Challenges To Develop and Draw Relevant Lessons From A Level 1 Internal Flooding PSA

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Abstract: In the framework of the 4th Periodic Safety Review (PSR) of the 1,300 MWe French Pressurized Water Reactor (PWR) series, in the streamline with previous PSR, Electricity of France (EDF) has developed a large span of Probabilistic Safety Analysis (PSAs) that cover Internal initiating Events (IE), but also internal hazards (fire, flooding, explosion) and external hazards (seismic, flooding, heat wave and high winds). To support its review of the EDF PSA, IRSN (as Technical Support Organization (TSO) of the French Nuclear Safety Authority (ASN)) has also developed in-house internal initiating events and limited scope hazard PSA. When performing hazard PSA, attention must be paid on the hazard characterization (magnitude/frequency), identification of the most important scenarios and assessment of the hazard impact on the plant and on the conditions to perform emergency human actions to mitigate the accident. Generally, the PSA assumptions are best estimate and may be different from the deterministic study conservative assumptions. As hazard PSAs cover many complex scenarios, it is a challenge to develop a complete set of representative supporting studies and to evaluate all hazard impacts on the plant and the human factors. In addition, the hazard characterization is challenging because representative data and operating experience are rare. Therefore, the interpretation of hazard PSA results, risk ranking, and safety insights must rely on an acute analysis of the PSA limits.
This paper focuses on the recent lessons learned from the Level 1 internal flooding PSA developed or reviewed by IRSN.

Keywords: PSA, Internal Flooding, Walkdowns, Periodic Safety Review.

1. INTRODUCTION

As requested by the French Nuclear Safety Authority (ASN), Electricity of France (EDF) continued Probabilistic Safety Analysis (PSA) developments by addressing progressively the risks associated with hazards of internal or external origins, for both the reactor and the spent fuel pool of its nuclear power plant fleet. For the 4th Periodic Safety Review (PSR) of 1,300 MWe Pressurized Water Reactor (PWR) series, EDF developed the following hazard PSA: level 1 and 2 internal fire PSA, level 1 and 2 internal flooding PSA, level 1 internal explosion PSA, level 1 and 2 seismic PSA, level 1 external flooding PSA, level 1 high temperatures PSA and level 1 high winds PSA.

The Institute of Radioprotection and Nuclear Safety (IRSN), as Technical Support Organization (TSO) of ASN, also developed independent internal initiating events PSAs and limited scope hazard PSA, in order to facilitate the review of the EDF PSA. These PSAs are also applied for daily safety analysis. In general, the hazard PSA are developed by EDF and IRSN based on internationally recognized methods (International Agency of Atomic Energy (IAEA), Electric Power Research Institute (EPRI), etc.) but some approaches, methods and assumptions can differ.

In the framework of the 4th PSR of the 1,300 MWe PWR series, EDF also enhanced the hazard deterministic studies (application of the single failure criteria, sensitivity studies on important assumptions…). These studies were also reviewed by IRSN. Many insights gained from these deterministic and PSA studies were discussed during the PSR.

The following paragraphs present some lessons learned by IRSN from internal flooding PSA activities (PSA development by IRSN or review of EDF studies).

2. IRSN APPROACH FOR INTERNAL FLOODING PSA

A PSA, through its systematic analysis, is not intended to cover the same accident scenarios as deterministic studies but to complete them. To develop flooding PSA accident scenarios, IRSN considers the following items:

- flood initiator: frequency of occurrence of an internal flood whose source is located in the room XY,
- probability of failure of the isolation action,
- probability that the doors of the room XY are initially open,
- probability of failure of a sealed penetration in room XY (or neighboring) under water load (15 cm),
- probability of leak from a sealed penetration on the floor of room XY (or neighboring) under water load (10 cm).

The Figure 1 represents this modelling with an event tree. To properly consider the water propagation between rooms, the sequences are linked to the event trees of the neighboring rooms (horizontal or vertical propagation).

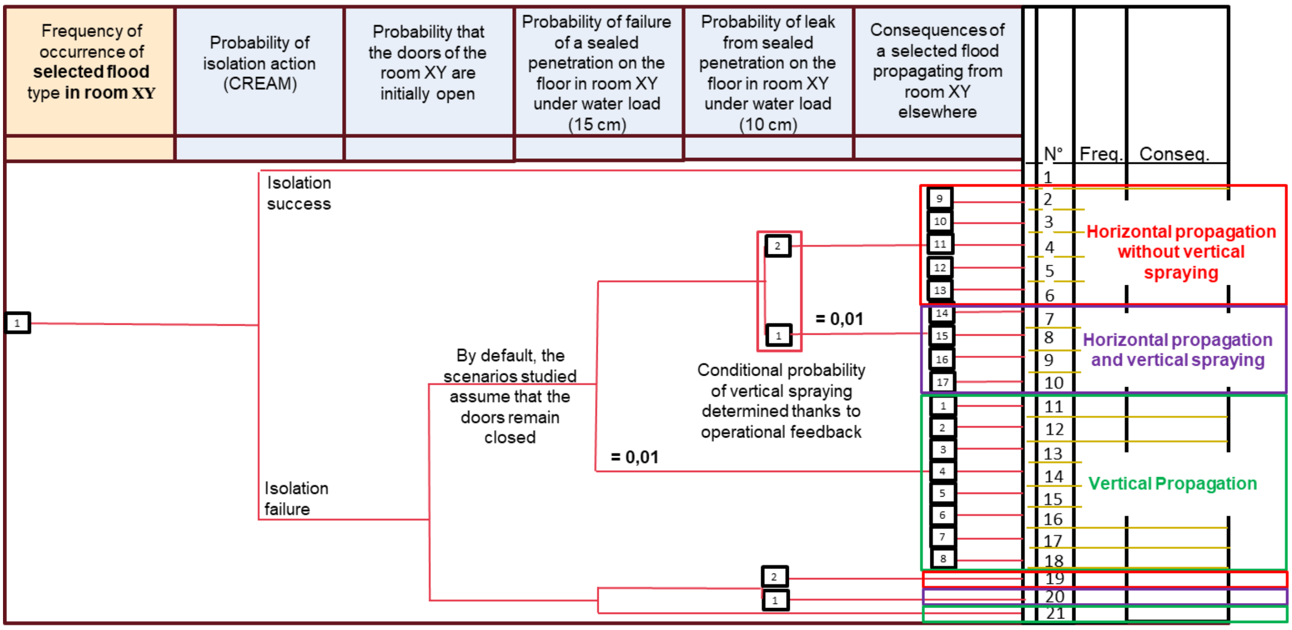

Figure 1. Modelling of the IRSN IF-PSA Event Tree for a Flood Initiated in Room XY and Propagated

The PSA modelling also distinguishes the flooding sources which are initially filled with water or air: this concerns the firefighting circuits which are either empty or filled with water depending on their location in the plant or depending on the plant operating state. More generally, the PSA modelling addresses the specific configurations of the plant in low-power or shutdown states.

A particular attention is paid by IRSN to:

- the scoping, to focus the analysis on the relevant flooding sources and important scenarios. This was performed by IRSN based on qualitative or quantitative considerations (as recommended by internationally available guidance: NUREG[1], The American Society of Mechanical Engineers (ASME), IAEA…) and on insights from previous studies performed by IRSN or EDF,
- the identification of the possible accident scenarios induced by the flooding, after combining realistic hypotheses for the failures of prevention or mitigation measures,

[1] NUREG: reports or brochures, produced by the Nuclear Regulatory Commission (NRC), on regulatory decisions, results of research, results of incident investigations, and other technical and administrative information.

- the study of the impact of the flooding on Structures, Systems, and Components (SSC) and on human actions.

PSA assumptions are realistic as much as possible. Since a flooding PSA generates many scenarios for water propagation, it is difficult to develop a comprehensive set of supporting hydraulic studies to assess the impact of the flooding on SSC and on the conditions to perform emergency human actions for all these scenarios. Some simplifying (conservative) assumptions can be used.

2.1 Identification of Internal Flood Sources

IRSN has developed an internal flooding PSA considering the design of the French 1,300 MWe PP4[2] PWR series. This limited-scope PSA consider only the core damage frequency (spent fuel pool is not included).

The flooding sources considered in this flooding PSA are pipe or tank failures, or leaks due to human errors (systems configuration, maintenance…) that can impact the electrical building (dominant risk as identified previously in the 3rd PSR): IRSN retained pipe flooding from the fire systems located in the electrical building and pipe failure on the steam generator feedwater supply system, that could also lead to water propagation in the electrical building area.

The EDF internal flooding PSAs are more complete and address both the reactor (CDF) and the spent fuel pool (FDF) for both P4 and PP4 PWR series. Nevertheless, they considered only the floodings with impacts in the electrical building (firefighting and feedwater systems).

In parallel, in the deterministic framework, EDF has developed many studies that cover a wider spectrum of flooding sources. These studies were conducted for all buildings containing important equipment for safety or radiologically contaminated fluids: pipe failures are postulated in all relevant rooms or groups of directly connected rooms.

2.2 Initiating Event Frequencies, Flooding Flow Rate and Water Volume

In IRSN and EDF internal flooding PSA, the pipe ruptures are categorized in spray, medium and major floodings based on leak rate. This meets general categories suggested by EPRI [1].

For determining the flooding initiating events frequencies, the operating experience feedback was considered by IRSN: failures of passive piping and non-piping elements, human-caused flooding during maintenance, spurious triggering of fire systems, etc. EDF flooding initiator frequencies, other than pipe failures, are based on the operating experience feedback and, for pipe failures, EPRI data are used (this category contributes to more than 80% of the overall risk).

In practice, IRSN notes that the frequency obtained based on EPRI data are consistent with the French operating experience.

In PSA, the flooding flow rate is determined with a realistic law considering pressure losses (linear in the pipes or from singularities). The flow rate is generally calculated with a circumferential pipe break assumption and with manual isolation of the leak after one operating shift succession (about 8 h).

Deterministic internal flooding studies performed by EDF distinguish two categories of leaks based on the water spread conventional volume: minor if lower than 6 m^3, major if higher than 6 m^3. The following assumptions are used for the pipe failures and leak rates:

- pipes with diameter lower than 1 inch: no failure is assumed. Nevertheless, sensitivity studies are performed for internal flooding caused by a purge valve left open on a pipe with a diameter lower than

[2] The 1,300 MWe PWR series include two designs, namely P4 and PP4.

or equal to 1-inch (this situation was revealed by the operating experience). In this sensitivity study, an independent means is credited to mitigate the situation (mainly by isolating the discharge flow),

- Moderate-Energy Line Breaks (MELB) and lines with diameter upper than 1 inch: only small leak is assumed,
- High-Energy Line Break (HELB): a circumferential pipe break is assumed,
- additional pipe failures induced by HELB: a circumferential pipe break lasting one hour is assumed.

In these studies, leak rates are calculated without considering the pressure losses. However, pressure losses are considered if the flooding consequences are too conservative.

Except in case of additional pipe failures induced by HELB (see above), the leakage isolation time is by convention:

- if the diagnosis is based on "safety classified" sensors or alarms: 20 minutes when the action takes place in the control room or 35 minutes if the action is outside the control room[3],
- otherwise (for example, when detection is carried out by sump level sensors): 16 hours (succession of two operating shifts).

It can be noted that the probabilistic and deterministic methods to evaluate the flooding flow rate and flooding water volume are different. The deterministic studies should be conservative and PSA studies should be realistic. However, for some cases it is not obvious to evaluate the degree of conservatism or realism of the studies. The detailed comparisons of the studies (deterministic and PSA) and the sensitivity analysis (for example, additional failure approach in deterministic studies) can enhance their representativeness and highlight useful insights.

2.3 Identification of Water Propagation Paths

In its internal flooding PSA, IRSN consider that the initial flood area is the room of the flooding source. The propagation of water from this room is then studied.

An alternative (used by EDF) is to group some rooms in a flooding area to simplify the PSA development by reducing the number calculated water propagation paths. This is relevant in case of instantaneous water spreading after a major flooding with large openings between rooms. Nevertheless, such grouping is less relevant for slow flooding or if limited openings exist between rooms allowing water retention in some rooms (other water propagation paths can then appear).

The identification of the water propagation paths in the IRSN flooding PSA is based on the following assumptions:

- doors status:
    - by default, all doors are considered closed. A sensitivity study could be carried out to consider doors open due to human error, such as leaving or keeping the doors open to perform maintenance when they should be closed (a probability recommended by NUREG/CR-6850 for fire PSA (7,3E-03) can be used),
    - water propagation via gap under doors is assumed,
    - resistance of doors to the level of water accumulation: initially, the resistance height of the door was postulated at 0,3 m in the closing direction and 0,9 m in the opening direction. As part of the 4th PSR of 1,300 MWe reactors, thanks to a test program performed by the licensee, this height was increased to 1 m in the opening direction and to 2 m in the closing direction,

[3] Sensitivity studies for all the rooms of the nuclear island were also carried out, considering the operators intervention times as for the European Pressurized Reactor (EPR) of Flamanville 3: 30 minutes if isolation is done from the control room, 60 minutes if isolation is done by local manual actions.

- resistance of sealed penetrations in the floors or in the walls: a sealed penetration is likely to break when the water layer is greater than the water level resistance criterion (15 cm). A conditional probability equal to 10^{-2} is applied for this failure. As around fifty sealed penetrations can be found in some flooding area, this assumption is only applied to the penetrations which failure leads to water propagation paths with impacts for the plant safety (for example, loss of redundant safety systems).

  In addition, IRSN considers possible water ingress through a floor penetration (no major failure) - when the water layer is between 10 cm and 15 cm - and spraying of safety targets located below the penetration (if any). A conditional probability equal to 10^{-2} is also applied for this failure.

  Nota: EDF internal flooding PSAs consider that if the water level in the flooding area exceeds the penetrations resistance criterion (15 cm), all penetrations will be failed: this assumption promotes the vertical propagation paths compared to horizontal ones. However, a sensitivity study has been performed by EDF for several flooding areas to evaluate the impact of this assumption,

- floor siphon and drainpipes clogging: some flooding scenarios involve the clogging of one or more siphons or drainpipes. In this case, the frequency of the scenarios is obtained by multiplying the frequency of the flooding source by a conditional probability of clogging. The operating experience of the French PWRs shows that a clogging problem is often not limited to a single siphon or drainpipe, as floor drains located in the same flooding area converge towards a single header drain, without any redundancy (however, separate headers are provided for different safety train rooms). Therefore, in IRSN flooding PSA, the conditional probability of clogged floor drains is assumed to be independent of the number of floor drains. IRSN retained a probability of 0,27 when only one safety train is involved in the flood path according to the scenario, and 0.27 x 0.27 when both redundant safety trains are involved.

  Nota: EDF flooding PSAs do not consider the possibility of floor drains clogging,

- the propagation of flooding through ventilation ducts is not yet systematically considered in the flooding PSA while it has been systematically considered by EDF in the deterministic studies,
- proportion of room surface area occupied by equipment – water spread surface: generally, a fixed value is applied to define this proportion (about 15 %), but this value can be adapted for each room to be more realistic. This hypothesis is also considered in deterministic studies,
- flood diagnosis and mitigation:
  - flood scenarios from fire systems:
    - for fire ramps initially filled with water, detection is supposed to be immediate by the reduction in pressure on a fire ramp signaled by sensors. Detection of a decrease in fire water tank level can also be assumed,
    - for fire ramps initially dry, in the event of a flood due to human origin, detection may involve the discovery of filled sumps in some area,
  - pipe failure on the normal steam generator feedwater system:
    - detection is supposed to be done in conjunction with the automatic emergency shutdown of the reactor. Very shortly after, the feedwater high flow valves close and the low flow valves reach their minimum flow position. Then, the feedwater supply pump stops,
    - according to emergency operating procedures, manual isolation of the gravity flow through the failed pipe would be necessary to complete isolation of the leak flow (a 20 min mean intervention time is generally assumed).

  The reliability of human actions to isolate the flood was analyzed by IRSN based on the Cognitive Reliability and Error Analysis Method (CREAM) method, considering:
  - the steps of the isolation actions (detection, manual actions from the control room or local actions),
  - four different categories defined by combining the three aspects below:
    - the available time to carry out the action: long (> 2 h) or short (< 20 min),
    - the priority level of flood isolation actions versus plant operating actions,
    - the needed time for the detection of the flood: “adequate” (fast enough) or “priority” (based on the emission of priority alarms linked to emergency procedures).

The failure of flood detection means is not considered in the IRSN internal flooding PSA (optimistic hypothesis).

2.4 Accident Scenarios: Defining The Functional Consequences of The Flooding

Water propagation

To evaluate the functional consequences of the flooding on the installation, the flooding propagation needs to firstly be studied. For PSA, the flooding propagation is studied for each scenario of the event tree: the water level in each flooded room is calculated in function of time (dynamic evaluation). The water propagation depends first on the flooding source flow rate and volume and then on the status of different elements (doors, penetrations, evacuation means…) which are probabilized.

In deterministic approach, the water propagation calculations are static, based on postulated flooding source volumes and performed step-by step:

- step 1: water propagation in a semi-sealed zone (flooding source room and directly connected rooms without physical separation (doorstep for example)),
- step 2: water propagation to adjacent rooms, considering the resistance criterion of doors and sealed penetrations to the water level.

If new water propagation paths are identified (at step 2) due to the failure of a door or a penetration, steps 1 and 2 are then repeated for the new flooded rooms. And so on, until the water level stabilizes below a harmlessness height. If a new propagation zone opens onto the exterior of the building, then all the water is evacuated, and the propagation is stopped. In this case, it is verified that the effluent sent outside is not radiologically contaminated.

Floor drains in flood zones are supposed to be available in deterministic studies. If the flooding source flow rate is lower than the drain capacity, then the scenario is not retained. However, a sensitivity study was carried out considering a drain clogging ("additional failure" approach).

Flooding Impacts

In flooding PSA, the vulnerability of equipment to spray and submersion are systematically considered. From information on water propagation paths, a list of electrical and electronic equipment likely to be impacted has been defined. The reliability of post-accident human actions is re-evaluated considering the context of the internal flooding by a method called "scoping" (EPRI guide [2]).

Note: the spurious I&C orders have been ignored and HELB (and impacts on neighboring equipment) are not yet systematically considered. This could be considered later.

In deterministic studies, the assessment of water impact on equipment includes failures by submergence, spray, humidity, condensation, and temperature. In the case of flooding involving HELB, the pipe failure can additionally lead to pipe whipping and jet effects on equipment located nearby.

3. REVIEW BY IRSN OF EDF INTERNAL FLOODING PSA

As part of the 4th PSR of 1,300 MWe PWRs, EDF updated the Level 1 internal flooding PSAs for these reactors by considering the technical state foreseen at the end of the 4th PSR, with plant reinforcements in relation with long term operation and post-Fukushima program. In this context, EDF has developed new tools allowing to identify more precisely all safety equipment that can be impacted by a flooding. Additionally, the systematic modelling of ventilation as a support system for electrical panels in level 1 PSA provided relevant information in flooding context (if water impacts some ventilation electrical supply).

IRSN considers that these progresses are satisfactory. The CDF and FDF values obtained by EDF for this 4th PSR are reasonably low without, however, being negligible. One category of scenarios will be further examined in conjunction with the deterministic framework: HELB including pipe failure on the steam generator feedwater supply system.

4. LESSONS AND PERSPECTIVES

Significant efforts are done in France to identify and control the specific risks due to internal flooding on the operated PWRs. This involves both deterministic and probabilistic approaches with some different rules for the studies.

A major difficulty of internal flooding PSA is the identification of the relevant water propagation paths or water retention zones for the risk assessment. Walkdowns are of key importance for this identification. A modelling of doors or floor penetrations failures under water height is needed but lead to a multiplication of the possible water flow paths.

A modelling of floor drains clogging is also needed, including possible backflows through obstructed drain lines. Moreover, the water propagation through ventilation ducts could be systematically considered. This contributes also to the multiplication of the possible water flow paths.

Likewise, the impact of the HELB effect can be significant, increasing the leak flow rate and spread water volume, and leading to additional equipment failures.

To control this multiplication of water flow paths, a screening approach is needed to model in PSA only the water flow paths that can threat the plant safety (typically when redundant safety trains are impacted): this can only be done by cross-checking the hydraulic modelling of water propagation in the plant with the functional consequences of flooded equipment failure. Thus, the flooding PSA quality will be progressively improved with a reasonable complexity.

References

[1] Pipe Rupture Frequencies for Internal Flooding PRAs, Revision 1 – Technical report EPRI 1013141, Final report, March 2006.

[2] Guidelines for Performance of Internal Flooding Probabilistic Risk Assessment - Technical report EPRI 1019194, Final report, Decembre 2009.