore, it is not always clear in the answers, whether the explanations regarding the duration of the flood events refer to protection structures or the procedures or both.

Some of the received answers are summarized below:

- One country mentions that the duration of the flood events is not explicitly considered in the reliability evaluation.
- Another country states that as the installation of protection walls has to be undertaken before the river level is too high, only time until critical water level is reached is important. Flood protection devices are passive and therefore independent of the duration of the event.
- In one country, in the design of the flood protection system a riverine flood duration of one week is considered. For the supplies (water, fuel, etc.) needed for the ultimate system a minimum duration of one week is also considered.
- Another country mentions that the duration of the flood event considered for the design is derived from hydrologic studies. Site protection (material and organizational) is defined considering this duration. In case of riverine site LUHS (Loss of Ultimate Heat Sink) vulnerability, the duration is 2.5 day (conventional delay).
- Another country indicates that the duration from the flood is considered in the reliability evaluations for protection structures and the technical specification and the emergency operation

procedure for shutdown of NPP shall be prepared for each flood condition that affect the safety related structures, systems and components.

Insights into how hydrologic and debris loadings are considered in the protection evaluations

This issue is treated differently in the participating countries:

- One country indicates that the hydrostatic and hydrodynamic effects, including debris loads, have been considered in the design of the flood protection system. The protection system (concrete wall and water intake structures) can resist the impact of small debris (e.g. trees). To protect the protection system from bigger objects (e.g. drifting boats), an additional dike has been built upstream of the site.
- In another country, hydrologic loads are computed by considering static load due to the water height along the protection (as a consequence of the reference flood scenarios RFSs). The wave's effects are accounted for in site protection (e.g. dyke). Debris loadings are mainly considered in clogging risk assessment of the heat sink.
- Another country mentions that hydrostatic, hydrodynamic, and debris loadings are considered in the protection evaluations in the regulatory guide to flood protection of nuclear power plants.
- In one country, hydraulic loadings are considered quantitatively (calculated), debris loading qualitatively.
- Another country states that hydrologic and debris loading is not a major issue, since the protection of the plants relies mainly on the elevation of the plant and water tightening of buildings.
- Another country indicates that hydrologic and debris loadings should be considered in the design of flood protection barriers.

Quality assurance and quality control guidance for flood protection measures

Most countries do not have specific quality assurance and quality control guidance for flood protection measures. General quality control procedures, which are part of the regulatory framework for quality assurance, apply also to flood protection measures.

Insights into how hydrological and meteorological warning systems are used to inform the decision to implement flood protection measures

In most countries forecasting services (meteorological, hydrological) provide information regarding flow rates directly to the nuclear power plants. Flood warning systems are in place in some countries which will provide NPP staff with the relevant information. Triggering of flood protection measures differs usually from site to site (e.g., river level exceeding a specified value, warning by operator of upstream hydro installation).

One country indicates that flow rate estimations are provided on a daily basis using meteorological data and hydrologic models. During flood events data on an hourly basis are provided.

Another country mentions that the sites of its nuclear power plants are protected against the design basis flood by permanent protection measures and that therefore no information from hydrological and meteorological warning systems are needed for the implementation of these protection measures. Nevertheless, the sites have established an information exchange with flood warning systems.

Whether the regulatory body has established requirements for demonstrating the timely implementation of flood protection measures

Most countries do not have in their regulation formal requirements for demonstrating timely implementation of flood protection measures.

One country mentions that general requirements for operator actions apply (operator actions have to be prepared, and time window has to be large enough for diagnosis and completion).

In another country, temporary flood protection measures are only acceptable if sufficient lead time is available. The demonstration of the availability of sufficient lead time is reviewed by an expert organization on behalf of the regulatory authority. No specific guidance is provided for this purpose.

In one country information requests to all NPP licensees, which required the performance of walkdowns of their credited flood protection features and procedures were issued.

5. BEYOND DESIGN BASIS - RIVERINE FLOOD PROTECTION AND MITIGATION METHODS

This section is focused on understanding how approaches for addressing beyond-design-basis events are used to demonstrate how a nuclear power plant can ensure that it is adequately prepared to avoid or cope with a severe accident, resulting from a riverine flood that exceeds the design and licensing basis limits. The questionnaire explores the following areas / topics:

- Approach for protection and mitigation methods of beyond design basis riverine floods,
- Insights into how reliability and risk assessments (PSA/PRA) are applied to beyond design basis floods, including protection measures and barriers, and SSCs,
- Regulations and guidance on flood mitigation strategies and procedures.

Approach for protection and mitigation methods of beyond design basis riverine floods

Some countries do not have any regulatory requirements with respect to the protection against beyond design basis riverine floods. In a number of countries beyond design basis floods are defined by adding a margin to the design basis riverine flood level. One of these countries defines the design basis riverine flood level as an annual probability of exceedance of 10^{-4}, the beyond design basis riverine flood level as an annual probability of exceedance of 10^{-5} and considers floods due to precipitation or due to dam failure. In another country, beyond design basis flood is being raised above the design basis by defining at what water levels SSCs are supposed to fail. Yet another country mentions that beyond design issues are assessed via margin analysis for safe shutdown paths (with respect to flood height) and via PSA.

In another country beyond design basis riverine floods are considered in the context of a Mitigation Strategies Order requiring all NPPs in the country to implement strategies that will allow them to cope without their permanent electrical power sources for an indefinite amount of time. The strategies focus on keeping the reactor core cool, preserving the containment's barrier that prevents or controls radiation releases, and cooling the spent fuel pool. The mitigation strategies are expected to use a combination of currently installed equipment (e.g., steam-powered pumps), additional portable equipment that is stored on-site, and equipment that can be flown in or trucked in from support centers.

Insights into how reliability and risk assessments (PSA/PRA) are applied to beyond design basis floods, including protection measures and barriers, and SSCs

For beyond design basis floods most countries rely mainly on a deterministic approach. In a few countries the external flood hazard is modelled in the PSA/PRA. One country indicates that beyond design basis floods are modelled in the PSA and evaluated with regard to regulatory requirements (safety level of the plant, balance of risk contributions of initiating event categories, sequences, components, and operator actions). In another country, the use of the PSA/PRA approach is envisaged in order to implement the revised WENRA Reference Levels (2014) into the regulations. Another country indicates that the use of formal PSA/PRA methods to beyond design basis floods is currently limited and that more qualitative risk-informed approaches are applied to address adequacy of protection measures and mitigation strategies.

Regulations and guidance on flood mitigation strategies and procedures

Several countries indicate that they do not have any specific regulation on flood effect mitigation strategies. One country plans to introduce flood effect mitigation strategies and procedures including the riverine flood hazard into its regulation. Another country plans to transpose the revised WENRA Reference Levels (2014) and the WENRA Guidance on External Flooding once it is published into its regulation.

Another country mentions that after Fukushima and in the course of the European stress test, the resistance of plants against extreme natural hazards, long lasting losses of electrical supplies and heat sink was reviewed. This holds also for all other countries that have participated in the European Stress Test. With the objective of limiting the releases in case of severe and rare external hazards it was decided to implement specific design provisions qualified to ensure the fundamental safety functions in case of beyond design external hazards (including external flooding) and a Nuclear Rapid Response Force to provide off-site support after 24 hours such as human means, and equipment.

In another country, the regulatory agency issued an order to all operating nuclear reactors to develop, implement, and maintain guidance and strategies to maintain or restore core cooling, containment, and spent fuel pool cooling capabilities following a beyond-design-basis external event (also known as the Mitigation Strategies Order). The three-phase approach described in the order is a conceptual framework built upon the need for a licensee to address challenges to the safety functions when they occur using installed structures, systems, and components for a specified coping period until portable mitigating equipment can be used to address those challenges. The finite level of resources on site typically makes the arrangement of off-site resources necessary to address potential widespread catastrophes, where restoration of off-site power is precluded by damage associated with the same event. Licensee’s emergency operating procedures provide the command and control structure in response to this hypothesized beyond-design-basis external events.

6. ONGOING AND PLANNED RESEARCH ACTIVITIES

This section is focused on research activities regarding river floods. The questionnaire explores the following:

- Research activities on riverine flood hazard assessments and protection
- Research on climate change

Research activities on riverine flood hazard assessments and protection

In some countries there are ongoing research activities with respect to riverine flooding hazards. But the nuclear community is not necessarily involved in these activities. In particular, in those countries, where there are no nuclear power plants at inland river sites, the nuclear regulatory authorities typically do not pursue specific research programs.

This survey does not identify a common focus of individual research projects: the type and subject of flooding research seems to vary according to the regional characteristics and the specific regulatory needs. Whereas, e.g., some countries look into the characteristics of a variety of flood hazards, others investigate the reliability of protection measures. Nevertheless, two topics seem to be of particular general interest: the improvement of hazard assessment methods (by combining paleo / historical data, statistical methods and mathematical models) and the development of probabilistic approaches (for hazard assessment and flood protection).

In one country there is a research project with the aim to close knowledge gaps and harmonize the flood hazard assessment by combining historical and climatological analyses with statistical approaches and mathematical models. As part of this project in particular the phenomena high precipitation, erosion, channel relocation, sediment deposition, landslides, debris jams and dam failures will be studied taking into account uncertainties and interactions. Similar issues (paleoflood hydrology, climate impacts on future flooding risks, stochastic flood modelling, numerical simulation methods for flooding processes, dam failures) are also addressed by research projects in another country.

Two countries highlighted research on probabilistic issues, one focusing on the flood hazard (probabilistic flood hazard characterization) and the other focusing on flood protection (risk-informed flood protection strategies and the reliability of flood protection and mitigation features and procedures). The development of flood forecasting tools was also mentioned in the survey responses.

Two countries which have no nuclear power plants at inland river sites are performing research on issues that might be of interest to other countries. One of these research projects addresses beyond design basis external events, including flooding from nearby rivers or reservoirs, and the other research project is focusing on piping-failures of dykes due to droughts.

Research on climate change

Although almost all nuclear regulatory authorities neither pursue nor fund climate change research projects themselves, they track and monitor national and international research activities associated with climate change to incorporate the results into their hazard assessments. In this context three countries emphasise the fact that the local / regional scale is most important as the effects on this scale may differ significantly from global trends. Nevertheless, two countries do also consider global climate change when updating flood hazard assessments or calculating exceedance criteria for flood protection measures.

Only one country mentions a specific nuclear research project that addresses the impact of climate change on the occurrence of weather related extreme events.

7. IDENTIFICATION OF POTENTIAL AREAS FOR FUTURE COLLABORATION

The questionnaire provided beneficial insights into how the contributing countries are assessing and reviewing the adequacy of protection against riverine floods. Based on the evaluation of the answers several areas have been identified where the approaches differ significantly between the responding countries or where the applied methods have not yet reached the same level of maturity. These areas could benefit from further exploration either in the framework of a workshop or in future dedicated activities of the WGEV.

REGULATORY APPROACHES

Spectrum of flood scenarios to be considered at river sites

The spectrum of considered flood scenarios (e.g. river discharge from large watershed to small catchment areas, local precipitation and associated site drainage, dam breach scenarios and flood-wave routing) varies considerably between the responding countries. A potential collaborative activity could be to construct a generic list of flooding sources and associated flooding mechanisms that is as complete as possible. This generic list could then be used by designers, regulators, and licensees to prepare a site specific list by a systematic screening approach that identifies the flooding sources and mechanisms relevant to the site under consideration also taking into account associated phenomena that may be reasonably combined (e.g., flooding in estuary sites, where storm surge and riverine flooding may impact the site).

Approaches of regulatory authorities for reviewing assessments submitted by licensees

To review the hazard assessments performed by licensees requires specific scientific and technical knowledge. Future work could be done to identify commendable approaches which ensure that assessments submitted by licensees can be thoroughly reviewed before the site hazard assessment is approved by the regulatory body.

TECHNICAL METHODS

Reasons for and benefits of using specific types of hydrologic and hydraulic models

Based on the results of hydrologic and hydraulic assessments, the resulting water levels and velocity distributions will vary across the site and over time. A common understanding of best-practice methodologies for application of specific types of models (multidimensional in space and dynamic in time) and best-practice presentation/standardization of model results (dynamic maps of site inundation, velocity contour maps and limitation for human actions, etc.) would be desirable.

Flood characteristics (including hydrographs)

The robustness of the site's flood protection will likely depend on characteristics of the flood wave, including debris load, sedimentation, erosion, water velocity and the availability of warning time, the duration of site inundation, and the quantity of time for the flood wave to recede from the site and surrounding areas. These characteristics vary significantly based on the flood scenario(s) under consideration. For example, a dam failure scenario will cause a different hydrograph, sediment load, and warning time than a precipitation-driven event in a local catchment basin. Collaborative efforts could be taken to improve the identification and modelling of flood characteristics (including hydrographs) that could challenge the site, including the range of associated effects and flood event durations, resulting from various flood-causing phenomena that may challenge the site.

Approaches to account for climate change effects

Consideration of climate change effects in flood hazard assessments is a common requirement in most nuclear regulations. But up to now, no established approaches are available to comply with this requirement. Although the problem can partially be mitigated by means of bounding assumptions and/or adequate re-assessments, enhanced approaches to account for climate change should be explored.

Extension of the available database

Measurements of meteorological and hydrological parameters are available for the last 50 to 150 years. This limited amount of measurement data leads to limitations in the extrapolation to rare events. Therefore, approaches should be explored that are suitable to increase the meteorological and hydrological database. Potential additional sources of information are historical reports, paleo-data, and simulations, but their integration in existing assessment approaches might be challenging.

DESIGN BASIS

Revisiting the dry site concept

The dry site concept provides a robust first line of defence against off-site flooding. But depending on the flood scenario (e.g. local intense precipitation) it might not be sufficient, or even relevant to protect safety related structures, systems and components from being flooded. Therefore, the benefits and drawbacks of the dry site concept should be further explored.

Temporary flood protection measures and flood mitigation

There are several issues related to temporary flood protection measures. (i) Between member countries the definitions of temporary flood protection measures vary. (ii) As IAEA and WENRA clearly prioritize permanent flood protection measures, it should be examined under which conditions temporary flood protection measures might be acceptable to protect important-to-safety and safety-related structures. (iii) In this context, a clear distinction should be made between flood protection measures that play a role in safety demonstrations and flood protection measures installed for operational availability. (iv) The implementation of temporary flood protection measures relies on knowledge of warning time prior to inundation, operator actions, and the availability of necessary equipment. Therefore, the prerequisites for and boundary conditions of the implementation of specific temporary flood protection measures should be further investigated.

Active flood protection measures

The issues with respect to active flood protection measures are similar to those addressed in the context of temporary flood protection measures. In particular the different definitions and prerequisites for active flood protection measures should be discussed.

BEYOND DESIGN BASIS

Definition of beyond design basis floods

Frequently, any flood elevation exceeding the design basis flood elevation is defined as a "beyond" design basis flood, regardless of the other flood characteristics. This definition is solely based on an elevation-to-elevation comparison without taking into account warning time, associated effects such as debris or sedimentation loads, or site access. Nevertheless, for safety assessments and in particular for designing additional protection measures, it is sometimes necessary to define hydrodynamic loads on structures, warning time and other flood event duration parameters, and site access restraints or limitations. How should these associated effects and flood event duration parameters be compared to the design basis, and what is an expedient and systematic way to discuss these non-elevation-related parameters?

Approaches to deal with beyond design basis floods

Besides the need for a definition of beyond design basis floods that looks beyond solely the peak water level, the question that should be discussed is how beyond design basis floods could be dealt with: What level of detail and conservatism is appropriate in the assessment? How should additional protection measures be classified, e.g. as safety systems or on a lower classification level? What distinguishes protection against beyond design basis floods from the protection against design basis floods, e.g., in terms of requirements with respect to redundancy, diversity, independence, qualification, and periodic inspections?

RESEARCH ACTIVITIES

Methods for probabilistic riverine flood hazard assessment and for flooding PSA/PRA

For seismic hazards, well established methodologies are available to conduct probabilistic hazard assessments (PSHAs) and probabilistic safety/risk assessments (PSAs/PRAs). The available approaches for flooding have not yet reached the same level of maturity. Therefore, in a couple of countries research is ongoing with respect to probabilistic assessments. The scope of the research being conducted includes, amongst others, human factors and capabilities, use of paleo-information, flooding fragilities of components, combination of different flooding sources, and extrapolation to rare events. This research would certainly benefit from international collaboration or coordination.

PLANNED ACTIVITIES

Some of the identified issues will be discussed in a WGEV workshop on Riverine Flooding being held in March 2018. This workshop gives the opportunity to discuss the issues identified in this

Technical Note on a broader basis including experts from the non-nuclear field. In addition, issues related to flooding protection measures will be addressed in a future activity of the WGEV.