Internal Flooding Level 2 PSA in Belgium

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In the frame of the Belgian action plan answering the Western European Nuclear Regulators Association (WENRA) Reference Levels of 2007, a representative study of the internal flooding level 2 Probabilistic Safety Assessment (PSA) has been performed by Tractebel on a Belgian 1000MW-Pressurised Water Reactor (PWR) Nuclear Power Plant (NPP).

The internal flooding level 2 PSA has been elaborated as an extension of the internal event level 2 PSA so that the methodologies developed for the internal event level 2 PSA regarding containment isolation analysis, Human Reliability Analysis (HRA) and basic events quantification remain globally valid for the internal flooding level 2 PSA. Only limited adaptations had to be introduced in the containment isolation analysis methodology and in the HRA methodology for internal flooding specificities.

Besides these methodology adaptations, the level 1/level 2 interface process, providing the status of the sequences leading to core damage in so-called Plant Damage States (PDS) has also been performed specifically for the internal flooding sequences. The main outcome from this process is a direct consequence of the level 1 PSA results, namely that the Core Damage Frequency (CDF) for the internal flooding sequences represents solely 1.23% of the CDF for internal event, thus two orders of magnitude lower. Consequently, it is already known beforehand that the internal flooding hazard has a minor impact on Belgian NPPs and that the outcomes and recommendations coming out of the internal flooding PSA study will be of low importance with respect to those derived from the internal events PSA.

Nevertheless, risk metrics for the internal flooding level 2 PSA study have been computed, i.e. Containment Failure (CF) modes, Containment Failure Frequencies (CFF) and Fission Product (FP) release frequencies, and put in comparison with internal event level 2 PSA results.

This paper aims at presenting the work carried out as well as the results of the internal flooding level 2 PSA that show that the associated risk can be considered acceptable in comparison with the internal event level 2 PSA results.

The main conclusions and recommendations identified with this study are the following:

- *The internal flooding CFF is only 1.63% of the internal event CFF, thus two orders of magnitude lower;*
- *The ratio of the CFF divided by the CDF for internal flooding is higher than the one for internal events. This means that CDF sequences induced by internal flooding lead more likely to CF;*
- *One main reason of the higher CFF/CDF ratio is due to the lower probability of successful accident management actions in internal flooding situations. Therefore, during operators' training, internal flooding situations could be simulated;*
- *Another reason is the higher unavailability of safety systems due to internal flooding. Therefore, mobile alternative means[1] such as alternative containment spray system and alternative injection system are even more useful in internal flooding situations.*

[1] Mobile alternative means alike FLEX means which are accessible in flooding situations and that can be deployed on site.

I. INTRODUCTION

I.A. Background of the Study

The Western European Nuclear Regulators Association (WENRA) Reference Levels of 2007 (Ref. 1) were translated in the Belgian Royal Decree issued on 30th November 2011. This Royal Decree indicates in its Article 29 that: "For each unit, level 1 and level 2 Probabilistic Safety Assessments (PSA) must be established. However, the level 2 PSA can be performed for a unit considered as representative of several units, based on an interpretation of technical characteristics. The PSA will consider the contribution to the risk in all plant operation modes, and will take into consideration a relevant set of initiating events, including internal fire and flooding"[2] (Ref. 2).

In the framework of the WENRA Belgian action plan (Ref. 3), the flooding level 1 PSA has been launched. In February 2013, Belgian authorities required a representative study of the internal flooding level 2 PSA to be realized. The study has been performed by Tractebel on a Belgian 1000MW-Pressurised Water Reactor (PWR) Nuclear Power Plant (NPP).

This paper aims at presenting the work carried out and the results for the internal flooding level 2 PSA.

I.B. PSA Development and Practice in Belgium

In Belgium, level 1 PSA and level 2 PSA models are developed separately: level 1 PSA models with RiskSpectrum, and level 2 PSA models with EVNTRE. Consequently, a level 1/level 2 PSA interface is required and established for each couple of level 1 and level 2 PSA studies of a given unit.

As shown in Fig. 1, the level 1/level 2 PSA interface translates core damage sequences (provided by level 1 PSA) into Plant Damage States (PDS, needed by level 2 PSA). Each PDS in the interface has a certain probability in percentage of the total Core Damage Frequencies (CDF), and is characterized by the PDS attributes which describe the initial and boundary conditions for level 2 PSA analyses, including notably the plant operating state, the initiating event, the primary loop pressure level, the status of power supply, of safety systems and of the containment isolation at the moment of core damage.

For the internal flooding level 2 PSA study, the level 1/level 2 PSA interface including the CDF and the PDS specific to internal flooding has been elaborated and incorporated into the level 2 PSA model.

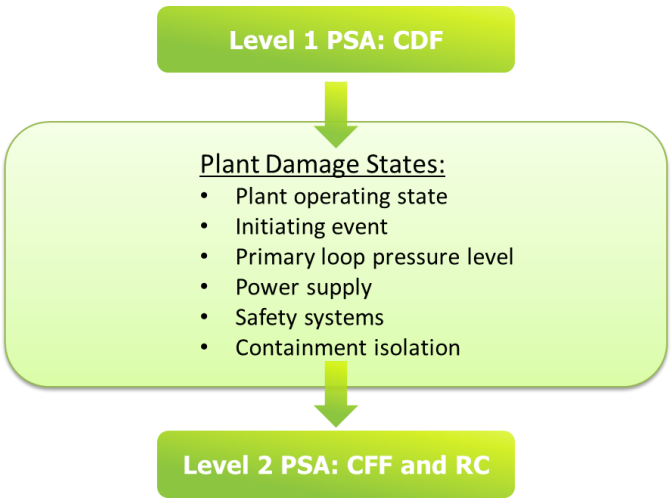


Fig. 1: Illustration of level 1/level 2 PSA interface

[2] Translated from the text originally in French: *« Pour chaque centrale, une étude probabiliste de sûreté de niveau 1 et 2 doit être établie. Toutefois l'étude probabiliste de sûreté de niveau 2 peut être réalisée pour une unité jugée représentative de plusieurs unités sur base d'une interprétation des caractéristiques techniques. L'étude probabiliste de sûreté étudiera la contribution au risque dans tous les modes d'exploitation de la centrale et prendra en considération un ensemble pertinent d'événements initiateurs, y compris l'incendie et l'inondation internes »*.

Finally, in Belgian level 2 PSA, four Release Categories (RC) are considered based on the releases in Iodine and Cesium, namely:

- Small releases: less than 0.01% of the initial core inventory;
- Medium releases: between 0.01% and 0.1% of the initial core inventory;
- Large releases: between 0.1% and 1% of the initial core inventory;
- Very Large releases: more than 1% of the initial core inventory.

II. LEVEL 2 PSA MODEL EXTENSIONS TO CONSIDER INTERNAL FLOODING EVENTS

The internal flooding level 2 PSA is an extension of the internal event level 2 PSA, which was completed by the end of 2011. The current chapter describes all the adaptations made to consider internal flooding events.

II.A. Methodology Adaptations

The methodologies developed for the internal event level 2 PSA regarding containment isolation analysis, Human Reliability Analysis (HRA) and basic events quantification remain globally valid for the internal flooding level 2 PSA. Only limited adaptations were needed in the containment isolation methodology and in the HRA methodology, due to internal flooding specificities. The adaptations are further explained here-after.

II.A.1. Containment Isolation Methodology

The containment isolation methodology determines the proportions of the four outcomes of the PDS attribute #CI in the level 1/level 2 PSA interface. The four outcomes are:

- CI: The containment is fully isolated at core damage;
- CO: The containment workers air lock is open at core damage;
- FSIG: The containment isolation has failed due to isolation signal failure;
- FIV: The containment isolation has failed due to isolation valve(s) failure.

In internal event level 2 PSA, FIV can occur only due to intrinsic equipment defect. However, in internal flooding level 2 PSA, besides equipment intrinsic defect, internal flooding can induce equipment defect leading to FIV as well. Therefore, for each internal flooding CDF sequence, the proportion of FIV has been re-evaluated.

II.A.2. HRA Methodology

The HRA methodology determines the Human Error Probabilities (HEP), which are then used to calculate the probabilities of successful Accident Management (AM) actions in the basic events quantification.

For internal flooding level 2 PSA, the two Performance Shaping Factors (PSF) related to “Stress” and “Experience/Training” have been reviewed to compute the HEP as they can be negatively affected by internal flooding events.

In addition, one new factor for Main Control Room (MCR) inaccurate indications has been introduced in the formula to compute the HEP. Consequently, the number of flooding-affected MCR indications has been provided for each PDS as an additional output of the internal flooding level 1/level 2 PSA interface.

II.B. Basic Event Quantification for Internal Flooding Events

For internal event level 2 PSA, the basic events quantification is realized throughout 35 quantification folios, each one for a certain subject.

For internal flooding level 2 PSA, a review of the 35 quantification folios has been performed at first, to identify the folios which needed to be adapted for internal flooding events. The basic events have been re-evaluated accordingly. Then a

new folio for "Inaccurate indications of key-parameters for AM" has been added, to consider the fact that flooding may affect the accuracy of MCR indications (as mentioned in §II.A.2).

The values of the basic events related to the probabilities of successful AM actions are significantly lowered for internal flooding than the ones for internal events. The main reasons are:

- The PSFs concerning "Stress" and "Experience/Training" are adapted to penalize internal flooding situations;
- A new factor for MCR inaccurate indications is added as indications of key-parameters for AM may be lost in flooding situations.

The other changes in the basic events values are mainly related to the internal flooding level 1/level 2 PSA interface and are rather negligible.

III. INTERNAL FLOODING LEVEL 2 PSA RESULTS ANALYSIS

With the model extensions described in §II, internal flooding level 2 PSA results regarding Containment Failure (CF) modes, Containment Failure Frequencies (CFF) and Fission Product (FP) release frequencies are obtained and compared to the internal event level 2 PSA results.

In a first place, it is noted that the internal flooding CDF is only 1.23% of the internal event CDF, thus two orders of magnitude lower. Consequently, it is already known beforehand that the internal flooding hazard has a minor impact on Belgian NPPs and that the outcomes and recommendations coming out of the internal flooding PSA study will be of low importance with respect to those derived from the internal events PSA.

III.A. Containment Integrity Related Results

The first result coming out of the Level 2 PSA for internal flooding is that the CFF equals to only 1.63% of the internal event CFF. It is therefore, alike the proportion on the CDF, two orders of magnitude lower as well. It is however slightly higher due to the reasons provided hereunder.

The CF modes with their proportions in percentage relative to the corresponding CDF are shown in Fig. 2. The probabilities of CF in percentage (i.e. the ratios of the CFF divided by the corresponding CDF) are given in the brackets in the titles of the pie-charts. Globally, the probability of CF for internal flooding (70.3%) is higher than the one for internal events (53.2%).

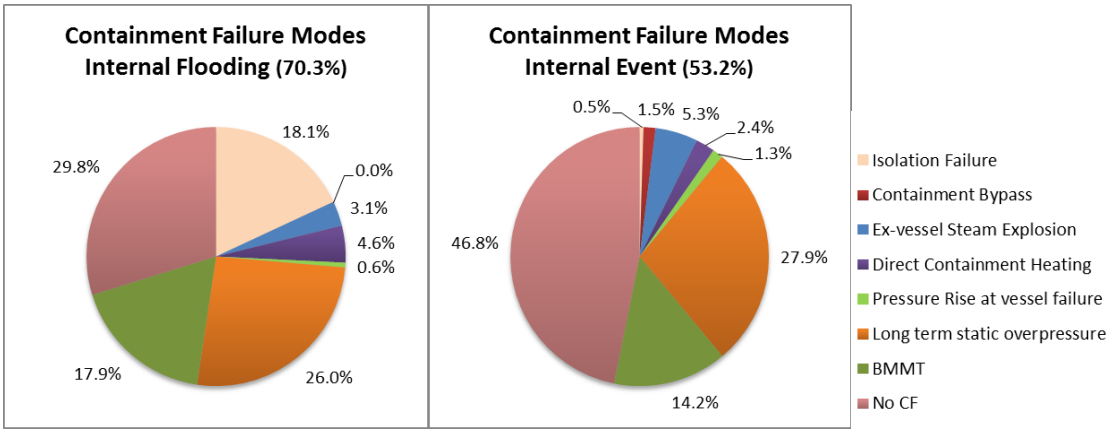


Fig. 2: Containment failure modes

Regarding the CF modes, it is noted that the proportion of isolation failure is much higher for internal flooding (18.1% versus 0.5% for internal events). This CF mode is further explained in §III.A.1.

Then no containment bypass sequence is observed at the level 1/level 2 PSA interface for internal flooding (0.0% versus 1.5% for internal events). Therefore there is no CF mode associated to containment bypass in the level 2 PSA results.

Finally, the proportion of Basemat Melt-Through (BMMT) is only a few percent higher for internal flooding (17.9% versus 14.2% for internal events). However, the probability of BMMT (relative to the corresponding CDF) is much higher in reality, due to the fact that the proportion of CF modes shown in Fig. 2 corresponds to the first CF mode occurring in a level 2 PSA sequence, while the different CF modes are not necessarily exclusive. This is further explained in § III.A.2.

III.A.1. Isolation Failure

Containment failure due to isolation defect is directly related to the containment isolation status at the interface (i.e. the PDS attribute #CI). As shown in TABLE 1, the significant increase in the proportion of isolation failure for internal flooding is due to the increase of the proportion of FIV (i.e. containment isolation defect due to isolation valve(s) failure) in the interface.

Indeed, as explained in §II.A.1, in internal flooding level 2 PSA, FIV includes both intrinsic equipment defect and flooding-induced equipment defect. This means internal flooding can yield a significant damage on containment isolation valves.

TABLE 1: Proportions of containment isolation outcomes - level 1/level 2 PSA interface

#CI	Internal flooding	Internal event
CI	0.814	0.995
CO	< 0.001	< 0.001
FIV	0.181	0.001
FSIG	0.004	0.004

Nevertheless, it should be noted that, although the proportion of isolation failure is much higher for internal flooding (18.1% versus 0.5% for internal events); the isolation failure frequency in case of internal flooding is only 44.5% of the one in case of internal events, given that the internal flooding CDF equals only 1.23% of the internal event CDF.

III.A.2. Basemat Melt Through

In level 2 PSA there are two types of CF: CF leading to atmospheric releases (thus failure of the upper structure) and BMMT. These two CF types are however not exclusive and can also occur in one single level 2 PSA sequence.

Fig. 3 shows the proportions of the three combinations of the two CF types and of "No containment failure". The sum of "CF leading to atmospheric releases only" plus "CF leading to atmospheric releases & BMMT" is equal to the sum of all CF modes except "BMMT" in Fig. 2. Then, "BMMT" in Fig. 2 is equal to "BMMT only" in Fig. 3. This means that "BMMT" in Fig. 2 represents level 2 PSA sequences for which BMMT is the only CF mode.

Further, by summing "CF leading to atmospheric releases & BMMT" and "BMMT only" in Fig. 3, the probability of BMMT relative to the corresponding CDF can be obtained: 67.1% for internal flooding and 50.3% for internal events.

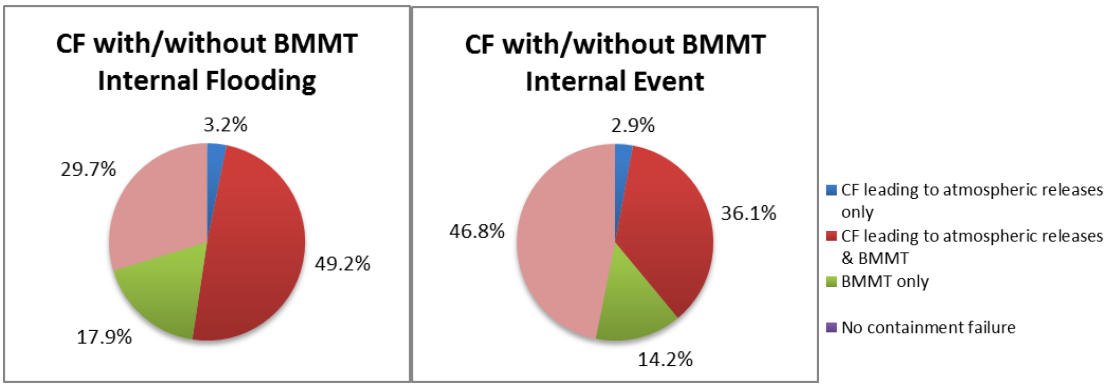


Fig. 3: Containment failure with or without BMMT

The higher probability of BMMT in the internal flooding level 2 PSA is mainly due to two reasons:

- The lower probabilities of successful AM actions, as explained in §II.B;
- The lower availabilities of safety injection and containment spray systems, because of the damages on them by the internal flooding.

The combination of these two facts leads to a less coolable corium debris in the reactor cavity pit and a lower probability of long term continuous reactor cavity flooding, which in turn lead to a higher probability of BMMT.

III.A.3. Conclusion

Given the analyses in §III.A.1 and § III.A.2, it is concluded that the ratio of the Containment Failure Frequency divided by the CDF for internal flooding is higher than the one for internal events mainly due to higher probabilities of isolation failure and Basemat Melt-Through.

III.B. Fission Products Releases Related Results

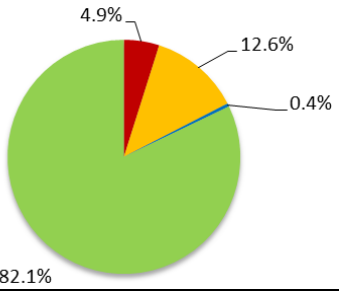
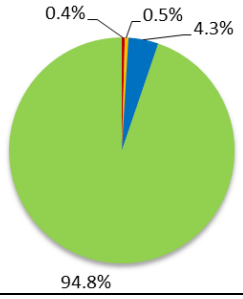
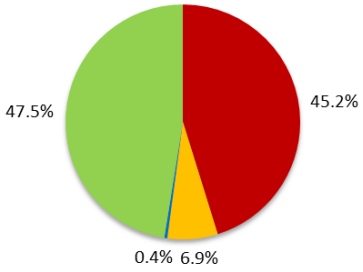
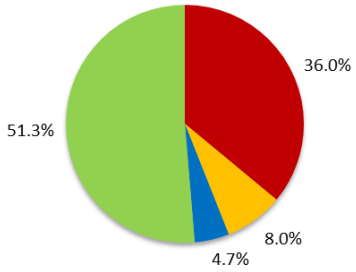
The internal flooding Early[3] and Late[4] "Not Small" RC (i.e. amount of releases more than 0.01% of the initial core inventory) frequencies equal to respectively 4.23% and 1.33% of the internal event ones.

TABLE 2 shows the proportions of Early and Late RCs for both internal flooding and internal events. When comparing the internal flooding level 2 PSA results to the internal event level 2 PSA results, the following remarks are made:

- For the Early phase, the proportions of Very Large and Large RCs increase significantly. For the Late phase, the proportion of Very Large RC is a few percent higher;
- The increases in the proportions of the RC mentioned above are mainly due to the higher probability of containment isolation failure in the internal flooding level 2 PSA;
- Nevertheless, the release frequencies of the RCs mentioned above are still much lower than in the internal event level 2 PSA, as the internal flooding CDF is two orders of magnitude lower than the internal event CDF.

[3] Early phase: before vessel failure
[4] Late phase: after vessel failure

TABLE 2: Early and Late FP releases

Phase	Internal flooding	Internal event
Early phase		
Late phase		

IV. CONCLUSIONS AND RECOMMENDATIONS

The internal flooding level 2 PSA results show that the associated risks, i.e. Containment Failure Frequency (CFF) and "Not Small" release frequencies, can be considered acceptable in comparison with the internal event level 2 PSA results, as the internal flooding CDF is two orders of magnitude lower than the internal event CDF.

This highlight the fact that the internal flooding hazard has a minor impact on Belgian NPPs and that the outcomes and recommendations coming out of the internal flooding PSA study will be of low importance with respect to those derived from the internal events PSA.

Nevertheless, the following conclusions and recommendations can be made:

- The internal flooding CFF is only 1.63% of the internal event CFF, thus two orders of magnitude lower;
- The ratio of the CFF divided by the CDF for internal flooding is higher than the one for internal events. This means that CDF sequences induced by internal flooding lead more likely to containment failure;
- One main reason of the higher CFF/CDF ratio is due to the lower probabilities of successful AM actions in internal flooding situations. Therefore, during operators' training, internal flooding situations could be simulated;
- Another reason is because of the high unavailability of safety systems due to internal flooding. Therefore, mobile alternative means[5] such as alternative containment spray and alternative injection systems are even more useful in internal flooding situations.

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