INTERNAL FLOODING LEVEL 1 PSA IN BELGIUM

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In 2007, WENRA published a version of its Safety Reference Levels which, among others, requested the development of a Level 1 Internal Flooding PSA for all operating states. This paper highlights how these requirements were met in Belgium and their conclusions. Based on an existing methodology by the Electric Power Research Institute an in-house methodology was prepared by Tractebel Engie with the emphasis on automation. The probabilistic IFPSA for the five most recent Belgian units of were successfully performed and submitted to the Belgian authorities by the end of 2015. The flood induced core damage frequencies were found to be one to two orders of magnitude below those due to internal events. Differences in design philosophies between sites, e.g. the placement of sumps and watertight doors, were clearly observed within the results as were their merits and potential risks. Low frequency but high flood rate scenarios were found to be more penalizing than high frequency low flood rate ones due to the onsite provisions. Furthermore, special flood mechanisms such as the spurious activation of the fire extinguishing system or high energy line breaks (HELB) were found to have a negligible contribution to the total flood induced core damage frequency.

I. INTRODUCTION

The Oconee Nuclear Power Plant (NPP) Probabilistic Safety Assessment (PSA) was one of the first safety assessments to identify internal floods as a potential significant contributor to the Core Damage Frequency (CDF). Today, internal foods are considered to be one of the key risk contributors of PSA for any NPP. In 2007, the Western European Nuclear Regulator's Association (WENRA) published a version of its Safety Reference Levels which, among others, requested the development of a Level 1 Internal Flooding PSA (IFPSA) for all operating states. In Belgium this Reference Level has been converted into a Royal Decree with a transitory arrangement to end 2015. This dissertation highlights how this requirement was met in Belgium and what conclusions could be drawn from the project.

IFPSA was performed to evaluate flood induced impacts on Systems, Structures and Components (SSCs) important to safety. The flood sources within the plant that have a potential to create adverse conditions and/or affect the plant mitigating equipment were identified, and flood scenarios that contribute to CDF were examined and quantified. The scope of the study was defined as the production of an IFPSA complying with American Society of Mechanical Engineers (ASME) capability level 1 requirements. Combinations of floods with other independent internal or external events and structural integrity assessments were considered out of scope of the project.

II. METHODOLOGY

A. Overview

Based on the 'Guidelines for Performance of Internal Flooding Probabilistic Risk Assessment'[1] by the Electric Power Research Institute (EPRI) an in-house methodology has been prepared by Tractebel ENGIE consisting of 3 qualitative and 7 quantitative evaluation tasks. The methodology distinguishes itself by a stronger emphasis on automation and early identification of the most significant parameters and information. A methodology that can easily be automated and modelled into computer algorithms strongly reduces execution times allowing a more gradual and focused approach to data collection. Such an approach was required in order to meet the strict deadlines associated with the study.

For each of the tasks of the methodology as described below, assumptions were made to be used in case the required information was not readily available. It was a clear decision at the start of the project to use already available site specific data, but to limit any additional data collection for the first iteration to those data whose absence would impede the execution of the methodology and which could not be replaced by conservative assumptions. These assumptions were also to be validated by means of sensitivity studies at the end of the assessment. The conservative assumptions were gradually replaced by additionally collected information in consecutive iterations for those scenarios which were found to dominate the results. This process continued until further refinement and conservatism decrease for the most significant scenarios did not cause any change in conclusions of the study.

Examples of such conservative assumptions include: the assumption that for equipment for which geo-localization was absent that any passive component rupture within the area could cause damage to the equipment due to spray or other dynamic effects of the component failure; using conservative estimates of drain capacities and the capacity of doors to withstand the hydraulic pressure. Assumptions were not limited to flood effects and mitigation means, but for initiating frequency calculations for those areas were less data on piping properties were available.

The methodology comprises following tasks:

- Task 1 consists of the identification of those areas and buildings in the plant that contain flood sources or safety related components, can act as a flood conduit during flood propagation and/or contain flood mitigation features. All potential flood areas, their features (such as floor area, elevation level, ceiling height, mitigating features, etc.) and their interconnections (such as doors and openings) have been identified and listed.
- Task 2 consists of identifying all flood sources, flood mechanisms and SSC that can potentially cause or be impacted by flood events. This includes identifying all passive components (e.g. piping, valve bodies, pump bodies, reservoirs etc.) within each area. Following failure modes were considered as flood mechanisms:
  - Passive component failures,
  - Human-induced mechanisms (e.g. maintenance induced floods)
  - Actuation of the fire extinguishing system (spurious or following a high energy line break (HELB);

  Similarly, to the identification of all potential flood sources, all equipment potentially affected by the flood environment and important for safety has been identified. Equipment were retained if they either have an initiating - loss of the equipment potentially causes or contributes to causing an initiating event - or mitigating - equipment used following an initiating event in order to prevent core damage - function within the internal events PSA model. Table 1 shows an example of equipment screening: for each component type it is indicated whether it is considered to be possibly impacted by the flood environment.

Component Type	Impact of Flood Environment
Motor-operated valve	Possible Failure
Pneumatic Valve	Possible Failure
Hydraulic Valve	Possible Failure
Solenoid Valve	Possible Failure
Manual Valve	Operability Affected
Check Valve	Not Affected
Relief Valve	Not Affected
Pumps	Possible Failure
Compressors	Possible Failure

Table 1 - Components possibly affected by flood water

- Task 3 comprises walkdowns performed in order to collect the required information for the SSC, flood sources and flood areas identified in the previous tasks. During the first iteration this task was limited to validation and collection of the imperative data. For following iterations, the objective of this task was to provide additional information and details for the most penalizing scenarios identified during the previous iteration. Interviews with plant personnel were also conducted during this task. These aided in the identification of potential human-induced floods (task 6) as well as in the identification and quantification of potential mitigating actions (task 8);

- Task 4 involves assessing the worst case possible flooding consequences for floods starting within each area identified in task 1. Simplified hydraulic models were applied in order to assess flow rates through openings and door crevices. The presence of migration means such as sumps and drains have been considered within the propagation analysis using conservative estimates for their capacity. Based on available deterministic studies it was justified that each fire resistant door is able to withstand the hydraulic pressure due a flood height of one meter on either side of the door. When the water height within the room exceeds this level the door is considered to collapse, no longer forming any barrier for the flood water. Submarine type doors are considered to be water tight and to be sufficiently rigid to withstand any hydraulic pressure due to flood water within the plant they could be subjected to. If the area itself or the potential flood propagation path in case of the maximum possible source rate for this area, contains equipment that is required to prevent core damage in response to an initiating event or emergency plant shutdown the area is retained for further detailed analysis.

- Task 5 develops a list of flood scenarios for those areas retained after task 4. These scenarios will define the scope for the further quantitative evaluation in tasks 6 to 10 and will form the backbone of the PSA that is constructed. Per area so called spray, flood and up to three major flood scenarios are developed based on the characteristics of the flood sources (water inventory, possible break size diameters, system pressure etc.) within the area. For these flood mechanisms full propagation calculations are performed to determine the water level evolution as a function of time.

  Potential additional effects of the flooding event are taken account at this stage. Additional events include high energy line breaks - assumed to cause the immediate loss of all equipment affected by the released steam -, and dynamic effects of the pipe rupture. During the first iteration all equipment within 20 feet of the ruptures pipe are assumed to be lost due to the dynamic effects of the break. Possible dynamic effects include spray and pipe whip.

  As part of this task two additional separate analyses are made. Firstly, the maximal possible flood level in the reactor building following a steam line break (SLB) and large loss of coolant accident (LBLOCA) are calculated. Whilst the layout and the equipment inside the reactor building is designed as such that no safety equipment is lost following a LBLOCA, this assessment is performed to assure that during shutdown conditions when the containment is potentially opened no water transfer to adjacent buildings is possible. Secondly, floods originating in underground galleries – such as the galleries containing raw water piping connecting the water intake with the plant – are examined. It is assured that any flood starting in these galleries cannot damage any PSA equipment contained in the buildings connected by the galleries;

- Task 6 involves the estimation of the flood initiating event frequencies due to failures of piping and other passive components like tanks, pump bodies, heat exchangers etc., due to human interference (maintenance errors) and due to the spurious actuation of the fire protection system. These frequencies are then assigned to the appropriate scenarios as studied in task 5. Piping and other passive component rupture frequencies (excluding for reservoirs) are calculated based on 'EPRI-1021086'[2]. Site specific safety factors are taken into account to account for differences in integrity management strategies, non-destructive essay (NDE) and time between outages. For leakages from reservoirs 'T-book'[3] is used as reference for determining the flood frequencies. Quantification of the frequencies of human induced floods are based on an analysis of the consignation procedures, testing procedures, corrective and preventive maintenance records for the past 10 operating years and the number and type of isolation measures available for the maintenance. Failure frequencies of isolations means are calculated based on 'T-book'[2]. The consequences of human induced flooding events are conservatively considered to be equivalent to a DEGB on the line containing the component under maintenance

  Spurious actuation frequencies of the fire protection system are based on an FMEA of the system with equipment reliability data taken from 'T-book'[2]. Fire protection systems are designed based on an area-of-protection approach. Flood source rates in case of their spurious actuation were taken from detailed hydraulic assessments of the systems taking into account pump characteristics and load curves, as opposed to using design values. For each automatic extinguishing system, it was also examined whether it would activate in case of high energy line break.;

- Task 7 evaluates the consequences of the retained flood scenarios in terms of damaged equipment and components. Thereby this task determines the induced initiating events (IEs) possibly occurring due to the flood event, based on the existing internal events PSA models. Furthermore, scenarios that do not cause an initiating event nor require an emergency shutdown of the plant are removed from the scope. Identification of internal events potentially caused due to internal floods was performed based on the minimal cut sets (MCS) of fault trees used within the internal events model to assess initiating frequencies. Cut-set which cannot be the direct consequence of a flood but require additional random or human failures were ignored. For newly identified initiating events as well as those internal events whose initiating frequency was derived purely from generic data new flooding specific fault trees were constructed;

- Task 8 consists of the flood mitigation and human reliability analysis (HRA). This task takes the consequences of the flood scenarios as determined in task 7 in terms of the time required for the water to damage the PSA equipment[a] and assess the ways the flood can be detected enabling the operators to perform mitigating actions. As part of this HRA analysis, new flooding specific human actions are defined consisting of the flood diagnosis and isolation of the flood source. In addition to the newly defined human actions, the Human Failure Events (HFEs) modelled in the internal events PSA have been re-examined in view of the additional stress and other environmental challenges induced by a flood scenario.

  For the first iteration, re-evaluation of the existing human errors was performed based on the flowchart given below. Depending on the existence of a procedure requesting the action in question, whether the equipment required to be operated in case of a local action is affected and whether the time available for the action is more than one hour the existing human error probability is respectively set to 0.1, 1, kept at its nominal value or multiplied by ten.;

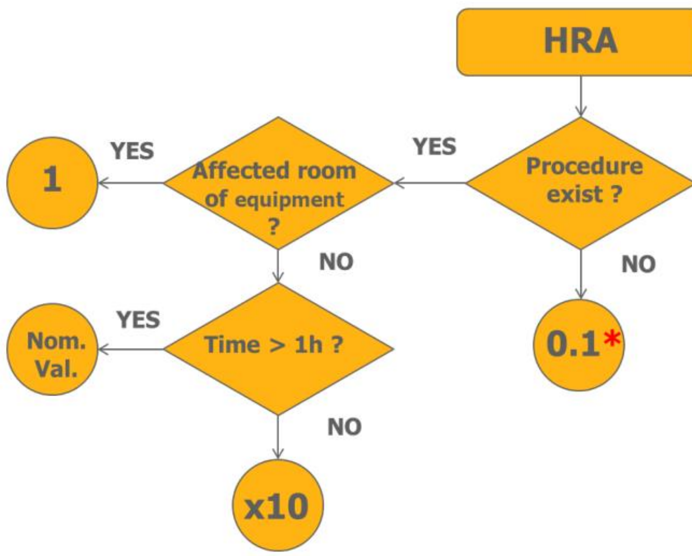

Figure 1- Flowchart for the re-evaluation of existing HRA, following flood events

  For the following iterations, diagnostic and recovery actions were assessed in greater detail for the dominating scenarios. Average movement rates of roving-personnel and paths from the main control room to the flooded area were assessed. For all iterations special attention was made to the accessibility of the areas to be visited (electrocution risk and radiation risk following floods of potentially contaminated water) and to the availability of detections means (e.g. level detectors).

- Task 9 involves the PSA modelling of the flood scenarios. To this goal, operator action (OA) event trees (ET) are created within the PSA model. Operator Action Event trees form the link between the flooding initiating events with frequency as determined in task 6 and the existing internal events event trees. In these trees the different branches differentiate the various evolution paths each flood scenario can take depending on the actions taken by the operator and the associated set of failed equipment which are modelled as sets of boundary conditions for the internal events PSA model. OA ET branches which correspond to an internal event are linked to the corresponding event tree of the internal events PSA model. Boundary conditions are inherited by subsequent internal event ET disabling equipment affected by the flood and limiting the mitigations options available for the internal event.

[a] By PSA equipment all components that are associated with a basic event identifier in the PSA model are meant. Some basic event identifiers however encompass multiple components (e.g. normal feedwater systems). In those cases for purpose of IFPSA, considered as PSA equipment are those components which can be affected by the floodwater and whose failure causes the failure of the comprising basic event.

- Task 10 consists of the quantification of the PSA model obtained after the insertion of the OA event trees constructed as part of task 9. The objective of this task is not limited to the calculation of the CDF but also consists of calculating importance measures, performing sensitivity analyses and using Monte Carlo simulation to evaluate the uncertainties on the obtained results.

  Furthermore, a separate study is conducted as part of task 10, which re-evaluates potential flooding impacts following internal events. At the onset of the internal events PSA models, additional flood consequences were treated in a simplified manner. As part of the internal flooding PSA study these consequences have been re-evaluated for steam line break, feed water line break and interfacing system LOCA scenarios and modifications to the existing internal events model have been suggested and their impact assessed.

B. Scope and Limitation

The general scope of the IFPSA developed for the Belgian NPP's is the following:

1. The methodology is an adaptation of the EPRI guidelines[1] and is adapted, when choice is given by the EPRI, in order to meet the capability level I of the 'ASME standards'[5]. For example, as the ASME standard does not require taking into account standby systems, these systems are excluded as flood source. The sole exception being the fire protection system, for which spurious actuation is considered.
2. The analysis covers every Plant Operational States (POS), from power to cold shut-down[3] (POS A to F);
3. The considered fluid is water (including High Energy Line Breaks), other fluids such as gasoil, oil, etc. are not considered;
4. The combination of a flooding with another independent internal event is not studied,;
5. The combination of an internal flooding event with an external event (earthquake, high wind, …) is not taken into account;
6. The structural integrity of the buildings is not assessed. All solid concrete structures are considered to be able to withstand the hydraulic pressure due to flooding. Other types of walls, such as cinder blocks are not considered as a barrier for water;

III. AUTOMATION EFFORTS

During a first application of the methodology data collection was restricted to a limited amount of imperative data complemented with conservative hypotheses. Obtained results successively identify those hypotheses which have a significant impact on the results, and serve as guidance for future information gathering and conservatism reduction efforts. Such staggered approach, with alternating data collections and short iterations, allows for more focused and limited walkdowns in terms of scope and time expenditure. For such an approach to be successful alterations to the EPRI methodology had to be made and flexible codes implementing the methodology had to be developed. These tools are able to, with minimal manual input and a varying degree of detail on input data, autonomously perform: flood propagation calculations, initiating frequency calculation and estimation, flood consequence analysis and operator action tree creation. Following sections detail two examples of the automation efforts performed as part of the internal flooding PSA project.

A. Example 1: Flood Propagation

A first alteration required to the default EPRI methodology was a transition from a qualitative to a quantitative screening phase. For this purpose, an algorithm had to be developed allowing the assessment of potential propagation paths for each flood area. This algorithm could also thereafter be used for the detailed flood propagation assessments.

For the automation of the flood propagation calculations two approaches with different level of precision were considered and developed. Taking into account calculation time, available computational power and precision of the results, one of the algorithms has been selected, so-called backtracking algorithm.

This approach consists of a backtracking algorithm. Based on the geometry of the plant in the immediate surroundings the area containing the flood source a first solution is calculated. It is then verified whether the solution meets all constraints imposed by the geometry as well as those by the methodology. If the solution does not meet all criteria, for example because the geometry in the vicinity of the flood source should have altered due to the collapse of a door under the load of the flood water the algorithm tracks back to this point of choice and continues from there on. This process is repeated until a solution is found matching all constraints imposed by the geometry and the hypotheses taken within the study. Figure 2 shows a graphical overview of the adopted algorithm.

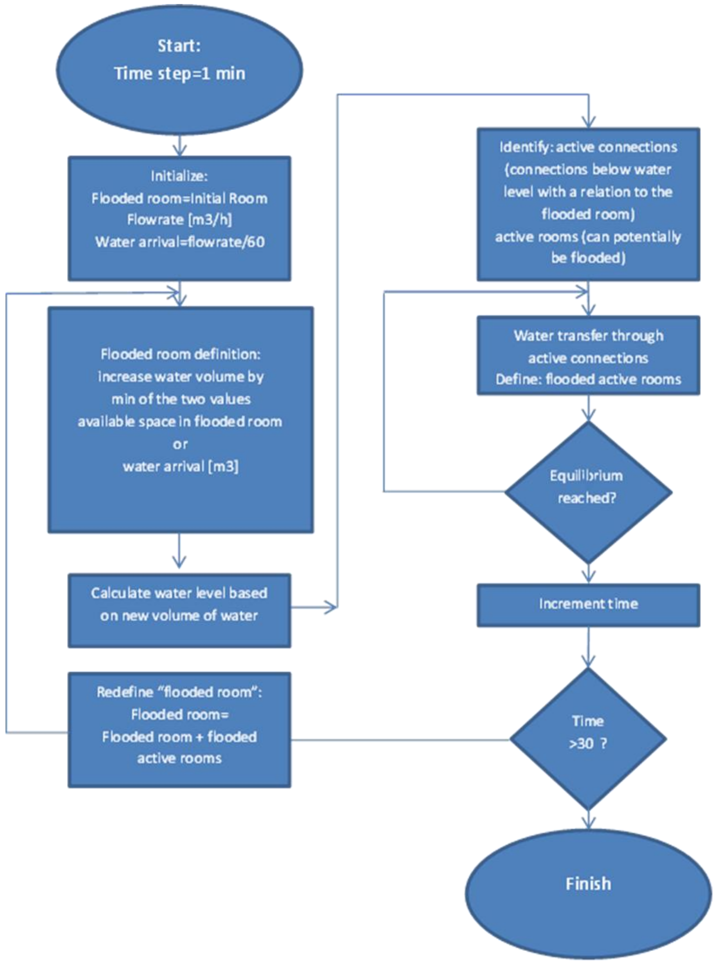

Figure 2 - Flood propagation backtracking algorithm overview

B. Example 2: Flood Source Grouping

In order to limit the amount of flood propagation calculations required potential flood sources within each retained flood area were grouped based on their source rate. All types of passive component failures leading to source rates below 23 m³/h were grouped into a so-called spray scenario. All possible passive component failures corresponding to flood sources between 23 m³/h and 460 m³/h were grouped into a so-called flood scenario and all other ruptures with greater flow rates as well as potential human induced floods (which were conservatively assumed to be lead to a double ended guillotine rupture of the piping system involved) were subdivided into 3 major flood groups. The source rate boundaries of these groups were selected such that a third of all potential scenarios with flow rates greater than 460 m³/h falls within each group.

Whilst such grouping efforts limit the amount of required flood propagation calculations, the approach also complicates flood initiating frequency assessment. Input refinement efforts for critical flood areas will require redoing the grouping for those areas. Tools were therefore designed aiding with the frequency calculation and grouping.

IV. OBTAINED RESULTS

A. General Results

The total Core Damage Frequency due to flood events was found to be in the order of **1E-07/reactor-year** for most of the units. The baseline CDF for the internal events PSA model for all studied units is in the order of **1E-05/reactor-year**. The risk due to internal flood hazards is thus found to be one to two orders of magnitude smaller compared to that due to internal events (e.g., transients, LOCAs etc.). One of the oldest units was found to have the highest CDF value among the studied units both in absolute terms and compared to the internal event CDF. One of the main reasons for this is the way physical separation between redundant trains is implemented in the oldest unit studied compared to its more rigorous implementation for the newer units. Another reason is the absence of a full second level of safety systems. For example, pumps of all component cooling trains are located within the same flood area and if the system is lost, contrary to the other units, there is no emergency cooling system to provide an alternative cold source. The results were further analyzed to determine the risk during each Plant Operating State (POS), contribution of risk from various types of flood scenarios, plant building wise risk distribution etc. Low frequency but high flood rate scenarios were found to be more penalizing than high frequency low flood rate ones due to the onsite provisions.

The Table 2 below gives the building dominating the results of the flooding PSA for each unit as well as the most frequent induced initiating event.

Table 2 - Dominant Buildings and Induced Initiating events per Unit

	Tihange 1	**Tihange 2**	**Tihange 3**	**Doel 3**	**Doel 4**
Most Frequent Induced Initiating Event	Loss of Component Cooling (56%)	Loss of Primary Pumps Seal Injection (81%)	Loss of Component Cooling (83%)	Loss of Primary Pumps Seal Injection (29%)	Loss of Feed water (69%)
Dominant Building	Nuclear Aux. Building (64%)	Deactivation Pool Building (77%)	Nuclear Aux. Building (81%)	Nuclear Aux. Building (32%)	Turbine Hall (34%)

For the **Doel 3** site the nuclear auxiliary building (ca. 30%), the electrical auxiliary building (ca. 20%) and the turbine hall (ca. 20%) were found to be the highest contributors to the flood induced CDF. The nuclear auxiliary building was found to have a high contribution due to the location of many critical safety systems in this building (e.g. component cooling, safety injection, chemical and volumetric control). A number of potential flood propagation paths were identified where, if combined with the probability of untimely flood detection and mitigation, the injection to the primary pump seals could be lost. A loss of coolant accident could emerge following the loss of injection to the pumps if the second level back-up system fails due to random failures. The return line of the seal injection system had prior been identified in the internal events PSA as being highly safety significant and actions have been taken to lower its significance. However these actions had not yet been incorporated into the PSA model prior to the start of the flooding PSA studies with Doel 3 being the first unit to receive the flooding PSA treatment.

Though main power distribution boards are located in zones of the unit with low amounts of piping, the loss of one of these boards has large consequences given the amount of equipment directly or indirectly dependent on it. Furthermore a high probability of untimely diagnosis and mitigation due to the inaccessibility of the rooms following a flood (electrocution risk) was assigned to the loss of electric boards scenarios. A few scenarios were identified where in case of large rupture sizes and untimely diagnosis flood water could reach these rooms, leading to 20% contribution of the electrical auxiliary buildings. While unlikely, due to the absence of any flood migration means within these rooms' potential consequences can be substantial with the potential loss of single or multiple safety class busbars. Recommendations included investigating the possibility of installing mitigation (e.g. level detectors allowing early detection) or migration means (e.g. flood barrier) within these areas.

The turbine hall contains the largest amount of piping as well as piping with the largest diameters. Furthermore as the pipes of the systems present within these buildings are not safety classified they host larger rupture frequencies, have larger test interval and physical separation within the building is less. However, the turbine building itself does not contain safety equipment. The main induced internal event due to a flooding event in the turbine hall is the loss of normal feed water. While such an event is not very penalizing (low conditional core damage probability) the large amount of piping present in the turbine hall leads to large frequencies of occurrence. Water tight doors are installed on-site to migrate the risk of a rupture of the normal feed water system affection the pumps of the auxiliary feed water system. The importance of the proper closing of this barrier was clearly observed within the results and since this these doors are now locked preventing their opening without permission from main control room personnel.

For **Doel 4** the results were found to be similar with the main difference being the reduced importance of the nuclear auxiliary building, which can be attributed due to the different design of the primary pump seal injection system. Flooding of the turbine hall leading to loss of normal feedwater was found to be the dominant contributors to the CDF.

For the units of Tihange 1, 2 and 3, very low contributions of the turbine hall were found (<4%). Despite the large flooding potential, the separation of normal and auxiliary feed water systems with no potential internal propagation path combined with the high redundancy of the systems explains their negligible contribution.

For all 3 units scenarios were identified where in case of large rupture sizes in the nuclear auxiliary building, - or the adjacent deactivation pool building[b] - and untimely operator action the component cooling pumps or the injection pumps of the chemical and volumetric control system can be lost. Due to these scenarios the areas in the vicinity of these pumps contribute to more than 80% of the total flood induced CDF for both units. The different trains of the component cooling pumps, while in located separate rooms were found to have only limited flood mitigation means. Given the low overall flood induced CDF, the contribution to the overall risk profile of the plant is however small. Nevertheless, sensitivity studies have been performed examining the impact of possible improvements. These improvements included the installation of watertight doors and the creation of flood penetrations altering flood propagation pathways.

The contribution of buildings housing intermediate cooling system and chemical and volumetric control system is found to be higher in Tihange, than in Doel. This can be explained by the location of this equipment and lay-out features of the units. Generally, in Doel the water has to fill up larger rooms and sumps before flood water is able to cross train. While floods affecting multiple trains are only possible in case of large spill rates and untimely operator intervention they were found to be more likely in Tihange as opposed to Doel. Similar reasoning holds for component cooling systems.

Special flood sources such as fire extinguishing system (spurious actuation or actuation by HELB) and tank rupture do not represent significant hazard from the flooding PSA point of view. Pipe ruptures with high spill rates were found to be the primary contributors to the CDF.

B. Sensitivity Studies

Sensitivity studies contained studies focused on the hypotheses and conservatisms taken as part of the methodology identifying the human reliability assessment and the considered flood capacity of systems (total potential flood volume) as key items for refinement for subsequent iterations.

Sensitivity studies related to suggested improvements to plant design such as the installation of watertight doors/thresholds, floor gratings and other means to prevent propagation were conducted and potential reductions in CDF calculated.

[b] In the unit of Tihange 2 the chemical and volumetric control system pumps are located within the deactivation pool building

V. REFERENCES

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