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IMPROVING QUALITY OF NPP PSA BY INTERNATIONAL COMPARISONS

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SUMMARY/ABSTRACT

A PSA comparison of various PSAs performed by different teams for nuclear power plants with a similar design has been conducted for three Framatome 900 MWe PWRs. This exercise appears to have been very constructive in particular for improving PSA quality and credibility.

The plants under consideration are the French 900 MWe PWR-series, the Belgian Tihange-1 PWR and the South African Koeberg PWR. The PSA comparison was conducted among the regulators of these countries, in a first stage for the French and Belgian PSAs, subsequently the comparison was extended to the South African PSA.

Up to the present, the comparison has been limited to internal initiating events and power states. The methodology used for these comparisons is a “top-down” approach, starting from an overall comparison of the results and trying to explain the most striking differences descending to an appropriate level of detail.

The differences identified may be due to differences in design, assumptions, completeness, data, or a combination of several reasons.

Many insights may be derived from this PSA comparison:

- Firstly, a general consistency of the models is observed.
- Many differences in the PSA results can be attributed to plant specifics;
- Design differences have in several cases had an unexpected effect, often being either a large effect of small differences or the contrary.
- Similarly, differences in assumptions, data, or completeness do not always have the expected effect.
- In many cases, a combination of differences is found, with an impact on the results that is difficult to foresee.

Such a detailed PSA comparison is, in fact, complementary to a very detailed review, yielding several additional insights attributable to the involvement of different PSA teams. The PSA comparison allows for the identification of potential PSA improvements as well as beneficial plant modifications, along with the effect on the risk profile to be expected. The comparison also indicates that improvements in PSA quality should not always be sought in more detailed or more realistic models, but may also be found in clarified presentations or improved justifications. In general, the insights allowed by the comparison are important aspects for effecting improvement in the PSA with respect to completeness, internal consistency, documentation and presentation.

The paper illustrates, by means of several specific examples, the value of this comparison exercise for improving PSA quality and usefulness. These examples particularly demonstrate the impact of:

- initiating event definition and frequency,
- design specifics,
- sequence analysis, including modelling assumptions and success criteria,
- data and common cause failures

The main benefit of this PSA comparison is an increased confidence in the studies and consequently a wider use of the PSA results.

INTRODUCTION

Within the framework of the French-Belgian regulatory working group on nuclear safety, a PSA comparison was conducted for a number of years by the technical support organizations IRSN and AVN. This comparison deals with PSA level 1 studies for internal events, performed for Framatome 900 MWe nuclear power plants of the same generation (the French 900 MWe PWR-series and the Belgian Tihange-1 PWR).

Within the framework of the cooperation between the regulatory authorities of the so-called FRAREG[1] countries, the previous PSA comparison was continued and extended to the Koeberg PWR of a similar Framatome design, with the participation of the South African regulatory body, NNR, and the utility Eskom.

The methodology, results and insights of the initial French-Belgian PSA comparison were presented at the PSAM5 and PSAM6 conferences [1, 2]. The current paper is intended to describe further insights from the recent French-Belgian-South African PSA comparison. For this tripartite comparison, the most recent PSA version was used, that is, the 2004 update for the French PSA, the 1997 version for the Tihange-1 PSA (an update being not yet available), and the 2002 version including a limited 2004 update for the Koeberg PSA.

These international PSA comparisons have proved to be a fruitful exchange of ideas and insights between PSA specialists of different organizations, being either PSA developers or PSA reviewers. The main benefits are an increased harmonization of the PSA models, and most importantly, a higher regulatory confidence in these plant-specific PSA when used for safety improvements (design, operating practices) or PSA applications (for example, precursor analysis).

GENERAL APPROACH

The general approach that has been adopted for the PSA comparison, consists of a direct comparison of the PSA results, with the primary objective to identify striking differences and to explain the results by examining design, operating practices, assumptions, models and data.

This approach turns out to be efficient and satisfactory as it leads to a straightforward identification of the differences, either between the PSAs or between the plants, which have a significant impact on the results. This approach was preferred to a rigorous, systematic analysis of all typical PSA elements (initiating events, accident sequences, systems, data, operating practices, human reliability), which would delay the interpretation of the PSA results till the end of the comparison exercise.

COMPARISON METHODOLOGY

Global comparison

The first stage of the PSA comparison exercise consisted of a global comparison of the results for all initiating event families for power states (including full and low power states, but excepting hot stand-by). At this stage, the exercise was limited to the comparison of the definition and frequency of all initiating events (IE) and the corresponding core damage frequencies (CDF).

It has to be noted that in order to allow for a consistent presentation of the results for the three PSA studies, and thus making the comparison easier, the definition or grouping of some initiating event families in the French PSA were changed and adapted to the definition used by the other PSAs.

This global comparison has allowed for a preliminary identification and explanation of some striking differences, mostly regarding specifics in plant design and operating practices. Nevertheless, to provide useful insights, this global comparison proved to be insufficient, indicating the need for a further more detailed comparison.

[1] FRAREG (Framatome Regulator Group) is an association of regulatory organizations of countries with NPPs of Framatome design.

Detailed comparison

In a second stage, it was therefore decided to select some initiating event families for a more detailed comparison. The main selection criterion was a significant CDF contribution (that is, at least 10^{-7}/r.y) in each PSA.

The detailed comparison has been performed down to the level of dominant core damage sequences or minimal cut sets, meanwhile also attempting to explain the observed differences by looking at data, system design characteristics, functional and thermal-hydraulic assumptions in accident sequence analysis, event tree construction, and human factor modelling.

Considering the aforementioned selection criterion, the following IE families were found to be suitable candidates for a detailed comparison: Small Break LOCA, Loss of the heat sink, Loss of off-site power, Loss of electrical buses, Primary transients. The latter, however, was rejected as a result of obvious design modifications to cope with dilutions, implemented at the Tihange-1 and in French 900 MWe plants, as reflected in the PSA results.

For various reasons, it was not feasible to compare all candidate IE families thoroughly, therefore, two important families were selected for the detailed comparison: Small Break LOCA (SBLOCA) and Loss of off-site power (LOOP).

It should be noted that the LOOP family was initially chosen for its significant CDF contribution, but then also for additional reasons, namely: an interest in comparing the impact on PSA results of some electrical equipment design specifics, of some modeling assumptions related to equipment involved in case of a total loss of both external and internal power supplies (Station Blackout), et cetera. For these reasons, the comparison of the LOOP family focused on the sequences including loss of internal power supplies, even if these are not the dominant sequences in each PSA.

RESULTS AND INSIGHTS OF THE COMPARISON

Initiating events

The definition of the initiating events (IE) or IE families (grouping of IEs) is very similar in the three studies. In general, initiating events correspond to events that lead to the actuation of a safety system (for example, safety injection) or reactor trip.

However, some particular initiating events have not been considered in each PSA. The most striking examples are the following:

1. In the 900 MWe PSA, some particular initiating events were considered that were not studied in the other PSAs:
   - “Small SGTR” (leakage) and “very small LOCA”, both being IEs without automatic actuation of the emergency core cooling system (ECCS). This choice mainly results from French operating experience. Nevertheless, for these IEs, it turns out that the CDF is not very significant.
   - A specific Interfacing System LOCA scenario: a large rupture of the thermal barrier of a primary pump, characterized by a significant primary water flow into the component cooling water system (CCWS), inevitably inducing a failure-to-close of the CCWS pneumatic isolation valve downstream from the thermal barrier leading to a rupture of the CCWS outside the containment in the CCWS pumps room. The CDF contribution is high.
   - Loss of both 6.6 kV emergency boards resulting from internal causes (potential common cause with long recovery time, derived from plant operational experience). The CDF contribution is high.

2. The loss of water intake by grid clogging (with recovery failure) was considered in the 900 MWe PSA and the Koeberg PSA, but it was considered negligible in the Tihange-1 PSA (the CDF is expected to be low as Tihange-1 has an ultimate heat sink). The high CDF in the 900 MWe PSA stems from the risk of not recovering the heat sink before depletion of all secondary water supplies (RHRS being unavailable).

3. The loss of reactor coolant pump (RCP) seal injection is considered in the Tihange-1 PSA and the Koeberg PSA, as it leads to a rather significant CDF. For the 900 MWe PSA, the CDF is expected to be low, due to a

more favourable design as the low-head safety injection system (LHSI) is still available in case of a loss of the cooling water system (ESWS or CCWS).

4. Small secondary line breaks are studied in the 900 MWe PSA and in the Koeberg PSA, but not in the Tihange-1 PSA (only large breaks). However, the CDF contributions are not dominant.

5. Secondary line breaks with an induced steam generator tube rupture were not studied in the Koeberg PSA. These IEs will be considered in a future update of the study.

Design specifics

General observations

The global comparison of the overall PSA results as well as the detailed comparison of the selected families (SBLOCA and LOOP) have revealed several *design differences*, that at times have a considerable effect on the PSA results. Some design specifics have a straightforward *positive* or *negative* effect on the CDF contributions, while other design specifics have a limited impact on PSA results.

In some cases, it proved to be rather difficult to reach a conclusion about the impact of design specifics on the PSA results. Indeed, quite often, sequences involving plant-specific systems simultaneously rely on various assumptions (functional, thermal-hydraulic, or modelling assumptions) or even simplifications that may differ from one PSA to another. In particular, the level of detail or conservatism of some assumptions may strongly depend on the range of CDF values found for the corresponding accident sequences. In other words, for the same type of accident sequence, a more favorable design may lead to the adoption of more simplified or conservative assumptions for the potential mitigating means or recoveries, whereas a less favorable design may be compensated for by more realistic assumptions, which may eventually lead to more or less comparable CDF values. Consequently, a straightforward comparison of the impact of design features is not always viable. Each assessment of the impact of a given design feature on PSA results should therefore be done carefully, taking into account all related assumptions (conservatisms).

Some design specifics

<u>Backup of LHSI pumps</u>

Some design specifics were pointed out when comparing the SBLOCA sequences.

The specific design of the containment spray system (CSS) at Tihange-1 allows for a backup of LHSI pumps: two out of six CSS pumps can be re-aligned from the control room with very little delay.

However, in the Tihange-1 design, the LHSI and CSS pump cooling by a common ventilation system leads to a dependency that somewhat decreases the positive effect of this backup.

On the other hand, the water make-up by the CVCS of the twin unit at the French plants also allows a backup of LHSI pumps. At Koeberg, cross-connection to the other unit is also possible, but not credited in the PSA.

<u>Secondary feedwater pumps</u>

A quick comparison of the sequences induced by a loss of the auxiliary feedwater (AFW) revealed some interesting differences in the main feedwater (MFW) system designs between the plants:

- only (two) turbine-driven MFW pumps are installed in the French plants, so AFW pumps have to be used during cooldown and startup of the plant;
- an additional motor-driven MFW pump (with a 45% capacity) was installed at Koeberg during construction and is mostly used, instead of AFW pumps, during cooldown and startup;
- atTihange-1, an even more favourable design exists as all MFW pumps are motor-driven pumps, allowing either MFW or AFW pumps to be used during plant shutdown and startup.

At Koeberg and Tihange-1, the different design of the MFW pumps allows a recovery of AFW failure leading to a very low probability of sequences corresponding to loss of secondary feedwater in power states. This positive impact was observed during the detailed comparison of Small Break LOCA.

These differences may also impact on the sequences and results in hot stand-by, hot shutdown and intermediate shutdown for the initiating event Loss of Feedwater (being Loss of AFW at the French plants). This IE was not examined in detail during this comparison of power states.

High-head safety injection system (HHSI) and HHSI pump cooling

Some design specifics at Tihange-1 significantly contribute to the core damage frequency:

- two manual valves of the essential service water system (ESWS) leading to a total loss of HHSI pump cooling, and hence HHSI unavailability, in case of mispositioning of one valve;
- a check valve located on the common suction line of the HHSI system.

Pressurizer LOCA

For Pressurizer LOCA, the highly different initiating event frequency is related to a different design:

- three parallel discharge lines with SEBIM valves (tandems) at the 900 MWe NPP and at Tihange-1;
- six parallel discharge lines in Koeberg (three lines with safety valves, three lines with a PORV and a block valve each).

This design difference proved less favorable at Koeberg for this particular IE (higher initiating event frequency).

Design modifications

Sequences leading to a heterogeneous dilution (non-borated and/or cold water slug sent to the core) were studied and modelled in each PSA. The design modifications to cope with such dilutions, as implemented at Tihange-1 and in the French 900 MWe plants, are clearly reflected in the PSA results. Implementation of a full set of modifications to cope with dilution is planned at the Koeberg NPP.

For all plants, it is worth mentioning that the implementation of an alternate scram system, in order to cope with the failure of reactor trip breakers, has led to a significant reduction of the CDF corresponding to ATWS sequences.

Design provisions in case of LOOP

A typical example of difficulty in comparing design specifics, as mentioned in the general observations above, is found in the Station Blackout sequences (LOOP with loss of EDGs).

On the one hand, the 900 MWe plants and Tihange-1 have dedicated on-site equipment (alternate power sources, alternate seal injection pumps), whereas such equipment is not available at Koeberg. However, these important design differences do not yield significant differences in the PSA results (CDF values). In fact, the less favourable design is compensated for by some more realistic assumptions in the Koeberg PSA: a more accurate modelling of DC battery depletion, meanwhile giving credit to operator actions related to DC battery load shedding (not considered in the other PSAs), and a less conservative RCP seal LOCA model (the time-dependent Westinghouse model, as against the more conservative models in the two other PSAs).

In this way design features and assumptions tend to balance each other out in the PSA. This clearly shows the need carefully to examine conservatisms and simplifications when comparing PSA results.

Data

Initiating event frequencies

LOCA

Dissimilarities are observed among the frequencies for large and intermediate break LOCA, whereas more agreement is found for small break LOCA frequencies despite their different origins. Improved justifications or some harmonization of such rare event frequencies, mainly stemming from expert judgment, may be desirable.

For Pressurizer LOCA, the differing initiating event frequency is related to a different design (as already mentioned).

LOOP

In general, for each PSA, the LOOP frequency, including the loss of both main and auxiliary power supplies, is based on the operating experience feedback of each country. A rather high IE frequency is found for Koeberg (0.33/r.y). This value is based on historical data and has to be attributed to the fact that the site is located “at the end of the grid" (about 90% of the South African power generation is located in the northern part of the country) and to weaknesses of the 400 kV supply lines connecting Koeberg with the grid.

The recovery time of the LOOP (used to define the mission time of the emergency diesel generators) differs between the studies (3 hours in the Koeberg and Tihange-1 PSAs, various times in the 900 MWe PSA because of French operating experience including hazard-induced events).

As a conclusion, some differences in the initiating event frequencies are justified by plant specifics (design, operating experience, maintenance…). Others are more disputable, notably the frequencies of rare events. Some effort toward harmonization of the approaches is desirable.

Reliability data

The reliability data used in the 900 MWe PSA and the Koeberg PSA is more recent and more plant specific (based on operating experience) in comparison with the mostly generic, less recent data used for the Tihange-1 PSA. In particular, the comparison of SBLOCA has shown the important impact of differences in component failure probabilities (most pessimistic data are found for the Tihange-1 PSA), which largely explains why the CDF of Tihange-1 is considerably higher for this IE. A similar effect is expected for other IEs. In this way, the PSA comparison clearly underlines the need for a regular update of data used in PSA, taking into account plant specific operating experience as much as possible.

Some specific examples are the following ones:

- The high CDF for ATWS sequences in the 900 MWe PSA is directly related to the high probability of stuck rods, based on French operating experience for one rod and on expert judgment for CCF parameters. This once again demonstrates the impact of plant specific data on the results.
- A dominant failure mode in the Koeberg PSA in case of LOOP (Station Blackout sequences, in particular) involves a common cause failure (CCF) of the 6 essential breakers of emergency boards, with no possible recovery even if the grid is recovered. This illustrates the need for further investigation of the CCF on such breakers in the other PSAs, as well as the assumption of non-recovery (conservatism).
- Regarding the probability of sump clogging considered in each PSA, in case of large or intermediate break LOCA, it has to be emphasized that the conclusions of the recent studies and experiments on sump clogging and the potential plant modifications have not yet been taken into account.

Success criteria

The comparison of SBLOCA has shown few differences in the success criteria derived from thermal-hydraulic calculations. For most sequences, the functional analysis and the success criteria are found to be consistent between the three PSAs.

A particular exception is the assumption related to the SI recirculation phase (required in the 900 MWe PSA and for the Tihange-1 PSA, but not required in the Koeberg PSA). This difference could prove to be important, however, its impact is compensated for by a conservative LHSI modelling (LHSI start in boosted mode). Nevertheless, the need for SI recirculation is currently being considered in the Koeberg PSA.

Modeling assumptions

Although the accident sequences modelling as well as many assumptions are very similar, the PSA comparison has revealed some dissimilarities that are reflected in the results, and therefore offered a good opportunity to assess their importance. Some examples are given below.

<u>Induced RCP seal LOCA</u>

Different models are used for induced RCP seal LOCA. An in-house model developed by IRSN is used in the 900 MWe PSA (RCP seal LOCA at t=0, with a two-step flow rate distribution), whereas the time-dependent Westinghouse model is used for the Koeberg PSA. In the Tihange-1 PSA, no specific RCP seal LOCA model is used[2], conservatively assuming a small LOCA at t=0. Assessment of the impact of these differences between the models on the sequences CDF is not straightforward.

Treatment of human actions

The detailed comparison for SBLOCA has revealed a difference having a large impact on the results, related to the treatment of human actions, their effect on CDF being either positive or negative.

- The introduction of an inadvertent shut-off of the safety injection (SI) system, considered in the 900 MWe PSA and Tihange-1 PSA, leads to a significant CDF contribution (negative impact). This demonstrates the need to examine such human error in the Koeberg PSA as well. Moreover, in the French study, the modeling and quantification of the errors of commission are more pessimistic, as an intervention of the emergency response team is not credited.
- The introduction of recovery actions, on the other hand, may have a significant positive effect. This is clearly seen in the 900 MWe PSA, and to a lesser extent in the Tihange-1 PSA. Perhaps the most striking example is the fast RCS cooldown and depressurization to LHSI conditions in case of HHSI failure. This action has a different impact for the three studies: a large positive impact in the 900 MWe PSA (as it greatly reduces the contributions due to HHSI failures), an intermediate impact in the Koeberg PSA, and a less pronounced impact in the Tihange-1 PSA (since its quantification is more pessimistic). However, the differences in the human error probabilities (HEP) mainly stem from differences in the accident procedures (potential operator or Shift Technical Adviser interventions).

Mission time

For the Tihange-1 and Koeberg PSA, the mission time of the systems in the SBLOCA sequences is 24 hours, being the typical value used in most PSAs. For the 900 MWe PSA, however, the mission time varies between 10 and 48 hours depending on the system mission which is considered (short term vs. long term missions). The impact of these differences on the CDF is limited for SBLOCA, at most a factor 2.

The same approach (realistic mission time instead of 24h) has been applied to other IE families in the 900 MWe PSA. In some cases (for example LOOP with long duration), a higher impact on the PSA results can be expected.

CONCLUSION

This international PSA comparison presents an excellent opportunity for the exchange of ideas about and insights into potential improvements and harmonization of the three PSAs, in terms of initiating events, models, assumptions and data.

In general, for the three PSAs involved in this comparison, it can be stated that:

- a general consistency between the models is observed;
- many differences in the PSA results can be attributed to plant specifics (design, operating practices, procedures, operating experience feedback);
- design differences have in several cases had an unexpected effect, often being either a large effect of small differences or the contrary;
- similarly, differences in assumptions, data, or completeness do not always have the expected effect;
- in several cases, a combination of several differences was found, having an impact on the results that is difficult to foresee.

Such a detailed PSA comparison is, in fact, complementary to a very detailed review, yielding several additional insights as a result of the involvement of various PSA teams. Indeed, the PSA comparison allows the identification of potential PSA improvements as well as beneficial plant modifications, along with the effect on the risk profile to be expected. The comparison also indicates that improvements in PSA quality should not always be sought only in more detailed or more realistic models, but can also be found in clarified presentations or improved justifications. In general, the insights of the comparison form an important aspect towards the improving of the PSA with respect to completeness, internal consistency, documentation and presentation.

[2] For the update of the Belgian PSA, including the Tihange-1 PSA, the Westinghouse RCP seal LOCA model will be considered.

The main benefits of this PSA comparison are an increased harmonization of the PSA models, and most importantly a higher confidence in these plant-specific PSA studies and consequently a wider use of the PSA results.

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