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External hazards related events

Volume I: Main report

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Volume I: Main report

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External Hazards II

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Foreword

The European Network on Operating Experience Feedback (OEF) for Nuclear Power Plants, or ‘European Clearinghouse', was established by European nuclear safety regulators to promote the regional sharing of operating experience, the dissemination of lessons learned from nuclear power plants (NPP) operation, and the understanding of the role of OEF systems in the safe and reliable operation of existing and new build NPPs. The centralised office of the European Clearinghouse (CH) is operated by the Joint Research Centre (JRC) of the European Commission.

More specifically, the CH project aims to:

- improve NPP safety by strengthening cooperation between licensees, regulatory authorities and the staff of their Technical Support organisations (TSOs) in order to collect, communicate and evaluate information on reactor operational events and systematically and consistently apply the lessons learned in all the European countries taking part;
- establish European best practice for assessing NPP operational events using state-of-the art methods, computer aided assessment tools and information 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 European Clearinghouse regularly carries out in-depth analyses of events related to a particular topic (the so-called "topical studies") in order to identify and disseminate the lessons learned aiming at reducing the recurrence of similar events in the future.

The present study deals with the risks posed by external hazards. Its results are presented in two reports:

- The Main Report (this document) summarises the results obtained by the study, prioritising the recommendations and is intended for unrestricted public distribution.
- The Technical Annex substantiates the recommendations presented in the Main Report, including details of the events reviewed. It is distributed to the organisations participating in the European Clearinghouse, as well as authorised users of the IAEA´s International Reporting System for Operating Experience.

Abstract

Topical studies are a major product of the European Clearinghouse providing in-depth assessment of safety significant events and generic safety issues. External hazards are a major challenge to nuclear safety as the Fukushima-Daiichi accident has shown. This is the second topical study from the European Clearinghouse on this topic taking into account recent nuclear power plant events in Europe and worldwide. These events are individually of minor safety significance, but the results of their analyses from different countries with various types of nuclear reactors should enable the EU Clearinghouse member countries to apply these generic lessons learned by their nuclear safety authorities on the respective nuclear installations.

The evaluation of national and international events caused or influenced by disturbances arriving from offsite the plant is the topic of this report. The external hazards comprise strong winds, flooding, intrusion of chemicals, vegetable and animals, fires and man-induced hazards stemming from e. g. traffic or nearby works.

In total 44 high-level lessons learned have been derived from the selected events. These are discussed and grouped according to the various hazards. Thus, a structured set of generic lessons learned are provided for the utilisation by regulatory bodies.

Executive Summary

This report on external hazards has two predecessor topical studies: the Topical Operational Experience Report on External Hazards related events at NPPs, 2012, /1/ and the Topical Study on Events Related to Flooding at NPPs, issued in 2018 /2/. The present report covers events occurring in the period between 2010 and 2020 starting with the end date of the first study on external hazards and in the period between 2017 and 2020 for the flooding events, respectively. The Fukushima-Daiichi accident occurred in 2011 is however not described here, as comprehensive and detailed reports about it have already been published and are publicly available.

The aim of the topical studies is to draw generic lessons from operating experiences in different countries with various types of NPPs to enable the EU Clearinghouse member countries to apply these generic lessons learned by their nuclear safety authorities on the respective nuclear installations.

The first step was the search of related events in the respective national event databases for NPPs of the Czech Republic, France and Germany. In addition, the database of the international reporting system on operating experiences (IRS) was used. This database, jointly operated by IAEA and NEA, is the most important source of significant events from NPPs worldwide.

The second step was focused on the in-depth analysis of the 166 events selected. The events are categorized in different groups and sub-groups as well as in various task and cause categories. In the present study, consistently with the first report on external hazards, the groups comprise:

- Group 1: extreme weather conditions with the sub-groups: storm/high winds, extreme (high/low) temperatures, high humidity, and precipitations (without flooding inside NPP buildings)
- Group 2: external flooding with two sub-groups: weather conditions (with flooding inside NPP buildings), and system failure/piping break (in connection with external environment)
- Group 3: earthquakes
- Group 4: external fires

- Group 5: lightning strikes
- Group 6: fouling events with fouling of water intake entrance and biofouling caused by external environment
- Group 7: chemical events comprising corrosion caused by external environment and chemical fouling caused by external environment
- Group 8: man-induced events with effects of nearby industries, river/sea traffic hazards, air traffic hazards, road traffic hazards, fire and explosion as well as working in NPP vicinity
- Group 9: other, including solar magnetic disturbances.

The results are shown in tables and charts. The comparison with the former report on external hazards has to consider that earthquake events were not covered in the first study and flooding events were only analysed after 2016 and therefore, figures reflect only rough trends. In this report, the groups “extreme weather conditions” (36 %), “fouling/biological” (20 %) and “man-induced events” (13 %) represented nearly 70 % of all selected events. The first two groups had already been the most populated in the first study. The third one had been the group on “lightning strikes” with 14 % that contributed only 5 % to the present report.

Similar analyses have been performed for the relative distribution of the selected events by mode of event detection, the relative distribution of the safety relevance, and the relative distribution of the systems affected. Electrical systems (28 % of the events), essential service systems (including component cooling water, essential service water, essential compressed air and refuelling water storage) (15 %) and feedwater, steam and power conversion systems (13 %) were affected the most often.

The most important part of the in-depth analysis is the derivation of high-level lessons learned. These are derived from the most important events in the respective groups. The events are described in detail to illustrate the recommended actions (what is recommended e. g. to prevent, to mitigate or to protect the NPP from recurring the same or similar events) including their purposes. In addition, the actual (observed) consequences motivating the recommended action are given based on event specific causes or lessons learned, which support or justify the high-level lessons learned.

Furthermore, the recommendations have been assigned to four major groups, for each event group according to the main lesson learned:

- Prediction and monitoring,
- Design and equipment related features,
- Procedures and training, and
- Review and management:

In total 44 high-level lessons learned have been derived from the selected events. Four groups/sub-groups represent the majority (34 out of 44) of the high-level- lessons learned:

- Group 3 (Earthquake events) with ten lessons learned,
- Group 8 (Man-induced events) with nine lessons learned,
- Group 1 (High/low temperature events) with eight lessons learned, and
- Group 6 (Fouling events) with seven lessons learned.

The results of this task on external hazards were also used to assess whether climate change influenced the safety of nuclear power plants. The events evaluated in the two "External Hazard" studies cover events having occurred in the last 30 years. There are several events that might be addressed to the "extreme (weather) events" like the long-term drought in France, in 2003, and a local rainfall event in Germany, in 2017, beyond the expected maximum.

The increase of climate change impact could be detected through the evolution of the occurrence frequency of the natural external hazards. However, the nuclear power plant's operational response to these hazards is also related to the countermeasures installed. These countermeasures were developed over time, in particular due to the national and European Stress Tests after the Fukushima Daiichi accident. Thus, the resilience of the NPPs against external hazards has significantly been improved in the last decades based on operating experiences. In this task, no significant impact of climate change could be determined on the frequency and nature of the selected events. But this is not an evidence that there has been no climate change impact on natural external hazards.

1 Introduction

This topical study on external hazards related events has been developed by a consortium of Technical Safety Organisations (TSO) – the French IRSN, the Czech SÚRO and the German GRS - on behalf of the EU Clearinghouse. The main bases of the evaluation and assessment have been the national event databases of the Czech Republic, France and Germany. In addition, the international event database IRS (International Reporting System on operating experiences jointly managed by the IAEA and the NEA) provided input from safety relevant events all over the world.

2 Methodology and database screening

2.1 Definitions of external hazards

The IAEA defines an external hazard related events as "Events unconnected with the operation of a facility or the conduct of an activity that could have an effect on the safety of the facility or the activity". Typical examples of external events for nuclear facilities include earthquakes, tornadoes, tsunamis and aircraft crashes. /6/

The IAEA Specific Safety Requirement SSR-1 /3/ lists external events to be considered in design of NPPs.

- Seismic hazards
- Volcanic hazards
- Meteorological hazards
- Flooding hazards
- Geotechnical hazards and geological hazards
- Other natural hazards such as wildfires, drought, hail, frazil ice formation, diversion of a river, debris avalanche and biological hazards (e. g. jellyfish, small animals and barnacles)
- Hazards associated with human induced events, like aircraft crashes, chemical hazards, events associated with nearby land, river, sea or air transport (e. g. collisions and explosions); fire, explosions, missile generation and releases of hazardous gases from industrial facilities near the site; electromagnetic interference.

For the purpose of this study, all natural and human-induced events not directly connected with the NPP operation are taken into account. These might also include events on-site but outside of buildings, for example if the consequences of an on-site fire are similar to those of off-site fires. Human-induced events caused by malevolent acts are excluded from this study.

2.2 Methodology

This report complements the findings which were developed in the first Clearinghouse study on external events /1/. While the first study covered the years up to 2009, the present one is based on the operating experience between 2011 and 2020. The consortium agreed to fill the period between the studies, in such a way that no event should be missed.

The development of the study was structured in four steps:

1. Selection of relevant events
2. Analysis of the relevant events in such detail that
    - the events could be attributed to the various hazards,
    - the affected systems could be identified,
    - causes of the events could be determined, and
    - lessons learned could be described.
3. Integration of the various events from the different databases to derive generic high-level lessons learned.
4. Compilation of the final report.

The consortium has analysed all the events screened per database. The result of the classification has been documented in a common list of events comprising the following items:

- hazard group,
- hazard sub-group,
- system affected,
- type of initiator (actual, potential or actual / potential),
- detection mode of the event,
- direct cause(s),
- root cause(s),
- corrective actions,
- consequences of the event,
- safety relevance, and
- lessons learned.

2.3 Description of categories

The search of the four databases was performed using specific codes and guidewords appropriate to the language and structure of the respective database. In total 166 reported events could be identified.

The events were grouped with the help of the categories used in the first study /1/. There are minor differences between the groups of the first study and those of the current study. The former group “extreme heat sink conditions” was subsumed under Group 1 as a new sub-group “extreme temperatures”. A new group “Earthquakes” was added. Earthquake related events had been dealt with in another former study /4/ and were therefore not been comprised in the first study on external hazards.

The following hazard groups and sub-groups were used:

Group 1: extreme weather conditions

- Extreme temperatures
- Strong wind, tornado, typhoon
- High humidity

Extreme precipitation Group 2: external flooding

- Weather conditions (including flooding inside NPP buildings)
- System failure/piping break (in connection with external environment)

Group 3: Earthquakes

Group 4: External fires

Group 5: Lightning strikes

Group 6: Fouling events

- Fouling of water intake entrance
- Biofouling caused by external environment

Group 7: Chemical events

- Corrosion caused by external environment
- Chemical fouling caused by external environment

Group 8: Man-induced events

- Effect of nearby industries
- River/sea traffic hazards
- Air traffic hazards
- Road traffic hazards
- Fire and explosion
- Working in NPP vicinity

Group 9: Other, including solar magnetic disturbances.

When an external event was initiated by the combination of different external phenomena, the event was in most cases classified according to the phenomenon having the main impact on the event initiation.

3 Screening results

In the following sections the results of the event analyses are shown in separate tables based on the groups described in section 2.3 and further categories. The results are shown in simple graphs and are compared with the results of the first study on external hazards /1/.

3.1 External Hazards

Table 3.1 shows the distribution of events for the hazard groups described in section 2.3. Some of the groups are divided into sub-groups to allow more detailed analyses.

Table 3.1 Results of the event analysis regarding the group and subgroup

External Hazard	
Event group **Sub-group**	**Number of events**
Extreme Weather Conditions	59
Extreme temperatures	30
Strong wind, tornado, typhoon	11
High humidity	1
Extreme precipitation	17
Flooding	12
Flooding by weather conditions	8
Flooding by a system failure/pipe break	2
Other	2
Earthquake	16

External Hazard	
Event group Sub-group	**Number of events**
External fire	2
Lightning strike	9
Fouling of water intake / biological	33
Chemical conditions	9
Seacoast sites (chemical)	0
Corrosion by water retention (chemical)	2
Other cases (chemical)	5
Other	2
Man-induced events	22
Human activities in the vicinity of the NPP (man-induced)	6
Other	15
Solar-magnetic disturbances	0
Other	3
Unknown / unspecified	1
Total	166

Table 3.1 shows the distribution of events regarding the initiator "External Hazard" with respect to the groups and sub-groups defined. The three most frequent initiators

have been “extreme weather conditions” (59 events / 36 % of all events), “fouling of water intake / biological” (33 events / 20 %) and “man induced events” (22 events / 13 %).

The comparison with the results of the first study on external hazards /1/ has some limitations. First, the time frame was different (10 versus 20 years) and the Czech events have not been included and evaluated in the first study. The different definitions of the groups have been respected with adapting the data of the first study to the definitions of the present one. It has also to be taken into account that seismic events were not included in the first study and that flooding events were considered in the second study only for those events that occurred after 2016.

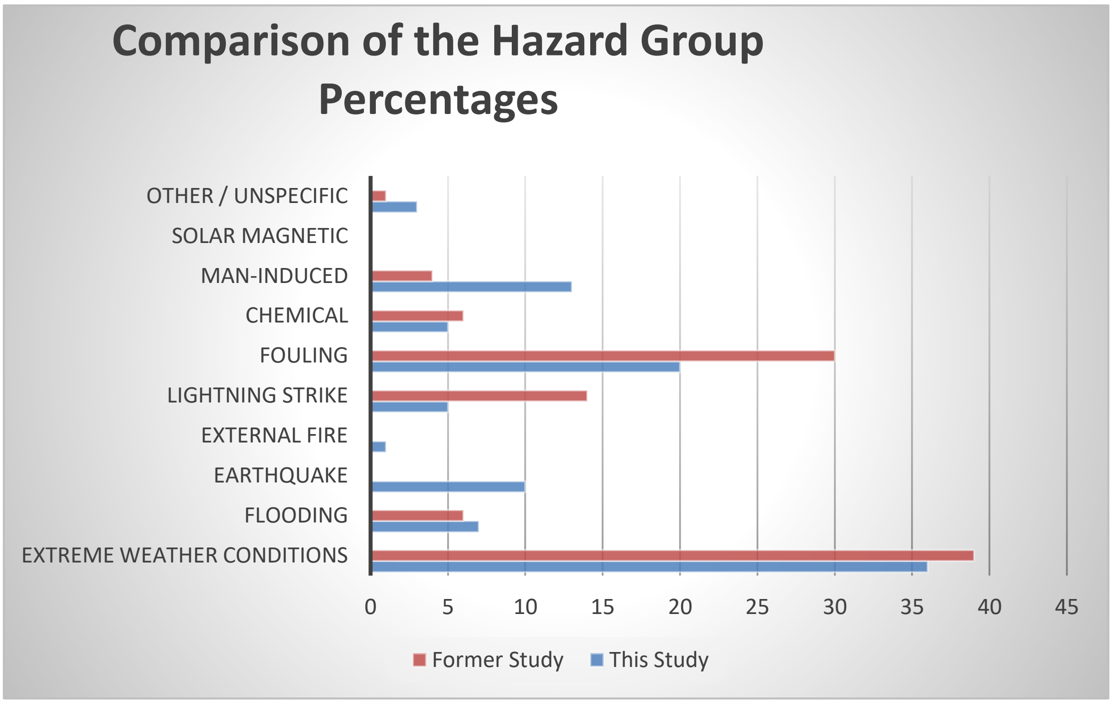

Figure 3.1 Comparison of the results of the relative distributions of external hazard related events in this study and the former study /1/

But within the most frequent hazards and as compared to the present study, “extreme weather conditions” and “fouling of water intake / biological” remained the two most frequent hazards (see Figure 3.1). Instead of “man-induced events”, the third most frequent hazards had been “lightning strikes” (31 events / 14 %).

More generally and considering the reasons mentioned above, the figures deduced from this report should not be considered in absolute terms, but rather as reflecting rough trends.

3.2 Type of Initiator

The key element factor “type of initiator / nature of event” allows to distinguish whether the initiating event has really occurred or whether there were findings that could have limited the ability of the NPP to control a potential event as foreseen in the design. For example, if a hurricane hits a NPP site and damages some equipment, then the event would be called an “actual” initiator. If a regular inspection detects loose wall cladding parts that would not withstand high wind velocities and could damage other equipment when getting loose, this would be marked as “potential”, because it was detected without a real initiator. There is a third choice named “actual / potential” that reflects those event reports that include several events constituted of “actual” initiators as well as of “potential” initiators. These event reports can be found in the IRS database namely for US information notices.

Table 3.2 Results of the event analysis by type of initiator

Type of Initiator	
	Number of events
Actual	138
Potential	21
Actual / potential	7
Total	**166**

Most of the events selected describe events with an actual initiator (138 i. e. about 83 %). There are 21 potential events (about 13 %) and 7 events (about 4 %) that either discuss as well actual as potential events (e. g. generic event reports describing several events) or events that have both characteristics. These latter events have had an actual initiator and revealed the potential for other initiators.

3.3 Detection Mode of the Event

The mode of detection of an event is interesting to define corrective actions. As external hazards are considered in the design of NPPs, measures and procedures are established to cope with the hazard. The corrective actions are meant to put the NPP into safe operating conditions again, by resolving the failures detected during the event.

Table 3.3 shows the result of the evaluation of the extended list of events regarding the mode of detection of the external hazard. It has to be noted that in two events there have been two modes of detection, which explains the total of 168 instead of 166 in Table 3.3. The most frequent mode of detection has been “alarms” (81 events / 48 %). The second most frequent mode of detection is characterized by “inspection and functional testing” (24 events / 14 %).

Table 3.3 Results of the event analysis by the detection mode of the event

Detection Mode of Events	
	Number of events
Multiple choices possible	
Alarm	81
Inspections and functional testing	24
Maintenance	8
Walkdown	17
Review/Analyses	17
Other	11
Unknown/Unspecified	10
Total	**168**

Figure 3.2 illustrates the results of the distribution of the key element factor “detection mode”.

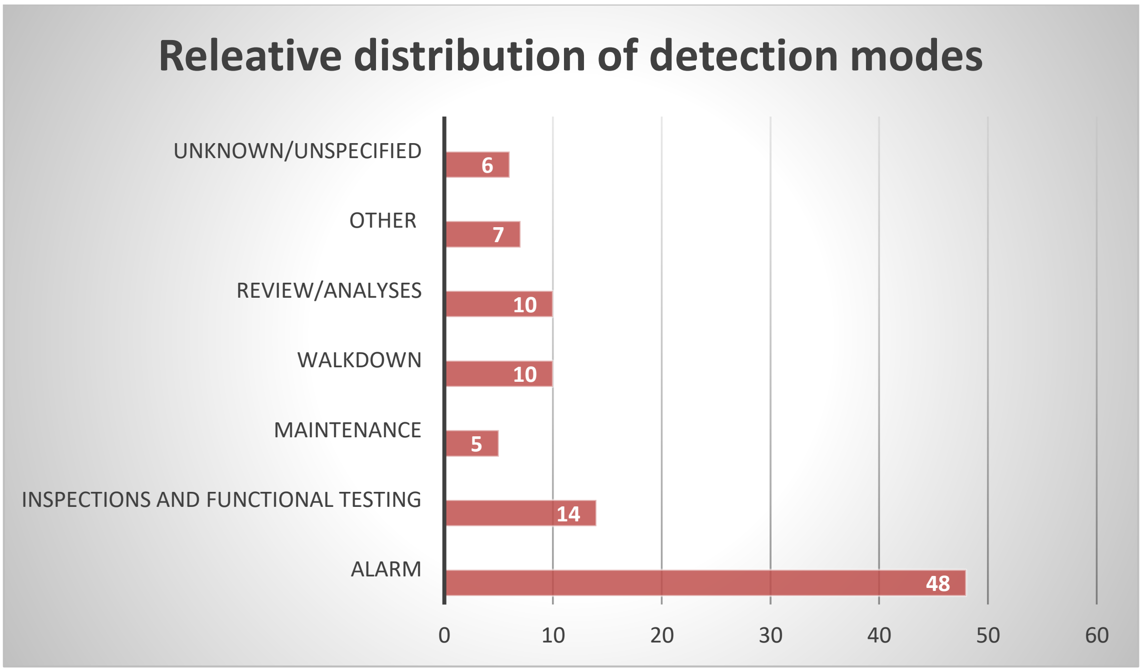

Figure 3.2 Relative distribution of the selected events by detection modes

According to Table 3.4, there is a significant difference in the detection mode between events with an actual initiator compared to events without an actual initiator.

While most of events with an actual initiator were detected by “alarms / inspections” and “functional testing” with 58 % and 12 %, respectively, the events with a potential initiator were mainly detected by “inspections and functional testing” and “review/ analyses” (8 resp. 9 events i. e. 36 % and 41 %). The percentages are always based on the total number of occurrences in the columns “actual” and “potential”, respectively. The analysis shows the expected result that actual initiators are mainly detected by alarms i. e. the control room personnel is directly alerted by the plant’s response to the initiator.

Table 3.4 Result of the event analysis regarding the dependence of the detection mode on the type of initiator

Detection Mode (MC) vs. Type of Initiator				
	Type of Initiator			
	actual	actual / potential	potential	Total
multiple choices possible				
Alarm	80	1	0	**81**
Inspections and functional testing	16	0	8	**24**
Maintenance	8	0	0	**8**
Walkdown	13	2	2	**17**
Review/Analyses	5	3	9	**17**
Other	10	1	0	**11**
Unknown/Unspecified	7	0	3	**10**
Total	**139**	**7**	**22**	**168**

3.4 Safety relevance

The common definition (see /3/) of safety relevance is related to the conditional core damage frequency (CCDF) of the event. This frequency can be assessed by precursor studies. The common definitions are:

- high safety significance: CCDF > 10 E-4
- medium safety significance: CCDF $\leq$ 10 E-4 but > 10 E-5
- low safety significance: CCDF < 10 E-5 but > 10 E-6
- no safety significance: CCDF $\leq$ 10 E-6

This common definition is not applied in the same manner in different countries. For many events (esp. events reported to IRS), the CCDF is unknown to the consortium analysts. Slight differences between the aforementioned generic definition and the assessments of specific events. In order to overcome this difficulty, this key element factor is named “safety relevance” instead of “safety significance”. To ease the assumption of the safety relevance, events with low or no safety relevance have been put into the same category “low safety relevance”.

In the “Flooding” topical study /2/, there was a further principle of classification used that is easier applicable:

- high safety significance: more than one safety function affected
- medium safety significance: one safety function affected
- low safety significance: safety function redundancy reduced
- no safety significance: no safety function affected

In this context, a safety function is a means to prevent or to mitigate potential radiological consequences of normal operation, anticipated operational events and accident conditions. The consortium analysts have classified the safety relevance of the events with respect to the impact on plant safety without using probabilistic safety assessment results. Thus, the evaluation mainly depends on expert judgment.

Table 3.5 Results of the event analysis with respect to safety relevance

Safety Relevance	
	Number of events
High	6
Medium	23
Low	137
Total	166

The analysis of the data shows that more than 82.5 % of the events are of low significance. There are 13.9 % of the events of medium safety significance and 3.6 % of high significance.

3.5 Systems affected

The evaluation of the events showed that a great variety of systems has been affected. The affected systems mainly comprise electrical AC systems (e. g. emergency buses) (58 entries) as well as essential service systems (including component cooling water, essential service water, essential compressed air and refuelling water storage) (30 entries) and non-essential cooling systems (like condenser cooling system) (26 entries).

Table 3.6 Results of the event analysis regarding the “Systems affected”

Systems affected	
	Number of events
Primary systems	5
Essential reactor auxiliary systems	13
Essential service systems	30
Essential auxiliary systems	4
Electrical systems	58
Feedwater, steam and power conversion systems	26
Heating, ventilation and air conditioning systems	9
Instrumentation and Control	16
Service auxiliary systems	15
Structural systems	11
Waste Management	3
Other, unspecified, no system affected	14
Total	204

In total, more than 60 different systems have been mentioned. In Table 3.6 and Figure 3.3 the systems have been grouped according to the main IRS categories. It has to be noted that more than one system could be attributed to a single event.

The major systems that were affected by external hazard related events are the electrical systems (28 %), essential service systems (15 %) and feedwater steam and power conversion systems (13 %), see Fig. 3.3. A more in-depth look into single systems reveals that high voltage systems (offsite and onsite) as well as essential raw cooling and service water systems are the most significant single systems involved in the selected events.

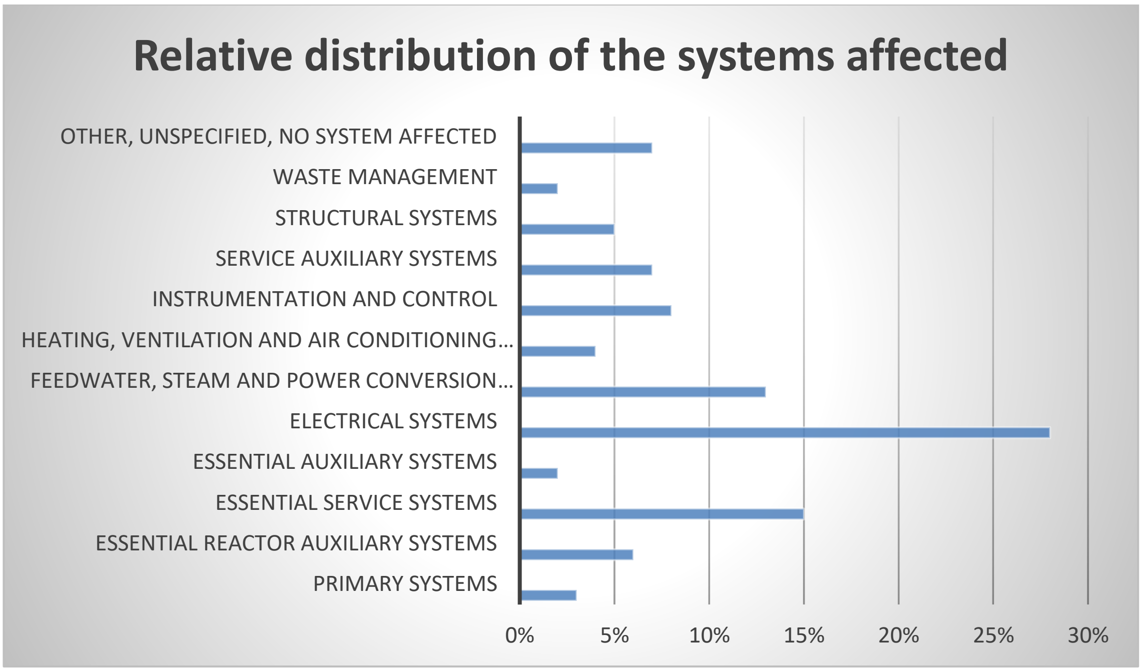

Figure 3.3 Relative distribution of the systems affected according to the main IRS categories

4 Results of the analysis

4.1 Comparison to first study on external hazards

The comparison of the results of this study and the previous report /1/ has to reflect the differences between the two studies. In the first one, seismic events were not considered. In the second study flooding events were only considered after 2016. Both constraints should avoid double work because of former studies on the respective topics.

The comparison shows nevertheless that the type of external hazards leading to events has still the two main groups “extreme weather conditions” and “fouling of water intake / biological”. These two groups have initiated more than half of the events described in the four databases used in this study and even about 2/3 of the events in the first study. With respect to the differences between the two approaches and the low number of events, the results show a satisfactory concordance.

The second key element factor that can be compared reflects the safety relevance of the events. In both studies about 80 % of the events were of low or without safety relevance and about 20 % of medium or high relevance. The generic significance of the events reported in the national databases and the IRS database seems to remain constant.

4.2 Influence of climate change

Climate change may have an important impact on nuclear reactor safety. The NEA has established an Ad hoc Expert Group on climate change: Assessment of the Vulnerability of Nuclear Power Plants and Cost of Adaptation (NUCA). The main threads related to climate change for nuclear reactor operation are listed in a common presentation of the NEA and the IAEA to the United Nations Framework Convention on Climate Change /5/. They distinguish between gradual changes and extreme (weather) events:

Gradual change: Changes in mean and variability over decades

- Temperature

- Precipitation
- Wind patterns
- Insolation
- Sea level rise

Extreme events: Occurrence above or below limit values, near to boundaries of observed values

- Heat waves, heavy precipitation, drought, high winds/storms, etc.
- Increasing frequency and intensity, affecting larger areas, prevailing long

The events evaluated in the two “External Hazard” studies cover events having occurred in the last 30 years. There are several events that might be addressed to the “extreme (weather) events” like a long drought in France, 2003, and an extreme, but local rainfall event in Germany, 2017.

The increase of climate change impact could be detected through the evolution of the occurrence frequency of the natural external hazards. The NPP operational response to these hazards is also related to the countermeasures installed which were developed over this time. As an example, after the Fukushima Daiichi accident and the subsequent national and international stress-tests were performed and several national rules and regulations were adopted. As a result, the NPP countermeasures against flooding have been strengthened. Thus, the resilience of the NPPs against external hazards has been improved due to safety related modifications in the last decades that were based on operating experiences.

5 High-Level Lessons Learned

The lessons to be learned from the review of operating experience have been split into the event groups, which have been chosen in this study to reflect the different external hazards. Within these event groups, further categorization has been done according to the sub-groups defined for the study, if their lessons learned apply in a major way to the sub-group itself and are not generally applicable to overarching event group. For example, a lesson learned to cope with high temperatures may not affect events with strong winds. Therefore, extreme temperatures and strong winds are separated sup-groups in the group “extreme weather”.

The extraction of the lessons learned from operating experience has been completed in two steps. First, the detailed, event-specific insights were categorised under one of the event group. Then, for each group, all information was reviewed in search of common concepts underlying the detailed insights, and these concepts were used to define one or a few high-level lessons learned for each group.

In this synthesis effort, lessons learned have been defined in a way that they are neither not too specific so that they would have a too limited applicability nor too wide in order they could be considered as common sense, already known to everyone.

Lessons learned have been elaborated containing the following elements:

— The recommended actions (what is recommended e. g. to prevent, to mitigate or to protect the NPP from recurring the same or similar events) including their purposes.
— The actual (observed) consequences motivating the recommended action based on event specific causes or lessons learned from the considered event, which support or justify the lessons learned.

Furthermore, the recommendations categorized within these sub-chapters have been assigned to four major topics:

- Prediction and monitoring:
  Lessons learned in this category predominantly address either the prediction of external hazards, as applicable, or monitoring of certain parameters to be early notified about imminent external hazards or their effects.

- <u>Design and equipment related features:</u>
  Lessons learned in this category predominantly address technical issues related to structures, systems, components, and mobile equipment, which may be used for preventing, protecting against or mitigating the effects of external hazards, independent of their use within normal operating procedures, emergency procedures or severe accident management guidelines. This also includes reviews and assessments, which are clearly aimed at identifying additional necessary measures, e. g. need for modification or further equipment.
- <u>Procedures and training:</u>
  This group contains lessons learned, which predominantly affect procedures and training. This also includes reviews and assessment, which are clearly aimed at developing new or amending existing procedures and corresponding training.
- <u>Review and management:</u>
  Lessons learned in this group are related to reviews, analyses and assessments themselves, independent of any necessary measures which might stem from these reviews. Examples might be periodic safety reviews, safety assessments, operating experience feedback, etc. Furthermore, this group contains lessons learned related to NPP plant management such as staffing, organizational issues, safety culture, etc.

The sub-chapters for each group and sub-group follow the same structure. At first, a short introduction of the scope of the group/sub-group is given. The high-level lessons learned derived from the events are presented in a table. Later, the reasoning behind each high-level lesson learned is explained. All high-level lessons learned are assigned to the four major topics described above.

5.1 Extreme Weather Conditions

The group Extreme Weather Conditions has several sub-groups (Extreme Temperatures; Strong Wind, Tornado, Typhoon; High humidity; and Extreme precipitation). For each subgroup, event samples and the related lessons learned are given in the corresponding subchapter.

5.1.1 Extreme Temperatures

The events triggered by extreme external temperatures led to different consequences such as:

- Equipment malfunctioning due to high temperature of the surrounding environment;
- Equipment failure/malfunctioning due to freezing of water;
- Short time change of pressure in the containment;
- Potential damage of structures, systems and components due to inadequate accommodation of maintenance processes carried out by internal or contracted personnel.

5.1.1.1 High-level lessons learned

The related individual lessons learned, and corrective actions indicate generic lessons that are provided according to the four categories:

1. Prediction and monitoring: LL Temp#1 ÷ #4;
2. Design and equipment: LL Temp#5 & #6;
3. Procedures and training: LL Temp#7;
4. Review and management: LL Temp#8.

Table 5.1 Lessons learned for events in Extreme Temperatures sub-group

Extreme Temperature related Lessons Learned
Temp#1: Additional and regular checks on the temperature regime
Temp#2: Check and monitoring of the equipment and buildings during or after extreme weather conditions
Temp#3: Preparation of systems due to expected weather changes
Temp#4: Checks, monitoring and analysis
Temp#5: Thermal insulation of exposed lines
Temp#6: Design assessment
Temp#7: Work planning and management, working procedures and training

Extreme Temperature related Lessons Learned
Temp#8: Instructions to avoid the loss of heating of several ventilation systems at negative external air temperature

5.1.1.1.1 Prediction and monitoring

- LL Temp#1: Additional and regular checks on the temperature regime

The Licensee should carry out additional checks on the temperature regime in the NPP process areas and if necessary, take steps to maintain the necessary temperature regime in the concerned areas.

- LL Temp#2: Check and monitoring of the equipment and buildings during or after extreme weather conditions

The Licensee should check as needed the state of the equipment and buildings during or right after the end of extreme weather episodes.

- LL Temp#3: Preparation of systems due to expected weather changes

Maintenance programmes of equipment (whether safety related or not) should take into account weather condition change and foresee subsequent protection means (e. g. insulation, heat tracing) to protect equipment against freezing. More generally, the licensee should check and avoid the presence of stagnant water in equipment (e. g. fire protection lines) likely to be exposed to cold weather and to freeze and damage the equipment.

- LL Temp #4: Checks, monitoring and analysis

In addition to the periodic safety review, continuous checks and monitoring need to be carried out to detect and address any places and any structures, systems and components that could eventually turn into a weak point in assuring the resistance of the NPP against extreme temperatures. These checks and monitoring should be carried as parts of regular daily walkdowns and standard inspections programmes and by specific walkdowns and inspections after the extreme temperatures die down. Analyses of extreme temperature events that occurred earlier on the NPP and other

NPPs of the similar type should also be carried out to identify possible risks as early as possible and minimize their impact on safety.

5.1.1.1.2 Design and equipment related features

- LL Temp#5: Thermal insulation of exposed lines

The Licensee should assess and ensure the thermal insulation of lines exposed to cold air temperature by appropriate means e. g. by heat tracing, avoiding heat transfer through contact with metallic material and by maintaining sufficient heating of the line rooms in hard winter conditions.

- LL Temp#6: Design assessment

NPP design should always be reassessed for resistance against extreme temperature when new relevant facts and experiences are identified and become known. When preparing design modification of structures, systems and components, their resistance against extreme temperatures under new configuration should always be assessed.

5.1.1.1.3 Procedures and training

- LL Temp#7: Work planning and management, working procedures and training

When planning and preparing activities on the site, risks related to possible occurrence of extreme temperatures shall always be taken into consideration. This also includes preparation and checks of procedures, means to be used and personnel. It should be assured that working procedures include measures and activities to cope with extreme temperatures. NPP personnel and contractors should accommodate their activities and use of means to temperatures on the site, specifically if freezing occurs or it is likely to occur. This may include emptying of outdoor water systems to avoid pipe cracks due to ice formation in stagnant water.

5.1.1.1.4 Review and management

- LL Temp#8: Instructions to avoid the loss of heating of several ventilation systems at negative external air temperature

Clear and firm instructions regarding operational modes of air intake systems at negative external air temperatures should be given to prevent overcooling and subsequent possible technical failures. These instruction concern operators of these systems, who adjust the operation mode of the respective system and the authorization of maintenance works on these systems.

5.1.2 Strong Wind, Tornado, Typhoon

5.1.2.1 High-level lessons learned

Strong winds, tornados and typhoons can lead to Loss of offsite power (LOOP) as well as degraded/impaired equipment or even further multiple failures, despite being known and measures have been taken or are in place in each NPP in accordance with their respective safety assessment. The individual lessons learned and corrective actions from these events indicate generic lessons, which are presented in the following main categories:

1. Prediction and monitoring: no LL
2. Design and equipment: LL Wind#1 to #3;
3. Procedures and training: LL Wind#4;
4. Review and management: no LL.

Table 5.2 Lessons learned for events in the Strong Wind, Tornado, Typhoon subgroup

Strong Wind, Tornado, Typhoon related Lessons Learned
Wind#1: Emergency Diesel Generator (EDG) lockouts during strong winds/low barometric conditions due to actuation of differential pressure measurements
Wind#2: Ensuring availability of EDG cooling and alternate AC power sources in case of debris accumulation due to strong winds/storms or tornados
Wind#3: Ensuring robustness of non-credited buildings and buildings owned by other companies on site or adjacent to NPPs to prohibit impact on plant equipment due to lack of structural integrity
Wind#4: Specific and integral procedures for strong wind/storm/tornados.

5.1.2.1.1 Design and equipment related features

- LL Wind#1: Emergency Diesel Generator (EDG) lockouts during strong winds/low barometric conditions due to actuation of differential pressure measurements

Licensees should assess whether EDG pressure signals which are used in EDG trip signals might be affected by low or very low barometric conditions. Even if such trip signals are bypassed by active emergency diesel generator actuation signals, an EDG lockout condition could result and lead to temporary loss of onsite AC emergency power if the corresponding barometric conditions apply prior to an emergency diesel generator actuation signal being active. High wind speeds and subsequent low barometric conditions may already apply before high winds/storms/tornados could lead to actual loss of offsite power. Thus, technical and/or procedural measures should be in place to ensure EDG availability in case of imminent high winds/storms/tornados, which might endanger offsite power supply. Similar effects, i.e. inadvertent actuation of safety signals, may also be affected by other safety related pressure measurements, which rely on differential pressure and may be affected by low or very low barometric conditions, e. g. containment pressure signals.

EDGs need to be able to perform their safety function. A lockout condition, albeit temporary due to manual resetting capabilities (e. g. locally at the EDG), may impair coping with loss of offsite power events especially in conjunction with other capacity impairments, e. g. ongoing EDG maintenance. Loss of offsite power events easily occur during strong winds, tornados and typhoons due to impacts on transmission lines further offsite the plant and thus pose a challenge albeit no immediate effects aside of low barometric pressure are experienced on site.

- LL Wind#2: Ensuring availability of EDG cooling and alternate AC power sources in case of debris accumulation due to strong winds/storms tornados

Licensees should be aware of potential impacts on EDG (and other safety related equipment) cooling ability by susceptibility of essential service water trains being clogged by debris accumulation during strong winds/storms/tornados. In order to preclude a negative impact on EDG cooling, alternate means for EDG cooling or additional AC power sources should be assessed, if not already in place. The availability of these alternate means should be assessed for potential impacts by strong winds/

storms/tornados too. Alternate means include suction sources, which are spatially significantly apart and thus are at a reduced risk of concurrent blockage, as well as mobile equipment that could either provide cooling water to EDGs or AC power themselves.

The clogging of essential service water trains due to increased amount of debris has been generally addressed in the family “biological/fouling of water intake”. Lessons learned and capabilities thus are partially applicable in case of high winds/storms/tornados here too. Alternate sources for EDG cooling or AC power generation have been introduced at NPPs as a result of Fukushima Daichi event but may not be specifically addressed or foreseen as mitigation measures for high winds/storms/tornado events.

- LL Wind#3: Ensuring robustness of non-credited buildings and buildings owned by other companies on site or adjacent to NPPs to prohibit impact on plant equipment due to lack of structural integrity

Licensees should ensure that non-credited (conventional) buildings (like offices) and buildings owned by other companies irrespective of being on site or nearby are sufficiently robust and properly maintained to withstand prevailing weather conditions to such an extent that they do not impact plant equipment or installations due to lack of structural integrity, e. g. tornado missiles, blown off roofs, dam failures etc. This is especially relevant for non-credited buildings or buildings owned by other companies which are adjacent to equipment/installations providing essential support to safety systems. Thus, giving advice and cooperation on civil inspection programmes or agreement of civil inspection programmes of partner organizations (on site) or neighbouring organizations may ensure early identification and amendment of defects or degradations.

Station switchyards and outgoing transmission lines can be easily impacted and fail due to tornado missiles, blown-off roofs, etc. which stem from buildings on site or adjacent to these installations and which might not necessarily be owned by the licensee during high winds. In conjunction with other impacts, such as offsite transmission grid problems (e. g. failed transmission lines, transmission grid substation problems) these could exacerbate NPP capabilities to cope with (partial) losses of offsite power during high winds.

5.1.2.1.2 Procedures and training

- LL Wind#4: Specific and integral procedures for strong wind/storm/tornados

Licensees should ensure specific procedures for strong wind/storm/tornados are in place and well understood and operating staff is trained to apply them. The procedures should cover all aspects of dealing with high wind/storm/tornados. These include being notified or monitoring potential for imminent high winds/storms/tornados, preparatory measures to be taken, triggers for assessing the extent of condition, restoring equipment including reconfiguration of electric systems, and clear exit conditions. In addition, respective emergency procedures to be applied during related risks to plant operations should provide plant personnel with necessary assistance to cope with such events. The procedures should be suitable to manage complex situations initiated by or cumulated with high wind/storm/tornados.

5.1.3 Extreme precipitation

In case of extreme precipitations, practically all events resulted in rainwater penetration into nuclear power plant compartments and subsequent damage or malfunctioning of equipment.

5.1.3.1 High-level lessons learned

The related individual lessons learned and corrective actions indicate generic lessons that are provided according to the following categories:

1. Prediction and monitoring: no LL
2. Design and equipment: LL Rain#1 and #2;
3. Procedures and training: no LL;
4. Review and management: LL Rain#3.

Table 5.3 Lessons learned for events in the Extreme Precipitation sub-group

Extreme Precipitation related Lessons Learned
Rain#1: Design of the roofs of buildings containing equipment important to safety
Rain#2: Design assessment of drainage capacity
Rain#3: Checks, monitoring and analysis

5.1.3.1.1 Design and equipment related features

- LL Rain#1: Design of the roofs of buildings containing equipment important to safety

The design of the roofs of buildings containing equipment important to safety should conservatively take into account the loads resulting from snow and frozen water that could accumulate on them. This design should be revised as soon as new data and/or assessment methodologies are available.

- LL Rain#2: Design assessment of drainage capacity

NPP design should always be reassessed for resistance against extreme precipitation (e. g. drainage capacity) when new relevant facts and experiences are identified and become known. When preparing design modification of structures, systems and components their resistance against extreme precipitations under new configuration should always be assessed.

5.1.3.1.2 Review and management

- LL Rain#3: Checks, monitoring and analysis

In addition to the periodic safety review, continuous checks and monitoring need to be carried out to detect and address any places and any structures, systems and components that could eventually be a weak point in assuring the resistance of the NPP against extreme precipitation. These checks and monitoring should be carried out in a form of regular daily walkdowns, specific planned walkdowns and inspections with a week or a longer time periodicity. Analyses of extreme precipitation events that occurred earlier on the NPP and other NPPs of the similar type should also be carried out to identify possible risks as early as possible and minimize their impact on plant safety.

5.2 Fouling of water intake/biological

5.2.1.1 High-level lessons learned

The selected events show fouling of the water intake or biological impacts persist, despite being known and measures have been taken or are in place in each NPP which relies on natural cooling water, i.e. rivers, lakes, coastal sites. The individual lessons learned and corrective actions from these events indicate generic lessons, which will be presented in the following main categories:

1. Prediction and monitoring: LL Foul#1 and Foul#2
2. Design and equipment: LL Foul#3 and Foul#4;
3. Procedures and training: LL Foul#5 and Foul#6;
4. Review and management: LL Foul#7.

Table 5.4 Lessons learned for events in the Fouling of Water Intake/Biological sub-group

Fouling of Water Intake/Biological related Lessons Learned
Foul#1: Prediction and forecasting of biological/marine formation and ingress.
Foul#2: Monitoring, trending and display of important cooling water performance parameters for identifying degrading performance
Foul#3: Monitoring and trending of mitigation measures, i.e. fish and trash nets, drum screens, strainers and sieves
Foul#4: Availability of backwashing and cleaning measures
Foul#5: Specific and integral procedures for marine ingress
Foul#6: Procedures for fouling of water intake/biological
Foul#7: Importance of management involvement to foster further mitigation of risks

5.2.1.1.1 Prediction and monitoring

- LL Foul#1: Prediction and forecasting of biological/marine formation and ingress

Prediction and forecasting of the locally encountered biological/marine formation as well as debris monitoring should be improved and utilized to enhance understanding of the formation and occurrence frequency. Increased amount of information can assist in predictive modelling and forecasting. This in turn should be used to provide plant personnel with necessary and sufficient information to take decisions and preparatory time to implement measures. Furthermore, risk assumptions can be updated and risk-assessment re-validated.

- LL Foul#2: Monitoring, trending and display of important cooling water performance parameters for identifying degrading performance

The monitoring, trending and display of important cooling water performance parameters should be assessed for improvement with regard to explicit use for identifying degrading performance due to ingress of biological, marine formation or debris. Information can support operators in conservative decision making, e. g. assessing the situation earlier by utilizing efficient monitoring means (e. g. walkdowns, visual checks) and therefore undertake the relevant actions (e. g. pre-emptive strainer/drum screen cleaning) and an adapted strategy for the operating of the reactor.

The given events led to loss of cooling water flow, e. g. by pump trips due to existing protection such as high drum screen differential pressure, and subsequently to turbine trips and shutdowns (either manual or automatic). As these protections worked as designed, the events showed that control room staff either experienced automatic protection measures or high alarm signalling, e. g. high drum screen differential pressure, which did not leave enough time to take preventive or remedial measures.

5.2.1.1.2 Design and equipment related features

- **LL Foul#3: Monitoring and trending of mitigation measures, i. e. fish and trash nets, drum screens, strainers and sieves**

The operating experience from these events indicate, that measures in place were not suited either for the amount of ingress experienced and/or the type of marine life encountered. Besides timely installation of retention measures, i. e. nets, which should be considered for permanent installation, the events showed tides, wave formation or low lake levels may impact the effectiveness of top net skirts. On other occasions, the screens and strainers eventually were damaged due to overwhelming loads of debris or were ineffective to remove the screened marine debris, which resulted in screen/mesh blocking and thus significant reduced water through flow.

Thus, licensees should monitor and trend the effectiveness of their mitigation measures, such as trash nets, drum screens, strainers and sieves. This applies to existing measures as well as measures taken in response to events of intake fouling by ingress of biological, marine formation or debris. Besides technical design features, e. g. overall retention capacities, monitoring and trending should also assess the impact of tidal or wave formations on nets, as well as the specific retention capabilities of the introduced measures with regard to type of biological and marine life existing at their respective plant locations. The monitoring and trending should be used to assess the existing and planned measures and derive necessary further actions, e. g. procedural updates or additional modifications (i. e. permanent or additional installation of measures).

- LL Foul#4: Availability of backwashing and cleaning measures

Licensees should assess the availability of backwashing and cleaning measures of screens and strainers and be aware of risk associated with insufficient removal capabilities of debris. The design of strainers and trash baskets should be of such kind, that even a high amount of cleared debris may be handled, e. g. by overall capacity of strainers and trash baskets or easy cleaning and emptying measures. The design of sluice channels should ensure the outlet channels do not re-feed debris into the intake channels in case of overflowing strainers or trash baskets.

In two events backwashing and cleaning measures were at least hampered by insufficient backwashing and cleaning capacities, which resulted in debris being partially re-fed to the intake channel. Thus, the screening process became ineffective and forced further plant measures, eventually resulting in plant shutdowns. In addition, the amount of debris being collected in the strainers, trash baskets and outlet channels made additional manual efforts necessary, e. g. emptying trash baskets and skips being transported to landfill.

5.2.1.1.3 Procedures and training

- LL Foul#5: Specific and integral procedures for marine ingress

Licensees should ensure specific procedures for marine ingress are in place and well understood. The procedures should cover all aspects of dealing with marine ingress. These include identifying potential for marine ingress according to forecasting and predictive modelling, preparatory measures to be taken, triggers for assessing the extent of condition, restoring equipment, clear exit conditions, as well as risks to plant operations and respective emergency procedures to apply in those cases in order to provide plant personnel with necessary assistance to cope with such events.

Every selected event identified a need to amend at least parts of its procedures for coping with marine ingress. Although the amendments differ individually, it highlights the need for specific procedures. Especially for external events, such as the marine ingress, which are not common or frequent and may result in plant shutdowns due to potential loss of cooling water the plant personnel should be able to take conservative decisions prior, during and after the event and be familiar with the risks and associated remedial measures.

- LL Foul#6: Procedures for fouling of water intake/biological

Licensees should ensure the availability of suitable procedures for fouling of water intake/biological and well-trained staff for their application. The procedures should cover all aspects of dealing with fouling of water intake/biological specific to the site as well as other system unavailability that might complicate their application.

5.2.1.1.4 Review and management

- LL Foul#7: Importance of management involvement to foster further mitigation of risks

Management should foster the importance of driving the right level of discretionary effort to mitigate risks that have already been accepted at a business level. Station operators have a key role in the identification of station/enterprise risk and need to be integral to the risk review process to challenge mitigation strategies. These should include Operating Experience, analyses and allocation of resources.

5.3 Man-induced Events

5.3.1.1 High-level lessons learned

The related individual lessons learned and corrective actions indicate generic lessons that are provided according to the following categories:

1. Prediction and monitoring: LL Man#1 and Man#2
2. Design and equipment: LL Man#3;
3. Procedures and training: LL Man#4 to #6;
4. Review and management: LL Man#7 to #9.

Table 5.5 Lessons learned for events in the Man-induced events sub-group

Man induced events related Lessons Learned
Man#1: Monitoring, trending and display of service water flow
Man#2: Monitoring, trending and display of the state of protections against external explosions
Man#3: Discharge Service Water piping design may promote silt and sediment blockage in discharge channels/rivers
Man#4: Prioritizing re-energization of transmission lines feeding NPPs
Man#5: Procedures/Programs for dredging activities
Man#6: Procedures and collaboration in case of fire underneath transmission lines in the vicinity of NPPs
Man#7: Safety area assessment and measures along grid transmission lines
Man#8: Safety assessment of the protections against external explosion
Man#9: Review and control of the construction and installation of protection means against external explosions

5.3.1.1.1 Prediction and monitoring

- LL Man#1: Monitoring, trending and display of service water flow

The monitoring, trending and display of service water flow should always be performed and maintained for identification of slow degradation of service water flow. Existing alarms only allow short-term measures, accompanied by unavailability or even loss of (partial) safety functions. Especially river sites indicate degradation by minor trending, while lake- and sea-sites indicate a fast degradation due to weather or biological/marine conditions. Identifying degradation early on can provide licensees with the time and opportunity to assess the situation and take compensatory or remedial measures, e. g. manual sounding and subsequent channel/river dredging activities.

- LL Man#2: Monitoring, trending and display of the state of protections against external explosions

The checks and monitoring of the state of the means (e. g. anchorage, blast shields) designed for the protection of equipment important to safety against external explosion should always be performed and maintained for identification of slow degradation (e. g. by corrosion). Identifying protection means' degradation early on provides licensees with the time and opportunity to assess the situation and take the relevant measures, including defining an adequate basic programme of preventive maintenance for those protections, to ensure their reliability on a long-range.

5.3.1.1.2 Design and equipment related features

- LL Man#3: Discharge Service Water piping design may promote silt and sediment blockage in discharge channels/rivers

Licensees should consider the possibility of service water discharge piping design promoting silt and sediment built up in the discharge channel/river, which in turn may lead to blocking and subsequent low flow of service water discharge. Low flow of service water discharge may impair the associated safety functions, i. e. heat removal from systems and components, or even lead to loss of safety functions in case of full blockage. Locating redundant discharge piping outlets in high flow areas of the discharge channel/river and/or in a given proximity to each other may prevent stagnant flow conditions at the outlets which promote accumulation of silt and sediment. Stagnant flow conditions may result from locations in low flow areas of the discharge channel/river, or single redundancy operation in such a distance the service water system outlet pressure has no effect in displacing silt and sediment in the neighbouring redundancy. Silt and sediment built up may be further exacerbated in times of unusual high discharge channel/river water levels.

5.3.1.1.3 Procedures and training

- LL Man#4: Prioritizing re-energization of transmission lines feeding NPPs

Licensees should analyse and establish an action plan to ensure the availability of the off-site power connection to other power generation sources, e. g. fossil fuel-fired power plant, in line with the related emergency procedures, which is to prioritize the re-energization of NPP power lines after a collapse of the national transmission grid. The operators should be regularly trained on the corresponding emergency procedures.

- LL Man#5: Procedures/Programs for dredging activities

Licensees should ensure specific procedures or programs for dredging activities are in place and well understood. The procedures should cover identifying the need for dredging according to formally established monitoring parameters, e. g. service water flow, and verification and assessing the extent of condition, e. g. by manual sounding, and measures to be taken in order to provide operators with sufficient time to prepare and execute the activities and prevent potential risks to plant operations. Given the circumstances and potential for prolonged time for silt and sediment build up to accumulate in challenging amounts, these procedures and programmes should be considered long term relevant. Procedures and programmes for dredging activities should therefore especially be developed and implemented if the licensee already had to perform dredging activities in the past. In one event the dredging activities had been performed once in 2009 and twice in 2012, thus indicating the potential time difference associated with the need for dredging activities.

- LL Man#6: Procedures and collaboration in case of fire underneath transmission lines in the vicinity of NPPs.

Licensees should consider collaboration with local administration, i. e. entity responsible for firefighting of fires under transmission lines, in the vicinity of their respective NPP. Potential support should include, having corresponding procedures for plant personnel in place. These should be established with regard to clear instructions for personnel to take preparatory safety measures to keep the NPP in a safe condition, e. g. under which circumstance to consider pre-emptive shutdown, as well as in terms of communication, responsibilities and support of local fire-fighting services by plant personnel. Furthermore, safety requirements regarding caution issues involved with extinguishing fire, e. g. by spraying water under the high-tension line should be stated and clearly understood. In addition, collaborative measures should include agreements on availability of equipment, facilities and training as they are part of fire protection measures for firefighting on site.

Fire protection and fire-fighting measures on site are required and well established in NPPs. Procedures to address perturbations of transmission grid lines, as well as partial and total loss of offsite power are also part of plant procedures. In one event, a very large external fire led to a phase ground fault of a transmission line, which was not be explicitly covered in plant procedures. In these cases, it might be considered to establish new or amend existing procedures. In the given event involving high voltage transmission lines, licensees can reduce the risk to plant safety in actively partaking and collaborating with public/local firefighting services in these cases, too.

5.3.1.1.4 Review and management

- LL Man#7: Safety area assessment and measures along grid transmission lines

Regulators, licensees, and transmission grid companies should have professionals assess the safety impact of vegetation, e. g. tree heights, on transmission lines via field evaluation. Thus, relevant safety and technical requirements can be deduced to determine the necessity of location and scope of separation lines for fire prevention below transmission lines, as well as requirements for pruning and pruning frequency. Since licensees are usually not responsible for pruning or cutting trees of grid transmission lines outside the plant site, a collaborative effort and clear-cut responsibilities should be determined to prevent negative impacts on NPPs, e. g. either transmission grid transients or partial/total loss of offsite power by ground faults due to heavy smoke or soot from burning vegetation. This could also reduce the risk of trees hitting transmission grid lines due to high winds, storms, etc. Partial or total loss of transmission grid lines can result in challenges.

Fires under transmission lines may either result from natural causes, e. g. lightning strikes, or man-induced actions. The susceptibility to this fire hazard is especially high in dry regions, dry seasons or during prolonged draughts as they are likely to occur more often due to climate change in certain regions. As fires can occur anywhere along transmission lines outside of NPP plant sites and are available to public access, man-induced fires might not be precluded and fire prevention, as well as fire-fighting measures reside with public services. Nevertheless, regulators, licensees and transmission grid operators should partake in determining necessary requirements and measures. In one event, a hill fire caused by playing children led to ground fault of a phase of the transmission line which resulted in a pre-emptive manual shutdown due to the difficulties involved with fire-fighting and thus uncertain subsequent consequences on the plant safety by further effects on the transmission line.

- LL Man#8: Safety assessment of the protections against external explosion

Protections against external explosions should be assessed between two successive periodic safety reviews as frequently as new data or new methodologies or guidelines are available. This assessment should support the installation of new protections as applicable, if there is evidence that the consequences of the failure of the existing protections, considering the most penalizing scenario specific to the NPP site, cannot be mitigated by existing emergency operating procedures and emergency plans.

- LL Man#9: Review and control of the construction and installation of protection means against external explosions

The protection means against external explosions should be constructed, installed and fitted in the civil engineering according to their design. The plant management should check the construction and installation work so to ensure the reliability of the protection means in a long-range.

5.4 Earthquake

The initial draft list of external hazards included more than 230 reported events. This list was reduced to events, which can have more severe consequences in case of potential earthquakes. To properly reflect all significant events without summarizing each one, they have been divided in the following 4 groups:

- Events in which the non-compliance was due to deficiencies in construction, calculations or even falsification of documents;
- Events in which the non-compliance was due to inadequate consideration of pairs of aggressor/target in case of earthquake;
- Events in which corrosion would induce the non-resistance of the corroded equipment to earthquake;
- Events in which the non-compliance was due to deficiencies in the design that could lead to potential consequences in case of earthquake.

5.4.1.1 High-level lessons learned

The related individual lessons learned and corrective actions indicate generic lessons that are provided according to the following categories:

1. Prediction and monitoring: LL Earth#1 to #3
2. Design and equipment: LL Earth#4;
3. Procedures and training: LL Earth#5;
4. Review and management: LL Earth#6 to #10.

Table 5.6 Lessons learned for events in the Earthquake group

Earthquake related Lessons Learned
Earth#1: Checks and monitoring
Earth#2: Checks and monitoring to develop a method to address the issue of non-compliant pairs of equipment with respect to seismic interaction
Earth#3: Checks and monitoring to optimize a method to address the issue of non-compliant pairs of equipment with respect to seismic interaction
Earth#4: Reliability and seismic qualification of fire extinguishing systems
Earth#5: Communication and training with public emergency services
Earth#6: Handling system structural failures could affect structures, systems and components, which are far-off from the load itself
Earth#7: Potential for structural failures and consequential plant damage for over-head handling systems
Earth#8: Tanks vulnerable to seismic hazards
Earth#9: Review updated seismic data
Earth#10: Need of assessment of safe shutdown states of units that are shut down at the same time

5.4.1.1.1 Prediction and monitoring

- LL Earth#1: Checks and monitoring

In addition to the periodic safety reviews and between two successive ones, checks and monitoring should be carried out, as needed, to detect and address any non-compliance to seismic resistance likely to lead to the loss of the affected equipment or the degradation or the loss of the safety function supported by that equipment. Those checks and monitoring, through walkdowns, inspections and analyses, should help addressing seismic non-compliance issues (e. g. the issue of non-compliant pairs of equipment with respect to seismic interaction), according to relevant national or international guidelines.

- LL Earth#2: Checks and monitoring to develop a method to address the issue of non-compliant pairs of equipment with respect to seismic interaction

Regular checks and monitoring should be used to support the development of a systematic method to address the issue of non-compliant pairs of equipment with respect to seismic interaction. This could be achieved at a first step by drawing-up a list of potential pairs of equipment that could interact as aggressor (non-seismically qualified equipment) and target (vulnerable seismically qualified equipment), and at a second step by identifying the non-compliant pairs with respect to seismic interaction and taking the appropriate measures so the risk of non-compliance with respect to seismic interaction is eliminated or reduced.

- LL Earth#3: Checks and monitoring to optimize a method to address the issue of non-compliant pairs of equipment with respect to seismic interaction

Regular checks and monitoring should be used to support the optimization of a systematic method to address the issue of non-compliant pairs of equipment with respect to seismic interaction and reduce the risk of such interaction.

This could be achieved by:

– Optimizing the current method for checking that certification is maintained over time through (i) selecting a representative number of pairs in each category from the list of pairs of aggressor/target at each NPP; (ii) checking the state of ageing of the equipment included in the sample as it relates to certification that the hazard has been managed; (iii) expanding these checks in the event that an excessive number of anomalies are detected in the sample for a given category.
– Identifying new potential pairs of equipment resulting from physical modifications, by

a. establishing records containing information categorized by issue and assessments required at the design phase;
b. updating the list to reflect any new relevant developments;
c. performing spot checks on the assessments conducted.

– Performing a hazard analysis following any incidental detection of a new pair of equipment and, if the deviation is substantiated, announcing a safety significant event or a safety relevant event and providing a resolution plan according to existing national or international guidelines for addressing conformity deviations.

5.4.1.1.2 Design and equipment related features

- LL Earth#4: Reliability and seismic qualification of fire extinguishing systems

Licensees should assess whether fire-extinguishing systems need to be improved in terms of seismic resistance. Comprehensive measures include assessing and improving the anti-seismic strength and structure of piping and water tanks according to nuclear and/or other industry standards, e. g. standards for oil and gas as well as identifying pipe joints, which should be modified to cope with ground deformation, e. g. flexible pipe joints. Further improvements should consider diversity and redundancy depending on the individual situation at each facility. These should improve reliability of fire extinguishing systems with regard to pipe breaks due to ground motion.

5.4.1.1.3 Procedures and training

- LL Earth#5: Communication and training with public emergency services

Licensees should consider assessing the reliability of facilities essential to firefighting activities and conduct regular training with public services to identify areas of improvement. These may comprise installations on site for communication, such as verifying seismic resistant or unaffected, communication lines (e. g. satellite phone) and buildings, which house facilities essential to firefighting, (e. g. fire station buildings or emergency response centres). These should further be assessed by conducting regular collaborative training with public fire-fighting services to improve procedures and firefighting plans, especially with regard to facilities with high risk of fire.

5.4.1.1.4 Review and management

- LL Earth#6: Handling system structural failures could affect structures, systems and components, which are far-off from the load itself

This LL considers less frequent activities (e. g. load handling for refurbishment etc.) and the effects potential load drops on structural systems, if the handling is performed during seismic activities, which are not considered during load handling.

Licensees should enhance the qualification against earthquake induced loads of handling systems, especially for activities of less frequent heavy loads movement for maintenance and refurbishment that have not been considered in the scope of the heavy load handling program, to manage an increase in risk associated with the maintenance activities or evaluate the effects of structural failures on equipment beyond the immediate vicinity of the load. These maintenance activities can involve the use of permanently installed cranes which have not been evaluated for use under all plant conditions or temporary overhead equipment. Handling system structural failures could affect structures, systems and components well away from the load itself because the overhead handling systems span long distances. Although load drop analyses typically evaluate the effect on structures, systems and components immediately below the load path, in one case the potential damage to piping systems below the overhead crane bridge was not considered in the completed load drop analysis, because the piping was not under the load. On another occasion, a temporary handling system collapse damaged fire protection equipment outside the footprint of the handling system structure in a similar way as seismic vibrations would act.

- LL Earth#7: Potential for structural failures and consequential plant damage for overhead handling systems

The second LL on load handling systems refers to the structural damage of handling systems themselves which have not been qualified for use during seismic activity.

Licensees should consider the potential for structural failures and consequential plant damage when assessing measures to manage the risk of heavy load movements using temporary overhead handling systems or permanent handling systems not previously evaluated for use under all plant conditions, e. g. during seismic events, for maintenance related activities. Material handling activities evaluated with the scope of licensee heavy load handling programs include consideration of the overhead handling system design, testing and maintenance thus providing assurance that the structure of the handling system is robust. Consequently, traditional load drop analyses only postulate failures in the hoisting machinery and rigging, limiting potential effects to equipment near the load. Temporary overhead handling systems or permanent handling systems not previously evaluated for use under all plant operating modes might not provide assurance for the structural integrity of the system.

- LL Earth#8: Tanks vulnerable to seismic hazards

Licensees should verify that safety related tanks and non-safety related tanks, the latter which might impact safety related equipment nearby in case of collapse or fall during seismic events, are adequately seismically qualified and are procedurally controlled to ensure that seismic vulnerabilities are appropriately managed. Seismic analyses of tanks should consider different tank levels, independent of their regular operational state (i. e. being full or empty). Procedural requirements should ensure system alignments connecting non-seismically qualified piping to seismically qualified and safety related tanks, e. g. Refuelling Water Storage Tank, or connecting seismically qualified and safety related piping to non-seismically qualified tanks are adequately addressed and necessary measures to ensure safety functions are in place.

- LL Earth#9: Review updated seismic data

New seismic hazard information should be routinely evaluated as it becomes available. This may include new seismic data, such as updated seismic sources and ground motion models from the nuclear industry as well as entities in the field of geological survey. Assessment should be carried out to identify whether these data affect the seismic response of existing plants at the design-basis level or beyond. New data could indicate increased likelihood of exceeding the safe shutdown earthquake. Further evaluation in conjunction with plant specific data may be used to update Seismic Core Damage Frequency of existing plants to identify the need for further assessment, e. g. backfits, to further reduce seismic risk. In addition, periodic safety reviews are key opportunities to re-examine all the safety hypotheses and issues, in particular, those relevant to seismic hazard, taking into account new information and new methodologies in a systematic way.

- LL Ear#10: Need of assessment of safe shutdown states of units that are shut down at the same time

In the cases where several units need to be shut down at the same time, the safest plant operating state for shutdown of these units should be defined on the basis of deterministic and probabilistic risk assessments.

5.5 Flooding

The subsection on flooding considers the generic lessons learned from the 2018 TOER by JRC on flooding /2/. Relevant events from the current study support these lessons, while other events from the current study require new high-level lessons learned. Nevertheless, the lessons learned from the former study remain valid.

5.5.1.1 High-level lessons learned

The related individual lessons learned and corrective actions indicate generic lessons that are provided according to the following categories:

1. Prediction and monitoring: no LL
2. Design and equipment: no LL;
3. Procedures and training: no LL;
4. Review and management: LL Flo#1 and Flo#2.

Table 5.7 Lessons learned for events in the Flooding group

Flooding related Lessons Learned
Flo#1: Regular assessment of existing data
Flo#2: Impact of external events on NPP surroundings indirectly affecting safety

5.5.1.1.1 Review and management

- LL Flo#1: Regular assessment of existing data

Licensees and regulators should regularly assess existing data and failure rates and check for new data on safety assessment. They assess the updated data according to site specific relevance. Using non-conservative screening values for dam failure frequency to evaluate the need for additional detailed analyses could result in under-estimating the risks to NPPs associated with external flooding or loss of heat sink from failure of upstream and downstream dams or levees. Thus, regular updated data and eventually safety assessment models ensure risk assessments are still valid or identify needs for amendments.

- LL Flo#2: Impact of external events on NPP surroundings indirectly affecting safety

Licensees and regulators should be aware and assess the impact flooding, e. g. heavy rainfall, dam failures, dam/water reservoir management, can have on townships and access roads in the rural environment, even if the NPP itself is not directly affected. Assessments should take into account the potential flooding of townships, which house plant staff and/or offsite emergency facilities as well as impairments of access routes to NPPs. Adequate measures should be taken to prevent an impact on plant safety by impediment of plant personnel and NPP supply access routes or the availability of offsite emergency facilities.

The necessary release of water from a dam/water reservoir, due to a week of unprecedented heavy rainfall led to overflowing of low lying areas of a township downstream inundating access roads to offsite emergency facilities located in the township, as well as some parts of access roads between the township and the NPP.

5.6 Chemical

5.6.1.1 High-level lessons learned

The related individual lessons learned and corrective actions indicate generic lessons that are provided according to the following categories:

1. Prediction and monitoring: LL Che#1
2. Design and equipment: no LL;
3. Procedures and training: no LL;
4. Review and management: no LL.

Table 5.8 Lessons learned for events in the Chemical group

Chemical related Lessons Learned
Che#1: In-time detection of corrosion

5.6.1.1.1 Prediction and monitoring

- LL Che#1: In-time detection of corrosion

Corrosion should be detected in-time and its kinetics studied in order to optimize the maintenance of the affected equipment and prevent that its failure leads to severe consequences (e. g. flooding, unavailability of equipment important to safety).

5.7 Lightning Strike

Nine events have been described in the last ten years concerning lightning strikes, the NPPs reacted after these off-site lightning strikes as designed, such no specific respective actions have been taken after these events. Therefore, no high-level lessons learned could be derived.

5.8 External fire

Only two events concerning external fires have been reported. No related generic lessons learned could be derived. One event containing an external fire was described in the subsection related to man-induced events. The lessons learned can be found in that subsection.

6 Conclusion

The aim of this study is to draw generic lessons from operating experiences in different countries with various types of NPPs regarding the topic “External Hazards”. The study updated the experiences described in two former studies and could thus update the generic lessons learned.

The first step of the study was the identification of related events in the respective national and international event databases for NPPs. The second step was focused on the in-depth analysis of the 166 events selected. The events are categorized in different groups and sub-groups as well as in various task and cause categories.

The results are shown in tables and charts. The comparison with the former study on external hazards has to consider that earthquake events were not covered in the first report and flooding events were only analysed after 2016 and therefore, figures reflect only rough trends. In this report, the groups “extreme weather conditions” (36 %), “fouling/biological” (20 %) and “man-induced events” (13 %) represented nearly 70 % of all selected events. The first two groups had already been the most populated in the first report. The third one had been the group on “lightning strikes” with 14 % that contributed only 5 % in the present study.

Similar analyses have been performed for the relative distribution of the selected events by mode of event detection, the relative distribution of the safety relevance, and the relative distribution of the systems affected. Electrical systems (28 % of the events), essential service systems (including component cooling water, essential service water, essential compressed air and refuelling water storage) (15 %) and feedwater, steam and power conversion systems (13 %) were affected the most often.

The most important part of the in-depth analysis is the derivation of high-level lessons learned. These are derived from the most important events in the respective groups. In total 44 high-level lessons learned have been derived from the selected events. Four groups/sub-groups represent the majority (34 out of 44) of the high-level- lessons learned:

- Man-induced events with nine lessons learned,
- Earthquake events with nine lessons learned,
- High/low temperature events with eight lessons learned, and

- Fouling events with seven lessons learned.

The results of this task on external hazards were also used to assess whether climate change influenced the safety of nuclear power plants. The events evaluated in the two “External Hazard” studies cover events having occurred in the last 30 years. There are a few events that might be addressed to the “extreme (weather) events” like the long-term drought in France, in 2003. The increase of climate change impact could be detected through the evolution of the occurrence frequency of the natural external hazards. However, the nuclear power plant’s operational response to these hazards is also related to the countermeasures installed. These countermeasures were developed over time, in particular due to the national and European Stress Tests after the Fukushima Daiichi accident. Thus, the resilience of the NPPs against external hazards has significantly been improved in the last decades based on operating experiences. In this task, no significant impact of climate change could be determined on the frequency and nature of the selected events. But this is not an evidence that there has been no climate change impact on natural external hazards.

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List of Abbreviations

AC	Alternative Current
CCDF	Conditional Core Damage Frequency
COP21	United Nations Framework Convention on Climate Change, 21st Conference of the Parties, Paris 2015
GRS	Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) gGmbH
EU	European Union
IAEA	International Atomic Energy Agency
IRS	International Reporting System for operating experiences
IRSN	Institut de Radioprotection et de Sûreté Nucléaire
JRC	Joint Research Centre
LL	Lesson learned
NEA	Nuclear Energy Agency
NL	Netherlands
No.	Number
NPP	Nuclear Power Plant
OECD	Organisation for Economic Co-operation and Development
SSR	Specific Safety Requirement
SÚRO	Statní Ústav Radiační Ochrany
TSO	Technical Safety Organisation
US	United States (of America)

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