ABSTRACT

In 2007, Slovenian Nuclear Safety Administration initiated the project on applications of Krško PSA model in the regulatory activities. As a part of the project, the Level 2 PSA model (internal events at power) was to be upgraded in a way that Level 2 risk measures can be computed more directly, for the purpose of regulatory applications.

One specific point of the initial Krško PSA study was that only the top 40 Level 1 core damage sequences were propagated to the bridge trees and Level 2, out of the total of 184 core damage sequences. At the time of the initial study, these particular 40 sequences contributed, cumulatively, more than 90% to the total core damage frequency. This approach can be considered acceptable for the long term averaged base case results, but may be questionable for the applications such as PSA-based event analysis where Level 2 results may need to be re-computed conditionally on the specific (e.g. failed) status of some containment systems.

Therefore, the model had to be upgraded in a way that all Level 1 core damage sequences are propagated to the Level 2. This involved Level 1 sequence grouping, upgrade to the bridge tree models, and propagating of a number of new plant damage states (PDS) to the radiological release categories.

The process resulted with a model which can be used for repeated computing of the Level 2 results with taking into account all Level 1 core damage sequences.

The paper describes the model upgrade and the results of new Level 2 quantification.

1 INTRODUCTION

One limitation of risk informed applications based on Level 1 PSA model is that they cannot define risk significance of those containment systems and functions which are not related to core damage risk, i.e. Level 1 risk measure. Those systems and functions can be related to Level 2 risk measures such as frequencies of events with different radiological releases to environment.

In 2007, Slovenian Nuclear Safety Administration initiated the project on applications of Krško PSA model in the regulatory activities. As a part of the project, the Level 2 PSA
model (internal events at power) was to be upgraded in a way that Level 2 risk measures can be computed more directly, for the purpose of regulatory applications.

The initial Krško Level 2 PSA study was performed in the 1993-1995 time frame, as a part of the Individual Plant Examination (IPE), [1], [2]. One specific point of the IPE study was that only the top 40 Level 1 core damage (CD) sequences were propagated to the bridge trees and Level 2, out of the total of 184 Level 1 core damage sequences, [1]. At the time of the IPE study, these particular 40 sequences contributed, cumulatively, more than 90% to the total core damage frequency, [1], [3]. This approach can be considered acceptable for the long term averaged base case results, but may be questionable for the applications such as PSA-based event analysis where Level 2 results may need to be re-computed conditionally on the specific (e.g. failed) status of some containment systems.

Therefore, for the purpose of future regulatory PSA applications, the model had to be upgraded in a way that all Level 1 core damage sequences are propagated to the Level 2 and their contributions taken into account when Level 2 results are re-quantified for the purpose of any PSA application.

Upgrade done to the model is fully described in the reference [4].

2 INPUT KRŠKO LEVEL 2 PSA MODEL

In Krško PSA, the quantification of Level 2 consists of two distinctive stages: 1) propagation of Level 1 core damage sequences to plant damage states (PDS) and 2) mapping of PDS to Level 2 release categories.

The first stage is performed by means of interfacing event trees or, so called, bridge trees, which are part of the RiskSpectrum PSA model. Referential RiskSpectrum PSA model for the Level 2 upgrade project is defined in the reference [4]. Each bridge tree is a model of response of containment systems to a postulated reactor core damage event. As pointed earlier, in Krško PSA only the top 40 (out of 184) Level 1 core damage sequences (as quantified by the IPE study, [3]) were selected for propagation to Level 2. For each of these sequences, a specific bridge tree was developed. The end states of bridge tree sequences represent plant damage states (PDS). Propagated to Level 2 were only those bridge tree sequences with calculated frequency of at least 1E-10 /yr, [1] (which is the second limitation of the original Level 2 quantification process).

The second stage of Level 2 quantification in Krško PSA is performed by means of an accident progression event tree or a containment event tree (CET). The nodes of CET represent various relevant containment phenomena taking place following a core damage event. Input into a CET is a specific PDS. The end states of CET sequences are release categories. Therefore, by means of CET, frequency of each PDS is mapped into a set of frequencies of different release categories. The mapping is performed externally to RiskSpectrum PSA model.

The bridge trees consider the following functions relevant for containment systems behaviour [1]:

- Reactor Coolant System depressurization (post core damage);
- Reactor Containment Fan Coolers (RCFC);
- Transfer of Refuelling Water Storage Tank inventory into containment (post core damage injection and recirculation);
- Containment Spray injection and recirculation;
- Containment isolation.

Table 1 presents six functional characteristics or attributes by which each PDS is defined. Table 2 presents 12 release categories defined in Krško Level 2 PSA.
Table 1: Krško PSA Plant Damage States Designators, [1]

<table>
<thead>
<tr>
<th>#</th>
<th>Functional Characteristic (Attribute)</th>
<th>Designator / State</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Initiator</td>
<td>A = Large LOCA</td>
</tr>
<tr>
<td></td>
<td></td>
<td>S = Small LOCA</td>
</tr>
<tr>
<td></td>
<td></td>
<td>T = Transient</td>
</tr>
<tr>
<td></td>
<td></td>
<td>V = Interfacing LOCA</td>
</tr>
<tr>
<td></td>
<td></td>
<td>W = SGTR</td>
</tr>
<tr>
<td>2</td>
<td>Time to core melt</td>
<td>E = Early (less than 4 hours)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>L = Late (more than 4 hours)</td>
</tr>
<tr>
<td>3</td>
<td>RCS pressure at vessel failure</td>
<td>H = High</td>
</tr>
<tr>
<td></td>
<td></td>
<td>L = Low</td>
</tr>
<tr>
<td></td>
<td></td>
<td>R = In-vessel recovery</td>
</tr>
<tr>
<td>4</td>
<td>ECCS status</td>
<td>N = No injection</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B = Injection before vessel failure</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A = Injection after vessel failure</td>
</tr>
<tr>
<td>5</td>
<td>Containment Heat Removal (CHR) status</td>
<td>N = No CHR available</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Y = CHR available</td>
</tr>
<tr>
<td>6</td>
<td>Containment Status</td>
<td>N = initially intact</td>
</tr>
<tr>
<td></td>
<td></td>
<td>I = isolation failure</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B = bypass</td>
</tr>
</tbody>
</table>

Table 2: Release Categories in Krško Level 2 PSA, [2]

<table>
<thead>
<tr>
<th>#</th>
<th>RC</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>RC1</td>
<td>Core recovered in-vessel, no containment failure</td>
</tr>
<tr>
<td>2</td>
<td>RC2</td>
<td>No containment failure</td>
</tr>
<tr>
<td>3</td>
<td>RC3A</td>
<td>Late (time frame IV) containment failure, wet containment (i.e. no Molten Core Concrete Interaction, MCCI)</td>
</tr>
<tr>
<td>4</td>
<td>RC3B</td>
<td>Late (time frame IV) containment failure, dry containment (i.e. MCCI takes place)</td>
</tr>
<tr>
<td>5</td>
<td>RC4</td>
<td>Basemat penetration (no overpressure failure or very late overpressure failure)</td>
</tr>
<tr>
<td>6</td>
<td>RC5A</td>
<td>Intermediate (time frame III) containment failure, wet containment (i.e. no MCCI)</td>
</tr>
<tr>
<td>7</td>
<td>RC5B</td>
<td>Intermediate (time frame III) containment failure, dry containment (i.e. MCCI takes place)</td>
</tr>
<tr>
<td>8</td>
<td>RC6</td>
<td>Early (time frame I or II)</td>
</tr>
<tr>
<td>9</td>
<td>RC7A</td>
<td>Isolation failure, wet containment (i.e. no MCCI)</td>
</tr>
<tr>
<td>10</td>
<td>RC7B</td>
<td>Isolation failure, dry containment (i.e. MCCI takes place)</td>
</tr>
<tr>
<td>11</td>
<td>RC8A</td>
<td>Bypass, scrubbed</td>
</tr>
<tr>
<td>12</td>
<td>RC8B</td>
<td>Bypass, unscrubbed</td>
</tr>
</tbody>
</table>

3 LEVEL 2 MODEL UPGRADE

3.1 Approach to Release Category Frequency Profile Quantification

Frequency of events with \( j \)th category of release \((j=1,...,12\), refer to Table 2\), \( f_{RC,j} \), can be calculated as

\[
f_{RC,j} = \sum_{i=1}^{N} p_{i,j} f_{PD,i} \quad , \quad j=1,...,12
\]
where
\[ N_{PD} \] total number of plant damage states in the model (i.e. number of different end states of bridge tree sequences);
\( p_{i,j} \) split fraction for mapping of \( i^{th} \) plant damage state to \( j^{th} \) release category (conditional probability that \( i^{th} \) PDS develops into \( j^{th} \) release category), where
\[ \sum_{j=1}^{12} p_{i,j} = 1 \]

\( f_{PD,j} \) frequency of events developing into \( i^{th} \) PDS.

Frequency of \( i^{th} \) PDS, \( f_{PD,i} \), is calculated as a sum of frequencies of all bridge tree sequences with an end state corresponding to the \( i^{th} \) PDS, i.e.

\[ f_{PD,i} = \sum_{k=1}^{N_{BT}} \sum_{l=1}^{f_{BTseq,i,k}} f_{BTseq,i,k}^{(i)} \]

\( i = 1, \ldots, N_{PD} \) \hspace{1cm} (2)

where
\[ N_{BT} \] total number of bridge trees in the model (covering all 184 CD sequences);
\( f_{BTseq,i,k}^{(i)} \) number of sequences in \( k^{th} \) bridge tree leading to the \( i^{th} \) PDS;
\( f_{BTseq,i,k}^{(i)} \) frequency of scenario of events associated with \( l^{th} \) sequence leading to \( i^{th} \) PDS in \( k^{th} \) bridge tree.

Frequency \( f_{BTseq,i,k}^{(i)} \) is, for every \( l \) and every \( k \), calculated by the RiskSpectrum PSA model, based on the corresponding minimal cutsets. The calculation takes into account contributions from all relevant Level 1 core damage sequences. This is achieved by a proper linking of the Level 1 event trees to the bridge trees.

The upgrades which had to be done to the model in order to be able to apply this approach to quantification of release category profile, and to eliminate the existing limitations pointed above, can be summarized as follows:

- Develop, instead of the existing 40 bridge trees for the top 40 Level 1 CD sequences, the bridge tree models which would appropriately represent a response of containment systems and functions to every one of 184 Level 1 CD sequences. Assign appropriate PDS to every bridge tree sequence in every bridge tree. Link the existing Level 1 event tree sequences to the new bridge trees in the referential input RiskSpectrum PSA model.
- Determine the inventory of plant damage states assigned to all bridge tree sequences. For every “new” PDS (i.e. a PDS not existing in the original Level 2 quantification), determine the set of split fractions for mapping to release categories \( (p_{i,j}, j=1,\ldots,12, \text{ in Eq. (1)})) \).

With this done, the Level 2 release category frequency profile can be calculated by applying Eq. (2) and Eq. (1).

### 3.2 Bridge Tree Modelling (Level 1 – Level 2 Interface)

In the upgraded model, all 184 core damage sequences had to be propagated to Level 2 analysis. Thus, all the CD sequences needed to be grouped in a way that the same bridge tree (containment systems response) could be applied to a particular group. The number of the obtained groups determined the number of the bridge trees needed. In this process, each of the 184 CD sequences was evaluated to determine the set of possible PDSs to which it can lead.

For example, regarding the PDS attribute “ECCS status” (possible states B,A,N - Table 1), the Level 1 CD sequences were divided into the following three categories:
• Sequences involving successful ECCS injection (high pressure or low pressure) in Level 1 event tree and, thus, leading to PDS “xxxBxx”;
• Sequences involving failure of all ECCS injection (in Level 1 event tree) and, thus, leading to PDS “xxxxbx”, where b=B,A,N, depending on the initiating event type and status of Containment Spray Injection (success or failure).
• High pressure sequences with unknown (unquestioned) status of ECCS injection in Level 1, leading to PDS “xxxaxx”, where a = A,N, depending on the status of bridge tree function “ECCS injection” (post vessel failure) or “Containment Spray Injection”.

Corresponding set of rules was applied for all other PDS attributes. Additionally to the possible PDSs, the CD sequence groups were further divided, as needed, on the basis of support system status, which is not explicitly considered in the six PDS attributes. In the last stage, system success criteria, timing and Human Reliability Analysis aspects were considered for establishing the final CD sequence grouping.

For bridge tree models definition, generic bridge tree and containment systems function events established in the PSA study, [1], were used. The process resulted with 44 bridge trees. (The top 40 sequences from the IPE study were also subject to grouping.) Linking of 184 Level 1 CD sequences to 44 bridge trees was performed by using RiskSpectrum event tree linking features, [5].

### 3.3 Mapping of PDS to Release Categories

Upgrade of the bridge tree models to cover all 184 Level 1 CD sequences resulted in a number of PDSs which were not considered in the IPE study, since they were not involved in the top 40 core damage sequences. (The upgraded model contains the total of 94 PDSs.)

![Figure 1: Containment Event Tree (Accident Progression Event Tree) (Part)](image)

For these “new” PDSs, mapping to release categories (RC) had to be performed, i.e. conditional probabilities \( p_{ij} \) for Eq. (1) had to be determined. This was done by propagating each new PDS through the Containment Event Tree (CET) established in the IPE study, [2]. The CET is large event tree structure (15 function events, 246 sequences) which represents accident progression in the containment by considering relevant containment phenomena. A part of the Krško PSA CET is shown in Figure 1. As an end state to each accident progression path (CET sequence), one among the 12 release categories from Table 2 is assigned.
The IPE study, [2], provides analyses of CET function events and associated probabilities for all relevant types of PDSs. This was used as a basis for quantifying the CET for each one among the “new” PDSs. Probabilities were assigned to CET nodes depending on the PDS of concern and CET path taken. The process resulted with a matrix containing conditional probabilities $p_{i,j}$, Eq. (1), for mapping the $i^{th}$ PDS into $j^{th}$ RC with $i = 1, \ldots, 94$ and $j = 1, \ldots, 12$.

4 LEVEL 2 REQUANTIFICATION

The Level 2 PSA results were re-quantified by the upgraded model. First, base case results were reproduced and then, to demonstrate usability of the model, two sensitivity cases were analyzed: Case 1 with assumed unavailability of Reactor Containment Fan Coolers (RCFC) at the time of initiating event occurrence, and Case 2 with assumed unavailability of both RCFC and Containment Spray.

4.1 Base Case

The Krsko PSA Level 2 results represent estimated frequencies of events with defined release categories. They are obtained by the approach presented in section 3.1, through the following major steps:

- Calculate frequencies $f_{BTseq,i,k}$, Eq. (2), for all bridge tree sequences. This is done by generating minimal cutsets through the corresponding sequence-type analysis cases, [5], in the upgraded RiskSpectrum PSA model. There is a total of 1416 sequences in the 44 bridge trees which need to be processed.
- Verify the total frequency by summing up all obtained 1416 $f_{BTseq,i,k}$ values and comparing the sum to the referential core damage frequency (CDF) from the Level 1 analysis. This is needed as a consistency check. The referential CDF is taken to be a sum of frequencies of 184 Level 1 CD sequences (sequence-type analyses, [5]). For the base case quantification, the difference is very small:

$$\text{Referential CDF} = 2.94E-05 \text{ /yr}$$
$$\text{Total BT Sequences Frequency} = 2.91E-05 \text{ /yr}$$

It is noted that the sum of frequencies of the 40 CD sequences which were propagated to Level 2 in the IPE study is 2.25E-05 /yr, which represents only 76.5% of the referential CDF.

- Combine bridge tree sequence frequencies $f_{BTseq,i,k}$ into PDS frequencies $f_{PD,i}$, Eq. (2), for all 94 PDSs ($i = 1, \ldots, 94$).
- Using the matrix with conditional probabilities $p_{i,j}$ map the frequencies of 94 PDSs into the frequencies of 12 release categories, Eq. (1).

The resulting RC frequencies are presented by Figure 2 (“Base Case”). As it can be seen, a core damage event would by 57% probability develop into one of the categories which are in the IPE study, [2], considered to be “very small releases”, RC1, RC2 or RC4 (refer to Table 2). By 41% probability it would develop into categories with intermediate or late releases, RC5A,B or RC3A,B. The remaining 2% is the probability that it would develop into what can be considered as large and early release, LER, (RC6 through RC8B).

The obtained results were compared to those which would be obtained by applying only the selected 40 CD sequences, [4]. The comparison has shown that the CDF difference (from non-propagated CD sequences) distributes among the general RC classes in similar proportions as the referential CDF itself (nearly 60% to very small, some 40% to late/intermediate, and several remaining percents to large / early releases).
4.2 Case 1: RCFC Unavailability

The representative fault tree gate for the RCFC function was set to failed state in the upgraded RiskSpectrum model and release category frequency profile re-quantified by the above outlined procedure. The results are shown in Figure 2 (“No RCFC”).

As it can be seen, there is no relevant impact on LER categories. (The differences as low as those of the order of 1E-09 /yr or lower may be caused by different minimal cutset modularization or even rounding errors, rather than being actual differences in probability.) However, the frequency profile has significantly shifted from the categories with no containment overpressure failure (RC2, RC4) to the categories with late or intermediate containment overpressure failure (RC3B, RC5A). Increased likelihood of containment failure following a core damage event comes from the fact that RCFC cannot provide containment heat removal (CHR) function. Containment failure can, however, still be avoided by the combined operation of Containment Spray and Low Pressure ECCS Heat Exchangers, which can provide the CHR function. For this reason, scenarios with no containment failure are still credible with conditional probability of 39% (RC1, RC2 or RC4) as compared to 57% base case probability for the same categories. This point is further demonstrated by the Case 2.

4.3 Case 2: Coincidental Unavailability of RCFC and Containment Spray

In this case, the representative fault tree gates for both RCFC and Containment Spray were set to failed state and Level 2 results re-calculated. They are shown in Figure 3. The impact on the LER categories is marginal (RC6). (Regarding the differences of the order of 1E-09 /yr or lower, the same remark applies as above.) However, conditional probabilities of categories with no containment failure (RC2, RC4) have been completely redirected to the categories with late and intermediate containment failures (RC3B, RC5A). With both RCFC and Spray unavailable, there is no option for CHR and scenarios with no containment failure are not credible (with the exception of in-vessel recovery, RC1).

5 CONCLUSIONS

The upgrade described has resulted with a model which can be used for repeated computing of the Level 2 results with taking into account all Level 1 core damage sequences. Recalculations can be done reasonably fast. It is, however, stressed that the most of the work
and effort in the PSA applications such as operational event analysis may relate to appropriate mapping of the observed event into the PSA model and to correct results interpretation, rather than to repeating the model quantification and producing of the results.

Demonstration examples have shown that assumed unavailability of RCFC and Containment Spray functions has only marginal impact on LER categories frequency. (This is not an unexpected result since the LER frequency is dominated by containment bypass sequences where any of these two functions (RCFC/Spray) has little or no influence.) However, these examples have shown significant impact on frequency of categories with intermediate or late releases. It is recommendable, when PSA model is used in the risk informed decision making process, that LER frequency is not taken as a sole criterion and that due attention is paid to the full and detailed interpretation of results obtained.

REFERENCES


