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# Operating experience with hydrological external hazards and their potential safety significance

**Keywords**

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**Abstract**

The nuclear accidents of Fukushima in March 2011 have indicated the significance of external hazards for nuclear installations safety. One lesson learned from post-Fukushima investigations worldwide is that the operating experience from external hazards, even if these did not pose any significant harm to the affected plant, do represent important precursors, which should be taken into account in deterministic as well as probabilistic safety assessment.
This paper provides an overview on the significance of events or event combinations involving hydrological external hazards. Some more recent examples of events from hydrological external hazards and their potential safety significance for nuclear power plants are discussed.

## 1. Introduction

The nuclear accidents at the Fukushima Dai-ichi nuclear power plants (NPPs) in March 2011 have demonstrated the significance of external hazards, such as seismic and hydrological ones, for nuclear installations safety. Investigations carried out after these accidents have indicated that external hazards do non-negligibly contribute to the overall risk for any nuclear site.

One specific lesson learned from post-Fukushima investigations is that the operating experience with respect to external hazards, even if these did not pose any significant harm to the plant where such hazard(s) occurred, do represent important precursors, which should be taken into account in deterministic as well as probabilistic safety assessment.

The more recent operating experience from NPPs involving hydrological external events, either as initial event or as consequential one to another external hazard, or occurring independently, but simultaneously to another hazard has been investigated.

In the following some generic aspects with respect to the potential safety significance of hydrological external hazards for NPP sites are presented followed by some examples of more recent events or event combinations involving hydrological external hazards.

## 2. Safety significance of hydrological external hazards for nuclear power plant sites

Worldwide operating experience from nuclear power plants (NPPs) provides increasing evidence that it is of fundamental importance to pay attention to impacts from hydrological hazards occurring outside or inside the plant boundary. Operating experience has also demonstrated that these hazards may create combinations of impacts which consequently constitute a major threat for the safe operation of NPPs. Moreover, special consideration needs to be given to the potential relevance of hydrological external hazards for the latent risk that these events particularly represent, if after event occurrence consequential damages occur due to deteriorating conditions, e.g. as in case of the Fukushima NPP site in 2011.

The hydrological events and event combinations provided and discussed below indicate the need for considering possible combinations of natural external hazards with other anticipated events including hazards with potential effects on safety related structures, systems and components (SSCs) within the safety assessment, in particular probabilistic analyses. A typical example to be analysed in more detail is a fire induced by a short circuit as a result of water ingress into electric equipment.

The events observed more recently clearly demonstrate the importance of re-evaluating risks from often neglected support and peripheral systems, particularly with respect to issues related to infrastructure and surrounding environment. These events also indicate some specific weaknesses in the plant design and/or deficiencies in plant operational and maintenance practice.

It has been also observed that the design should adequately address hydrological external hazards, e.g. with regard to systematic failures of passive systems (e.g., by considering permanent protection devices, water dams, drainage systems as relevant to safety). Such protective means are typically not classified as safety system and therefore designed only according to conventional non-nuclear regulations and common industrial standards. These systems should also be treated similar to safety related SSCs and undergo regular functional tests and become part of the periodic in-service maintenance and inspection program.

Moreover, it can be concluded, that even events with more extensive flooding of the reactor premises were likely and might have induced transients, which in turn means an aggravation of the risk of core or duel damage. These scenarios should be considered in PSA as additional risk contributors.

More recently occurred hydrological external hazards often represent complex scenarios. These are hard to map to PSA models due to their inherent simplifications, which in turn are often based on deterministic design assumptions. It has been recognized that the evaluation of the operating experience can contribute to the enhancement of probabilistic assessment methods including the existing PSA models by providing important insights regarding the safety significance of hydrological external hazards.

Finally, it has been demonstrated that it can be rather difficult to predict the impact of the entire environmental factors.

## 3. Operating experience from nuclear power plants with hydrological external hazards

### 3.1. Rainwater induced flooding

In 2016, a precipitation (rain) induced flooding event occurred at a Japanese multi-unit nuclear power plant site with two BWR (Boiling Water Reactor) units [6]. Following the nuclear accidents at the Fukushima Dai-ichi site in Japan in March 2011, more strict safety standards regarding measures to prevent flooding of reactor buildings came into effect in Japan. These standards include requirements for the construction of protection walls against Tsunamis and the installation of watertight doors. In order to implement the instructions of the Government, a reinforced concrete wall (4 m high, 700 m long, 11 m above sea level) against Tsunami was built on the plant site. Next to this wall, a new drainage gate was installed in order to minimize impairment of plant facilities in case of seawater rising beyond the protection wall and flooding the plant site. Other measures included the installation of an additional pump for reactor cooling by seawater and an additional power source for operating a valve for venting steam out of the reactors.

However, little attention was paid to flooding through penetrations of the plant's piping system and cable ducts. Moreover, since there are no nearby rivers, flood control measures for river floods were not of high priority for the plant. Also, penetrations for pipes and cable ducts routed to the reactor building were not required to be watertight.

At the time of the event, the plant was under shutdown. For road construction work, a drainage ditch next to the reactor building was partially covered. The heavy rainfall caused flooding of the road, with water entering cable ducts leading to the reactor building, because a lid had been partially opened to allow the temporary routing of a cable. It is assumed that the rainwater reached the floor above a room on the first basement floor of the reactor building where batteries for emergency use in case of loss of offsite power (e.g. caused by an earthquake) are installed. Power sources for emergency lighting shorted. Some of the rainwater having reached the first basement floor leaked through cracks in the floor and penetrated down to the second basement floor.

It was reported that approximately 6.6 t of rainwater entered the reactor building of the second plant unit. It was not expected that such a volume of rain could flood the building. Therefore, such a flooding hazard was not considered in the plant safety concept. Thus, even more extensive flooding of the reactor building could have happened, especially in case of a higher amount of rainfall in the vicinity of the plant. Consequently, losing safety functions as well as the simultaneous triggering of initiating events were likely due to the impact of such events. These scenarios should be considered within PSA as additional risk contributors.

### 3.2. Rainwater ingress into reactor and turbine building due to heavy rainfall

In September 2011 in the area around a single unit German NPP with a BWR reactor built to earlier standards, a thunderstorm with heavy rainfall occurred. The site is located on the estuary of a river. At the time of the event the NPP was under permanent post-commercial safe shutdown.

The thunderstorm lasted for approximately 6 h. The instrumentation at the site indicated a rainfall amount of 487 l per second and ha occurring within 5 min (i.e. 15 mm in 5 min). The rainfall within 10 min was 387 l per second and ha (i.e. 23 mm in 10 min). The high rainwater quantity led to an overload of pipe connectors at the downpipe bends of the roof drainage system [3]. These downpipes run partly inside the reactor and turbine building. Approximately 20 min after the onset of precipitation, water ingress into the reactor building sump was signalled in the main control room.

Inspections revealed the downpipe leakage of the reactor building roof drainage and leakages in the turbine building. A part of the rain water drainage system has a barrier function between the interior of the reactor building or the turbine building (controlled area) and the surrounding area. Due to the leakage in the rainwater conduits, the barrier integrity was impaired.

Rainwater ingress into the sumps of the reactor and the turbine buildings reached a total volume of approximately 100 m³. In addition to the leak from the drainage system rainwater also entered the reactor and turbine building via railway gates. In the non-nuclear area minimal water ingress into a storage facility was observed. Furthermore, the high precipitation during a short time period led to water accumulations at the NPP site with scouring at four construction sites.

The rainwater drainage system is not classified as safety system and is not subject to special leak tightness and material fatigue tests. The rainwater drainage was designed according to German non-nuclear industrial standards [1]. According to the current standard, the design is based on the local 5 min rainwater quantity statistically occurring every five years. For the region of the plant site affected, this is a rainwater quantity of 295 l/(s*ha). The statistical 10 min rainfall event which may occur once in a hundred years is 379 l/(s*ha) for the plant region. These values were exceeded during this heavy precipitation event.

In the event, the total water ingress of 100 m³ into the reactor and turbine buildings had no effects on safety relevant components. Even under the conservative assumption that the whole rainwater of a 6 h precipitation penetrates the buildings (147.4 m³ into the reactor building, 305.6 m³ into the turbine building), the total amount of water would still remain below the design basis for internal flooding events.

Nevertheless, the event showed that failure of the rainwater drainage systems could lead to a degradation of the barrier function of buildings and the subsequent flooding might impair safety functions. Hence - depending on the specific design - rainwater drainage systems maybe safety significant and should be classified accordingly. This also implies that they should be subjected to the periodic maintenance and inspection program, particularly with respect to leak tightness. They should be designed such that rainwater cannot endanger safety relevant plant parts and dispersion of radioactive substances can be practically excluded. This should also be ensured if the rainwater drainage system capacity is exceeded due to heavy rainfall events.

The potential impact of such events, particularly in case of precipitation amounts higher than anticipated, should be considered within PSA as an additional risk contributor.

### 3.3. Reactor scram and containment isolation caused by seawater leakage into the reactor building

In January 2015, a severe weather event with safety related consequences occurred at a coastal multi-unit NPP site with four reactor units, one BWR and three PWR (*p*ressurized *w*ater *r*eactors), located on the west coast of Sweden [4]. The hazard started with a storm with a peak wind speed of 38 m/s which together with heavy rainfall caused high seawater levels up to 140 cm above normal.

The event reported to the regulatory authority occurred at the BWR unit, where the lower levels of the reactor building and the surrounding bedrock are separated by a so-called bedrock gap of approximately 0.8 m width and 15 m depth. The drainage from underneath the turbine building is also routed to the bedrock gap. Water collected in the bedrock gap is drained by a drainage system consisting of two drain lines (diameter of 100 mm and with strainers placed in the drain lines at the bedrock gap floor) drilled in the bedrock to a lower level tunnel excavated in the bedrock about 11 m beneath the bedrock gap floor. Two submersible pumps automatically evacuate water from this bedrock tunnel either to the seawater outlet system or optionally to the liquid waste system. These rather conventional structures are not classified as safety systems.

An additional feature of the affected BWR is a safety hatch (approximately 50 cm x 50 cm) on an outer wall of reactor building, about 1.5 m above ground level of the reactor building. The hatch is installed in a room without any safety related equipment; however, it is not strictly separated from an adjacent room containing piping and equipment connected to the primary system, in particular I&C (instrumentation and control) equipment for actuation of scrams and containment isolation in case of pipe ruptures and leakages from the primary system. The hatch is designed to open in the event of internal flooding of the reactor building. The water will then be drained through the hatch to the bedrock gap and from there down the drain lines into the tunnel.

During the above mentioned severe weather event, water seeped from the sea through the bedrock to the drainage system surrounding the reactor building. However, since the strainers in the two drain lines from the bedrock gap to the bedrock tunnel were clogged by sediments, the water level in the bedrock gap outside the reactor building rose continuously up to 2.5 m. As water level transmitters were only installed in the bedrock tunnel (not in the bedrock gap) and only small amounts of water penetrated to the bedrock tunnel due to the clogged strainers, the accumulation of water went undetected (i.e. no high water level was detected). After several hours, the safety hatch in the outer wall of reactor building opened inadvertently and the water flew opposite to the intended flow direction into the reactor building and subsequently through the building sump into the room containing systems connected to the primary system. The water caused floor level transmitters in this room to actuate automatic reactor scram and containment isolation. The water level in the rooms of the reactor building floor reached approximately 0.3 m.

Reactor scram and containment isolation are routine transients considered in PSA. The event however demonstrates the importance of re-evaluating risks from often neglected support and peripheral systems, particularly with respect to issues related to infrastructure and surrounding environment. Moreover, systems, such as this drainage system, should undergo regular functional tests and should become part of the periodic maintenance and inspection program.

Even more extensive flooding of the reactor building was possible in this event and loss of safety functions might have occurred in the course of the transient. These scenarios should be considered within PSA as an additional risk contributors.

## 3.4. Ingress of plant debris into raw water pumping station

In February and March 2009 adverse cooling water conditions led to a series of pump trips of the circulating water system at a French NPP site [2]. These trips were caused by fouling of the drum screens due to massive ingress of biological debris (plants, decomposing leaves, etc.) and sediments from the river. The site is a multi-unit NPP with two twin-unit pressurized water reactors (PWR) situated on a river estuary. The four 900 $MW_e$ PWRs are cooled via an open circuit cooling system using the river as heatsink.

For each twin-unit PWR, the raw water supply system consists of a water intake structure (located on the bed of the river), two water intake ducts (one per unit) and four intake ponds serving as surge tanks to store surplus water in the event of a circulating water pump trip on the associated train. Each twin-unit PWR has a raw water pumping station that comprises the drum screens, the circulating water system (CWS) pumps and the essential service water system (ESW) pumps. The ESW serves to cool the component cooling system (CCS) which in turn provides cooling for components and systems (including those with safety functions).

The above mentioned pump trips of the CWS pumps were initiated by “high drum screen head loss” signals. In three cases, these trips also caused reactor scrams. Once a “high drum screen head loss” threshold is reached, the associated CWS pump is tripped. Loss of two CWS pumps in any one unit leads to loss of its condenser, turbine trip and reactor scram.

All incidents were caused by severe drum screen - clogging due to massive accumulation of plant debris and river sediment on the screens. Larger quantities of plant debris and sediment in the estuary are not unusual in February and March. However during this period in 2009, a combination of several events taking place over the same period led to a situation which could not be averted with existing operating procedures. The events leading to this situation were as follows: (i) floods at two tributaries upstream of the site at the end of January 2009 that displaced sediment which had accumulated since a previous flood event in 2004, (ii) a heavy storm and high tide with a height of 6.50 m (normal level: 6.00 m) in February 2009 that inundated the river banks and caused substantial resuspension of biological debris and sediments taking more vegetation than usual to the NPP pumping station, (iii) no dredging performed around the water intakes of the NPPs on the river.

The reactor trip sequences took place correctly. However, the severe drum screen clogging that led to the reactor trips could also have induced a total loss of heat sink. This would have caused an aggravation of core melt risk in one or more of the units at the NPP site.

The event shows, that it is necessary to consider possible combinations of natural phenomena/hazards in PSA together with potential effects on the safety systems of nuclear facilities. Again it is demonstrated how difficult it is to predict the impact of the entire spectrum of environmental factors. Moreover, it indicates the need to pursue this matter with careful attention.

### 3.5. External flooding and independent fire

In 2011 a combination of a long-duration external flooding and an independent fire was observed in a U.S. nuclear power plant at the Missouri river.

The 2011 flood on the Missouri river was one of the largest floods since the river became regulated by a series of large dams in the mid-20th century. The flood persisted through most of the summer and reached its maximum in mid-June 2011. The flooding was triggered by the melting of a record snowfall (212 % of the normal snowpack) in the Rocky Mountains of Montana and Wyoming along with extreme spring rainfall in Montana (in the second half of May 2011, almost the average annual rain fell over the upper Missouri River basin). All six major dams along the Missouri River released record amounts of water to prevent overflow causing flood threatening to downstream river sites. Two NPP sites in Nebraska were affected by these floods:

- NPP Fort Calhoun, a single block PWR, 484 $MW_e$, commissioned in 1973, and
- NPP Cooper, a single block BWR, 810 $MW_e$, commissioned in 1974.

Consequently, additional flood prevention measures were taken at the Fort Calhoun and Cooper NPPs. Cooper NPP remained under precaution in full power operation throughout the flooding event. Fort Calhoun NPP was in safe shutdown since April 9, 2011 when it entered a scheduled refuelling outage. According to press reports, Fort Calhoun NPP (Figure 1) declared a 'notification of an unusual event' (the least-serious of four emergency classifications for U.S. NPPs) due to some onsite flooding and the rising level of the Missouri River which was expected to reach 1004 ft (306 m) above sea level and to remain above that level for more than one month.

On June 7, 2011 an electrical component in a switchgear room caused a small fire which was automatically extinguished and no longer burning when the on-site fire brigade arrived.

*Figure 1*. Fort Calhoun NPP site during the Missouri flood in 2011.

According to a NRC statement, the plant temporarily lost its normal ability to cool the spent fuel pool (SFP). However, SFP temperatures remained within safe levels and SFP cooling was recovered without activation of any of the plant's multiple back-up systems.

The fire started in a replacement electrical breaker that had been modified to fit inside the existing electrical switchgear. The switchgear distributes power to vital systems and components needed for the safe shutdown of the plant. The fire affected two independent trains of the safety system [5].

As causes for the event poor alignment between electrical components and inadequate cleaning of the connections (hardened grease at the interface) have been identified, increasing the electrical resistance at the junction. These conditions resulted in a build-up of heat that caused a fire affecting one train. Electrically conductive soot and smoke spread past a barrier and tripped the breaker on the adjacent train. This electrical fault resulted in the above explained loss of spent fuel pool cooling.

Fort Calhoun was designed for floods up to 1014 ft (309 m) above sea level. Berms and temporary AquaDams had been installed around Fort Calhoun's main plant buildings as well as the electrical switchyard and administration area.

On June 26, 2011 one part of an AquaDam suffered a puncture (attributed to work at the plant site) allowing water to enter and to surround some of the plant buildings as well as the unit transformers. This prompted the staff to disconnect the plant from the offsite grid and to establish the energy supply of the plant safety systems from on-site diesel power by means of the diesel generators. This status remained until all the equipment checks confirmed that it was safe to terminate diesel power operation and to re-connect to the offsite grid. The NRC confirmed that cooling of safety relevant equipment was not impaired and that no water had entered the reactor building. Then, during the following weeks, the plant remained in safe shutdown throughout the event.

After the event the NRC inspection report concluded, that the protection strategy in the plant operating procedures would be insufficient to protect relevant plant facilities against an external flood of 1014 ft above sea level (design basis), which is an apparent violation of NRC requirements to be considered for enforcement action according to NRC Enforcement Policy.

An analysis has been performed to calculate the change in core damage frequency (CDF) for each postulated fire at a breaker. The total change in the CDF per reactor year (ry) was estimated to be 2.7 E-05 /ry (best estimate) and 8.1 E-05 /ry (conservative assessment) for the fire induced risk of single or multiple individual fire scenarios respectively caused by performance deficiencies representative for the risk from common cause failures of the breaker cabinets [5].

This hazard combination shows the need to be aware of the possibility of a fire and an independently occurring event. In case of external flooding, accessibility of the plant is necessary even under such extreme circumstances to ensure that technical support from outside, in this case by the local fire department, can be provided. Therefore the consequences of such hazard combinations (internal and external) should be assessed within PSA.

## 3.6. Rainwater induced events with consequential hazards

In the operating experience collected within the international OECD FIRE Database [5], one event of extreme weather with heavy rainfall conditions was observed. The rainfall event (hydrological hazard) caused a high energy arcing fault (HEAF) and consequential fire (both internal hazards). Even if this event sequence with more than one consequential event represents only a negligible contribution to the total number of event combinations collected in the FIRE Database and investigated in [5], some lessons could be learned from this combination.

The event sequence was as follows: (i) Rain water penetrated through the gap of a cable duct located outside of the turbine building. The rain water intrusion seems to be caused by a typhoon; however any heavy rainfall might have caused the water ingress. (ii) The water caused a short circuit with a longer duration arc resulting in a HEAF event of a 6.9 kV bus leading (iii) to a fire in a room for electric equipment. The fire was observed at the upper part of a 6.9 kV switchgear cabinet. The room was filled with smoke.

As corrective actions, fire-proof seals and drain functions were installed at the cable duct. Moreover, cables with fire retardant insulation materials will be used to prevent ignition.

It is known that other events resulting from rain water intruding through building ceilings have occurred in NPPs of other member countries. These events have not caused fires, but they might have had the potential to lead to the same or similar combinations of events. However, these events were a trigger to take such unlikely situations into consideration and resulted in some preventive actions taken in all NPP of the countries to avoid this type of event in the future.

In at least one of these not reported events rain water coming from the turbine building ceiling also affected the 6.9 kV bus of a nuclear power plant (but no fire was induced due to a prompt actuation). Corrective actions consisted of repairing the ceiling and, in addition, of installing a kind of roof for covering the 6.9 kV bus. This type of cover was extended to other important electrical equipment that could be potentially affected by this type of failure.

## 4. Conclusions

The operating experience from NPP sites worldwide (NPPs) has provided increasing evidence that attention needs to be paid to impacts from hydrological hazards occurring outside or inside the plant boundary. Moreover, the experience has demonstrated that these hazards may result in event combinations, which consequently may constitute a major threat for the safe operation of NPPs.

A majority of the events from hydrological external hazards reported so far did finally not impair the plant safety. However, since at least heavy rainfall precipitation as one of the initiators of hydrological hazards are more likely to occur in continental Europe due to global warming, such non-safety significant precursor events observed more recently should be systematically addressed in the safety assessment of nuclear sites.

In particular, the potential impact of hazards likely exceeding the anticipated precipitation amounts should site and plant specifically be considered in probabilistic risk assessment as an additional risk contributor.

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