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Analysis of Events Related to Flooding at NPPs

A Summary Report from the European Clearinghouse

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Abstract

This summary report presents the selected results of a statistical and engineering analysis of flooding and flooding protection related events registered in the following four databases: IRSN (*Institut de Radioprotection et de Sûreté Nucléaire*), GRS (*Gesellschaft für Anlagen- und Reaktorsicherheit mbH*), U.S. NRC (Nuclear Regulatory Commission) Licensee Event Reports (LERs), and the IAEA/NEA International Reporting System (IRS) during the last 20 years. In total 263 events reports are analysed including potential flooding.

The events were analysed and classified into thirteen categories. The frequencies of all categories and families were presented for each database separately and for all events combined. This allowed comparison of events characteristics among all databases and cumulative results. A trend analysis was also performed. Finally, selected events were used to derive findings (lessons learned).

No trend was identified over the whole analysed period. However, it is noticeable that the number of events is decreasing for all databases in recent couple years.

Most of the events occurred during power operation, for all except for the one database. In the majority of events a real flood occurred, except for one database where potential flood events are dominant.

Valves and passive components are the dominant direct causes in all databases, while seals and drainage are also important for the two databases.

Training, qualification and procedures, with design configuration and analysis, are the most important root causes and causal factors for all databases, while maintenance activity and the equipment performance are also important for one database.

Systems most often affected by flood are (reactor) auxiliary systems for all databases and additionally the waste management systems for one database. The majority of events do not have safety relevance except for one database, where low safety relevant events are dominant.

The main purpose of corrective actions is: prevention, early identification and reduction of flood; fulfilment of the probable maximum flood requirements; reducing flood risk from non-safety systems and improving maintenance, review and inspection.

Flooding and flooding protection related selected events were analysed in detail and the main conclusions are presented as list of more than 90 specific and 16 generic lessons learned. Findings are grouped related to the systems that has main role during the flooding event (i.e., non-safety systems interaction, buildings infrastructure and major cooling systems) and related to the type of activities that are (root) cause for the flooding event (i.e., maintenance, inspection, operating experience, analysis and configuration management). Generic findings are also addressing lessons learned related to mitigation, communication, modifications, requirements and configuration management.

The findings from this summary report could be used as recommendations and are expected to help the licensees and regulatory authorities to prevent flooding events from occurring, to protect safety systems from flood and to improve flooding protection and mitigation.

Foreword

The European Network on Operating Experience Feedback (OEF) for Nuclear Power Plants, hereafter referred to as European Clearinghouse on OEF, was established in 2008 by a group of European Nuclear Safety Regulators and institutions for promoting collaboration on OEF, dissemination of the lessons learned from NPP operating experience and understanding the role of operating experience feedback systems in safe and economic operation of existing, as well as new build NPPs and promotion of advanced event assessment approaches and methods.

Currently eighteen European nuclear safety regulatory authorities (Finland, Hungary, The Netherlands, Lithuania, Romania, Slovenia, Switzerland, Belgium, Bulgaria, Czech Republic, France, Germany, Slovak Republic, Sweden, Spain, UK, Ukraine and Poland) and three European Technical Support Organizations (TSOs, from Belgium, France and Germany) are represented.

The main objectives of the European Clearinghouse on OEF are to:

- Contribute to the improvement of the OEF in European NPPs through strengthening and sharing the competences in OEF, as well as improving communication and co-operation inside the CH network and with the international OEF community. Specifically cooperation between licensees, regulatory authorities and TSOs in order to collect, communicate and evaluate information on reactor operating events and systematically and consistently apply the lessons learned in all the members' countries;
- Establish European best practice for assessing NPP operating events, through the use of state-of-the art methods, computer aided assessment tools and information gathered from various national and international sources, e.g. EU national regulatory authorities’ event reporting systems and the International Reporting System for Operating Experience jointly operated by the IAEA and OECD-NEA;
- Provide staff to coordinate the OEF activities of the European Clearinghouse and maintain effective communication between experts from European regulatory authorities and their TSOs involved in OEF analyses; and
- Support the long-term EU policy needs on OEF by harnessing JRC and European TSO research competencies on the methods and techniques of nuclear events evaluation.

The office of the European Clearinghouse is operated by the Joint Research Centre of the European Commission. The European Clearinghouse regularly carries out in-depth analyses of events related to a particular topic (the so-called "topical studies") in order to identify main recurring causes, contributing factors and to disseminate the lessons learned aiming at reducing the recurrence of similar events in the future.

1. Introduction

The European Network on Operating Experience Feedback (OEF) for Nuclear Power Plants was established by European Nuclear Safety Regulators to promote the regional sharing of operating experience, the dissemination of lessons learned from operation, the understanding of the role of OEF systems in the safe and reliable operation of existing and new build NPPs, [1]. One of the technical tasks of the European Clearinghouse is to perform a depth analysis of families of events ("topical studies") in order to identify the main recurring causes, contributing factors and lessons learned to reduce the recurrence of similar events in the future.

This report is a summary one of such topical studies, concerning events caused by flooding issued by the European Clearinghouse in May 2018.

Appropriate flooding protection is built on the right implementation of design requirements, maintenance, inspection and periodic review. Nevertheless, operating experience (OE) is continuously proving how numerous water sources and systems interactions make flooding protection challenging. Selecting and analysing available flooding related operating experience in order to synthesize insights is the main objective of this study.

OE is indispensable in identifying the problems which went unnoticed during design, construction, maintenance, inspection or review. OE is useful in-house, for the industry and for the regulators. These events can also serve as motivation for additional checking and inspections. The Fukushima accident[1] triggered flooding-related reviews that make the operating experience of flooding events especially relevant.

The scope of this study is to carry out an engineering and statistical analysis of the relevant flooding events including degradation of flooding protection. Both external and internal flooding are considered in relation to structural protection (e.g., flooding barriers, drains, etc.), organizational measures (e.g., flooding protection procedures), and site accessibility assurance (e.g., during external flood). The study is covering all currently operating nuclear power plants. All modes of operation are considered. The related events are selected from the at least past 20 years.

Because serious flooding is not frequent, this study is also considering potential flooding events. This includes flooding protection related failures and deficiencies.

The final objective of the study is to synthesize both generic and specific insights (lessons learned) which could be used as recommendations to the members of the European Clearinghouse on OEF.

[1] The review of the Fukushima accident itself has not been included in this study, as it has already been the object of numerous and well known in-depth analyses.

2. Flooding protection issues and regulatory context

Flooding protection is important for nuclear power plant safety because flood can affect many areas at the same time and defeat safety related functions. With missing or failed protection, flooding is able to cause common mode failures (CMF) of redundant and diverse safety systems. The water source could be both external and internal. The amount of water varies but even smaller amounts might suffice to affect instrumentation and control or electrical supply for the safety related systems. Flooding protection is related to the design-basis flood level and it consists of three elements: structural, organizational measures and accessibility (e.g. [2] and [3] for the U.S. and Germany).

Determination of the design-basis water level is related to design basis flood and it is accompanied with uncertainties (e.g. [4]). Established design basis flood level is critical, as Fukushima Daiichi accident terribly proves, for designing appropriate flooding protection. Part of the challenge is the number of external sources for flood and potential concurrency. After Fukushima accident, additional requirement is established to assess and prepare protection even for the flooding beyond design basis level in cases where that significantly affects safety (i.e., "cliff edge" effect).

There are many possible external flooding sources, i.e.: high groundwater levels, intense precipitation, snowmelt, rivers, streams, dam breeches and failures, channel diversion or migration, lakes, sea, storm surge, seiche, ice induced, tsunami, high tide, and wind waves. The number of sources is also large for the internal flooding with several cooling systems, fire water protection and other systems in the vicinity of ventilation, electrical, and instrumentation and control systems. Internal flooding could be caused by entrance of water from outside and by water coming from inside thru walls, floors and numerous penetrations if they are not water sealed.

Structural measures are physically preventing flooding water to reach or damage safety related systems, and they can be permanent or temporary. Permanent flooding protection is installed to prevent both external and internal flood. External protection is made as primary barrier and depends on the source. Examples for external protection are: flood walls, earthen embankments, seawalls, bulkheads, revetments and breakwaters. Internal permanent protection consists of drainage, barriers, sealed penetrations, pumps, and water tight walls, floors and doors, e.g. [5]. Temporary flood protection, as additional measure, is accepted in some countries to cover extreme conditions. This can be created with sand-filled barriers or water-tight wall, with plans for quick installation including locally stored material and resources including assessed organizational capacity. Temporary protection could be also a way to respond to external flooding beyond design basis.

Organizational measures are important for temporary protection measures and for flooding mitigation. Better organization reflects on flooding protection review, inspection, maintenance and flooding prevention. Internal flooding is sometimes caused because of poor organization during maintenance, modifications and operation.

The third element of flooding protection is to assure accessibility to the whole site and safety related systems during the extreme external flood. It is important to assure access to the plant site during the flooding in order to assure backup for people and resources.

Appropriate flooding protection is built on the right implementation and maintenance of design requirements. Nevertheless, operational experience is constantly proving how numerous water sources and systems interactions make flooding protection challenging. Some recent reviews are emphasizing that there is not enough data to select best flooding protection, i.e. [6], and therefore redundancy, maintenance, inspection and review are essential. Prioritization is essential for flooding protection and it can be based on deterministic and probabilistic assessment.

Flooding hazard and operational experience was continuously subject of different studies and activities in the IAEA, NEA, JRC and U.S. NRC. Three relevant reports are consulted in this study:

1) IRS TS OEF External Flooding, IRSN 2010, presents assessment of 15 selected events in 6 groups (i.e., climatic conditions, tsunami, water infiltration, system failures/pipe breaks, human error and seismic – external flooding combination) with related conclusions;

2) JRC TS on External events, 2012, shows that about a third of 234 events is related to flooding;

3) NEA WGOE report on Fukushima Daiichi NPP Precursor Events, 2014, with two events from five presented, were related to flooding.

Therefore, this study could be seen as continuation of flooding related operational experience assessment. Coverage of recent both internal and external flooding events is unique.

All regulators have made significant effort to review the level of flooding protection at currently operating nuclear power plants. An illustrative and valuable example is the U.S. NRC.

Open access to U.S. NRC activities provides interesting and valuable source of flooding related operational experience. This includes LERs database, Information Notices (INs), Inspection Reports (IRs) and special activities. LERs are mainly used for this study. INs are providing brief descriptions of potentially important operational experience, including insights which are provided to the licensees for information only. There are 15 flooding related NRC INs for different issues, e.g.: water leakages through conduits into buildings; unsealed concrete floor cracks and equipment hatch floor plugs; backflow through equipment and floor drain system. The latest NRC IN 2015-01 presents 12 recent events related to degraded ability to mitigate flooding. These are examples of flooding prevention and mitigation deficiencies with equipment, procedures, and analysis.

In 2012, the U.S. NRC, as a post Fukushima activity, requested that each NPP site inspects flooding protection by performing a walkdown using Nuclear Energy Institute Walkdown Guidance 12-07, [7]. This has resulted in the discovery of numerous flooding protections related events.

Ongoing activity in the U.S. related to the flooding seals testing illustrates how challenging is to assure appropriate flooding protection testing, [8]. This is mainly because of numerous flooding seals types and configurations (round and squared openings with single and multiple cables, pipes, etc.). An additional challenge for review, inspection and maintenance is the number of sealed penetrations in the NPP (i.e. close to 2000).

Mentioned studies and experience are proving that for reliable flooding protection it is necessary to have adequate maintenance, to do regular inspections and perform periodic reviews. Maintenance and inspections are important for keeping and checking permanent protection reliability. Periodical review is necessary for assuring up-to-date flood hazard assessment and required protection. Finally, operational experience is indispensable in finding the problems which went unnoticed during design, construction, inspection, review and maintenance. These events can also serve as motivation for additional checking and inspections. The goal of this study is to provide renewed comprehensive quantitative and engineering assessment of the flooding protection related operational experience for flooding related events in the world.

3. Methodology for events selection, characterization and analysis

Four major databases were used in order to obtain information about flooding related events: IRS (IAEA/OECD), LERs (US NRC), SAPIDE (IRSN, France) and VERA (GRS, Germany). Operating events are identified, characterized and analysed in order to create insights. Based on the number of identified events time period is selected to be 20 years ending in 2016.

IRS database contains events reported to IAEA/OECD IRS by the IAEA members on a voluntary basis. The other three databases are subject to enforceable reporting requirements. Only the LERs are available to the general public..

The search for flood related events was done by using appropriate keywords and guidewords in each database, eventually removing non-relevant events.

The flooding related events are characterized in 13 categories, considering: plant state, flooding type, detection, causes (direct, system, component, and root causes/causal factors), effects (to systems, components and consequences), safety relevance, corrective actions and their purpose. Some categories have multiple coding. All categories, except "*Type of flooding*", are generic.

Characterisation provides structured information about all events (e.g.: where, why and with which causes and consequences are flooding events occurring) and initially identified specific insights from selected events.

Based on characterization and detailed assessment, events are grouped (by affected systems and common activities) in order to derive final list of specific insights (lessons learned). In general insights could be linked to the root or direct cause, but as well to the equipment or type of component affected, to certain activities or some type of human behaviour, etc.

Generic type of insights are created based on event-specific lessons learned. Generic lessons learned are defined in such a way that they are not too specific (e.g., they are applicable to more than one situation or NPP) nor that they are too wide (e.g., they are not stating simple common sense or well-known knowledge).

Insights presentation is completed with short description of several (usually three) illustrative events. Every insight is also base for suggesting certain action to be taken in order to prevent some unwanted problems and consequences.

4. Events screening and characterization

This section presents first the number of events after screening and then selected most illustrative and important results from characterisation. Characterisation results are presented only for aggregated events without details related to separate databases.

4.1 Screening

Events from database search are screened before detailed analysis. A total of 263 events remained to be characterised and analysed. The LER and SAPIDE events contribute similarly with about 40% each while IRS and VERA roughly share the rest of the events. For the U.S. events seven are selected from the flooding related NRC Information notice 2015-01. From the IRS relevant events about two thirds are removed because they are duplicates with other three national databases.

The relatively higher number of events for LERs and SAPIDE is mainly because of different reporting criteria. Because of the relatively few VERA events, they were selected from the whole database including additional 15 years. IRS events were treated without events from other three databases and they are all selected because of high relevance and international nature.

4.2 Events characterisation

Number of aggregate events per reactor is in the range from 0.05 to 0.33 with recent values around average, Figure 1. No particular trend could be identified. Number of events for several years after 2011 seem to be influenced by Fukushima related actions at least for some countries.

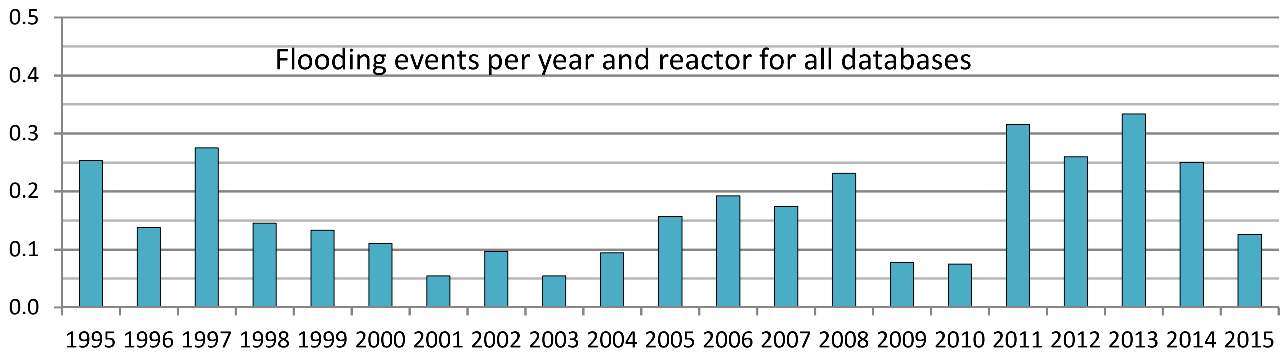

Figure 1. Number of flooding events per year and reactor for all four databases (normalised)

Aggregate characterisation results for four groups of categories are illustrated with selected results. The category groups are: conditions, causes, consequences and corrective actions.

4.2.1 Events condition

Event conditions are characterised with plant state, flooding type and detection.

Plant state: Close to 60% of events occurred during power operation. Only one database has more significant share of events during refuelling (with consideration of time duration for plant states).

Flooding type: Majority (90%) of events are internal flooding. One database has much higher share of external events. There is no significant difference of flooding events between different types of reactors.

Events detection: Almost 40% of events are detected during the operation on power. Second most important condition (22%) for events detection is audit (walk-downs, inspections, etc.).

4.2.2 Events causes

Event conditions are characterised with direct cause, systems, components, root causes and causal factors.

Direct causes: Flooding barrier problems and human factor are two most dominant direct causes (25% and 22% respective share). Difference between databases is high with two databases having much higher contribution from flooding barriers problem while one database has most important contribution from work activities.

Systems: Contribution from all systems with water as working fluid is similar with little bit higher share of flooding events caused by essential auxiliary systems (15%). The highest share of events (25%) has unknown contributing system.

Components: Passive components and valves are most dominant components causing flooding events (25% and 10% respectively).

Root causes and causal factors (RC&CF): Design configuration and analysis are most dominant RC&CFs (18%). Training, qualification and procedures are very close second most dominant CF&RCs (17%). Maintenance, testing and surveillance is also important like equipment performance (12%).

4.2.3 Events consequences

Event conditions are characterised with affected systems and components, safety consequences and relevance.

Affected systems: Most affected are essential reactor auxiliary systems and electrical systems (20% and 18% respectively).

Affected components: Pumps, compressors, fans and similar are the most affected components (27%). Electrical power components are the second most affected (19%). Significant number of events (21%) is without specified affected component.

Safety consequence: Highest share of events is without safety consequence (18%). All safety consequences have similar share. However, this distribution differs significantly between all four databases.

Safety relevance: Majority of events (63%) has no safety relevance based on judged CCDF (<1E/6/y) and affected safety functions. One percent of events has high safety relevance (CCDF>1E-4/y) while 11% of events has medium safety relevance.

4.2.4 Corrective action

Corrective actions are characterised with type and purpose.

Type of corrective actions: Restoration, repair and replacement is the most important (23%). Other types are important (~10%), e.g.: various modifications (maintenance, procedures and design), analysis and training

Purpose for corrective actions: Early identification, prevention and reduction of flooding is the most important purpose for corrective actions (26%). Fulfilment of requirements for probable maximum flood is the second most important purpose for corrective actions (20%).

5. Lessons Learned

Generic lessons learned are created based on the specific lessons learned derived from events analysis. Specific lessons learned are grouped to improve readability and in order to help identification and formulation of generic lessons learned. This section first presents some observations for specific lessons learned at the level of groups, and then generic lessons learned are presented.

5.1 Specific (low level/detailed) Lessons Learned

Specific lessons learned (SLL) from the analysed events are grouped by their similarity based on related systems and activities. About 40% of events is used to create specific lessons learned. Some events and related lessons learned are relevant for more than one lessons learned and they are included in more than one group. The number of lessons learned per group varies between six and almost three times more.

The following eight groups of specific low level/detailed LL were created:

1. Non-safety related structures, systems and components:
   1.1. Various non-safety systems,
   1.2. Drainage systems, and
   1.3. Water-based fire protection systems.
2. Buildings infrastructure (incl. cooling intake and pump house structures)
3. Major cooling systems
4. Maintenance activities
5. Inspections and walk-downs
6. Operating experience, analysis, revisions and response process related LL.

5.1.1 Non-safety related structures, systems and components

Non-safety structures, systems and components (SSC) have often caused safety relevant flooding events. Non-safety SSC are designed in accordance with industrial standards and are not subject to the flooding related analysis, requirements and maintenance. A non-safety system could be the source of a flooding or it could cause the breach of a flooding barrier. All non-safety SSC LLs are grouped in one general and two specific systems groups.

Various non-safety SSC

Common examples of non-safety systems containing significant amounts of water are fire protection system, potable water network, wastewater system, demineralized water systems, drainage system and cooling towers.

Operating experience event analysis shows that incorrect licensing bases documentation could affect safety SSC operability after internal non-safety SSC flooding events (e.g. from non-seismically qualified pipe breaks). Example of problems are: insufficient documentation related to internal flood protection requirements, incorrect calculation of water level, flow paths and flowrates, piping design deficiencies or SSCs not protected by flooding barriers.

Drainage systems

Malfunction of drainage systems (i.e. underground, floor and weather related drainages) results in excess water exposing flooding barriers (non-properly sealed penetrations, ceilings…) which can result in internal and external flooding events.

Problems are usually the result of poor design and inappropriate maintenance and inspections. Special consideration is necessary for common drain systems because of its interconnections and potential backflow including unexpected water flow. Insufficient drain capacity, drain lines plugging/degradations, check valves failure to close, missing parts and missing grates. Additionally, beyond design flood resulting from drainage failure should be also considered.

Water-based fire protection systems

Actuation (valid or spurious) of fire protection system releases water that may disrupt plant operation and lead to common mode failure of safety related systems. This is challenging because the fire protection system also prevents damage in case of fire. The problem reveals itself when flooding barriers are inappropriate or missing.

5.1.2 Buildings infrastructure with cooling water intake and pump house structures

Building infrastructures waterproofness (i.e. ceilings, roofs & floors, drainage, walls, penetrations, conduits) is a protection from flooding. Inadequate design and degradation of waterproofness compromise this flooding protection. Modifications and interaction with other SSC are potential source of flooding protection problems.

Construction deficiencies (mostly legacy issues) could result in flooding barrier degradation and flooding because they were not part of flooding analysis. The issue is inadequate or missing flooding protection, unidentified water sources, irregular inspection and inappropriate maintenance. Regarding the protection against design basis events, a particularly important issue is instability of structures due to elevated groundwater levels and external water ingress in buildings/rooms/shafts/openings housing which can flood SSCs.

Cooling water intake structures in coastal plants are challenged with tides and surges by design basis and its requirements should be reviewed to be up to date with state of the art in hazard understanding (e.g., severe weather). Their exposure to harsh environmental conditions and/or brackish water is an additional reason for the review.

The experience for building infrastructure shows how important is to prioritize inspection and maintenance, based on risk significance, for holes or unsealed penetrations in floors and walls between flood areas.

Available events assessed in this report for cooling water intake and pump house structures lead to conclusion that cracking and corrosion in reinforced concrete (walls, slabs, beams, and steel support members of the intake structures, equipment anchorage, buried piping or pipe supports) are causing major problems.

5.1.3 Major cooling systems

Major cooling systems such as Essential/Raw Water System (E/RWS), Cooling Water System (CWS) or Component Cooling System (CCS) can cause significant flooding events. It is found that inspection and maintenance activities over these systems are not always taking into account in the flooding risk assessment.

The number of events related to EWS/CCS reveals lot of deficiencies in design, failure analysis, maintenance and inspection activities that could affect directly flooding protection. These kinds of events are safety relevant because of the potentially large water flows involved and because they also have a potential for significant common mode failure impact through the loss or degradation of the plant heat sink.

Multiple pipe designs (e.g., puddles pipes, flanges or necks), thickness, materials (e.g. bonna, concrete, carbon steel, cast iron, and HDPE), and configurations (e.g., inaccessibility or blind spots for parts, underground, coating, and pump internal subcomponents) have to be properly considered by maintenance and inspections on these systems to control for corrosion, fracture risk and eventual leakages.

5.1.4 Maintenance activities

Inadequacy of maintenance practice appears frequently as direct cause of flooding events. In general, degradation of flood barriers was caused by inadequate maintenance in addition to inadequate design or improper construction.

Inappropriate maintenance of flooding barriers (i.e. piping penetrations seals, rubber expansion piece, electrical conduit penetrations seals, screw type conduit seal plug, conduit seal, manhole seals, wrong door settings, impaired water tight door) and human errors during maintenance activities (e.g. inadvertent opening valve/handhole cover and not using formal procedures) could lead directly to flooding.

A low risk perception associated to flood barrier program lead to deficient maintenance activities.

5.1.5 Inspections and walk-downs

This subsection presents specific LLs related to inspection and walk-downs activities for flooding barriers and flooding sources that are not already listed in other groups. During plant baseline inspections, personnel must be cognizant of plant areas which may be vulnerable to flooding events, particularly where a potential exists for common mode failures. Often flood protection inspections tend to focus on potential flooding sources from systems located within the room, as compared to sources located outside the room.

Incomplete documentation and design control are major reasons for ineffective inspections. Penetrations and flood seals related to safety equipment shall be included into periodic inspection program.

5.1.6 Operating experience, analysis, revisions and response process

Flood related vulnerabilities and events have been identified at nuclear power plants around the world. Analysed flooding events demonstrate that there is large potential to learn lessons from experience.

During engineering analysis and review process many flooding protection related issues can be timely discovered and solved. Flooding related events in this group highlight the importance of:

- Periodic reassessment of applied flood hazard methodology and estimated PMF,
- Design control and periodic inspections implementation,
- Realistic and validated (by multidisciplinary teams) flooding response procedures,
- Establishment of flood protection configuration management and engineering program.

As it was previously defined, beyond design flood category include events caused directly by exceeding the chosen design limits (e.g. storm level underestimated during design and cliff edge effect level). Experience shows that NPPs should assess them and be prepared to cope with this kind of events (i.e., with response equipment means, qualification, availability and maintenance).

5.2 Generic Lessons Learned

Generic LL are created following the previously presented groupings of specific lessons learned, considering related activities and affected systems. These generic lessons learned present directly some of specific lessons learned groups or their combination. Nevertheless, in order to express cross system and cross activities impacts five additional generic lessons learned are created for flooding mitigation, communication, design modifications, requirements and configuration management.

The following 16 generic lessons learned are formulated :

1. Non-safety water systems (e.g. cooling tower, wastewater system and atmospheric tanks) should be commissioned and inspected to ensure that, if they become the source of a flood, it will not affect safety systems. This is also significant for related training and procedures modification.
2. Drainage systems prevent flooding if they are properly designed, inspected and regularly maintained. Design review should include assumptions, safety relevance and all relevant scenarios (including beyond design). Inspection and maintenance should look for proper sealing, possible obstructions and unconsidered discharges.
3. Fire protection systems containing water could impact safety systems if they are not adequately considered in flood protection analysis, design, maintenance, inspection/monitoring and configuration control.
4. Building's leak tightness should be inspected and maintained for walls, floors, joints, conduits, sumps and drainages related to potential flooding issues (e.g., flexural cracks, building's sealants, and unexpected openings or pathways).
5. Major cooling systems (e.g. EWS, RWS, CCW) should be designed, commissioned, maintained and inspected with assurance that they will not cause CMFs flooding event. This is important for all safety system but also for the impact on other trains of the major cooling system. Inspection should also include parts of the system built to be operated without maintenance during the entire life of the plant.
6. Maintenance, with adequate frequency, planning, training and review, is important for flooding protection verification and restoration (flooding prevention with e.g., drainage checking, corrosion protection examination, leakage prevention, flood barriers review and repair).
7. Maintenance activities not related to flooding protection could directly cause flooding (e.g., by opening system filled with water). Adherence to procedures, activity risk analysis and adequate preparation are important.
8. Human errors made during maintenance could later cause flooding (e.g., by reversing drainage check valve, clogging flow, compromising water tight doors and flooding barriers). Following procedures and preparation are essential.
9. Periodic, prioritized and thorough inspections and walk-downs are needed to verify fulfilment of flooding protection requirements. Success depends on having updated design and architectural documentation. Blind spots should be assessed and if needed, new manhole should be installed. Prioritization should be based on the safety importance (e.g. SSC in emergency operating procedures). Contractors work needs oversight. To improve detection of external flooding protection deficiencies it is useful to inspect after extreme weather conditions.
10. A systematic periodic review of in-house and worldwide operating experience related to flooding events should be performed to prevent similar events from (re)occurrence. Operating experience could be useful for defining better regulatory requirements, improved mitigation measures and optimized scope and frequency for inspection and maintenance.
11. Periodical revaluation to verify and update flood risk analysis and assess required protection is important in order to benefit from the latest methods improvements and verify potential impact of plant changes (e.g., new PMF, information, BDB). This could potentially help to correct possible mistakes and improve flooding protection.
12. Successful mitigation response to flooding depends on having appropriate procedures, available resources and staff. Regulatory inspections have proved to be very useful to reveal unrealistic assumptions, inadequate preparation, or unreliable mobile equipment.
13. Unambiguous communication improves flooding response effectiveness and prevents human caused flood. Proper communication between shifts, control room and local operator improves mitigation response and reduces human caused flooding.

14. Design modifications involving non safety related items including conduits or new penetrations should consider flood protection design basis to prevent the creation of unexpected flood paths. Modifications, design, commissioning and impact analysis of non-safety systems which could contain water should consider their potential flood impact with modification file considering flooding hazard. Water tightness of rooms, including doors, could be also affected by modifications of non-safety systems.
15. Applicable flooding protection related requirements should be fulfilled, verified, inspected and maintained. Requirements should include realistic operating conditions and configuration including all potential flooding sources and flooding barriers.
16. Complete and up to date documentation and configuration control (management) is essential for better flooding analysis, inspection and maintenance. Adequate equipment labelling could minimize errors. Documentation should reflect flood protection design and identify all flood barriers and other related measures. This is necessary for improving flood protection and establishing flooding engineering program.

6. Conclusions

This topical study has been conducted to review the recent worldwide operating experience related to real and potential flooding events and flooding protection, in order to derive relevant lessons learned. Four sources of operating experience were used: the IRS database, the Licensee Event Reports of the U.S. NRC, the French operating experience database of the IRSN and the German operating experience database of the GRS during the last 20 years. After screening, 263 events are used for analysis, characterisation and lessons learned identification.

Characterisation helped identifying most important characteristics and contributions for event conditions, causes, consequences and corrective actions. The statistics is created for individual databases and cumulatively. Most of the events are occurring during the power operation in all except one database. However more flood events per unit time is happening outside power operation. In the majority of events a real flood occurred except for one database where potential flood is dominant.

Valves and passive components are mainly causing flood in all databases, while seals and drainage are also important cause for the two major databases. Training, qualification and procedures with design configuration and analysis are the most important root causes and causal factors in all databases.

Number of events per year vary significantly over the analysed 20 years period without identifiable trend. The number of events is decreasing during the last two years.

Finally, selected events were used to derive insights (lessons learned).

Essential auxiliary systems are the dominant source of flood for all but one database. Valves and passive components are dominantly causing flood in all databases.

The most affected systems by flood are (reactor) auxiliary systems in all databases. Electrical system is significantly affected in all except one database. Pumps and electrical components are most affected components by flooding event for all databases.

Significant number of events is without safety consequences for all databases. The majority of events do not have safety relevance except for the one database where low safety relevant events dominate.

Besides restoration, most dominant corrective actions are related to maintenance, procedure and design modifications. The main purpose of corrective actions is: prevention, early identification and reduction of flood; fulfilment of the probable maximum flood requirements; reducing flood risk from non-safety systems and improving maintenance, review and inspection.

Event analysis resulted in more than 90 specific and 16 generic lessons learned. Findings are grouped related to the systems (i.e., non-safety systems interaction, buildings infrastructure and major cooling systems) and type of activities that are cause to the flooding event (i.e., maintenance, inspection, operating experience, analysis and configuration management). It is important to have holistic view on the maintenance, inspection and analysis of flood hazard and protection measures. Especially for non-safety systems interaction, drainage system, fire protection systems, major cooling systems and all infrastructural barriers preventing water propagation. Generic findings are also addressing mitigation, communication, modifications, requirements and configuration management.

Presented findings could be used as recommendations and are expected to help the licensees and regulatory authorities to prevent flooding events from occurring, to protect safety systems from flood impact and to improve flooding protection and mitigation.

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Abbreviations

BWR – Boiling Water Reactor
CCDF/P – Conditional Core Damage Frequency / Probability
CCS – Component Cooling System
CH – Clearinghouse
CMF – Common Mode Failure
CWS – Cooling/Circulating Water System
DBE – Design Basic Event
DBF/L – Design Basis Flood/Level
DE – Germany
E/RCW – Essential/Raw Cooling Water
ECCS – Emergency Core Cooling System
EDG – Emergency Diesel Generator
FR – France
FSAR – Final Safety Analysis Report
GL – Generic Lesson Learnt
I&C – Instrumentation and Control
IAEA – International Atomic Energy Agency
IN – Information Notice
IR – Inspection Report
IRS – International Reporting System
JRC – Joint Research Centre
LER – Licensee event report
LL – Lessons Learnt
NEA – OECD Nuclear Energy Agency
NPP – Nuclear Power Plant
OECD – Organization for Economic Cooperation and Development
OEF – Operating Experience Feedback
PMF – Probable Maximum Flood
PSA – Probabilistic Safety Assessment
PWR – Pressurized Water Reactor
QA – Quality Assurance
RA – RiskAudit
RCPS – Reactor Control and Protection System SF – Safety Function
SL – Specific Lesson Learnt
SS – Safety System
SSC – Structures, Systems and Components
TS – Topical Study
TSO – Technical Support Organization
U.S NRC – United States of America Nuclear Regulatory Commission

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