ABSTRACT

The process of Safety Margin Assessment, as proposed in the SMAP framework (Safety Margins Action Plan), is based on the extensive application of uncertainty analysis methods with the objective of obtaining an estimation of the exceedance frequencies of specified limits. The Damage Domain approach is presented as an adequate method to perform the uncertainty analysis, especially suited for those sequences where some events occur at uncertain times. This approach has been proposed by Consejo de Seguridad Nuclear (CSN), Spanish Nuclear Regulatory Body, in the context of the application exercise SM2A (Safety Margin Application and Assessment) and has been used to develop the analysis of selected scenarios of loss of Component Cooling and/or Service Water as a contribution of CSN to SM2A exercise. Computations have been performed with the integral code MAAP and results are being compared with the best estimate plant simulation code TRACE. SCAIS (Simulation Code System for Integrated Safety Assessment) is the simulation-based computational framework that is being developed by the CSN to perform those computations.

1 INTRODUCTION

The OECD/NEA Committee for Safety of Nuclear Installations (CSNI) has promoted some international initiatives to develop suitable criteria for determining the “safety margins” to provide an acceptable level of safety in NPP, see ref [1]. With this purpose, the Task Group on SM2A has been set up to carry out a pilot application project of calculating the increase in exceedance frequency of damage resulting from a power uprate of 10% in Zion NPP.
Within CSN, and in particular in the Modeling and Simulation (MOSI) branch, it has been developing SCAIS, see ref [2], a simulation-based computational framework that implement the ISA methodology (described below). This methodology has been applied by the CSN, in collaboration with UPM and Indizen, in the exercise proposed by SM2A Task Group for sequences of loss of Component Cooling Water (CCW) and/or Service Water (SW) as initiating events.

The general block-diagram of the ISA methodology is shown in Fig. 1, see ref [2]. The numerical result of this methodology consists of the exceedance frequency of damage for the sequences stemmed from an initiating event. This is done along with the delineation of the dynamic event tree and the identification of the damage domains in the sequences that contribute to the total damage exceedance frequency. The damage domain is defined as the region of the space of parameters of interest that results in damage sequences.

![Fig. 1: ISA methodology general diagram](image)

This methodology consists of the following blocks:

- **Block B.** In the sequence generation module, a set of interconnected codes performs the automatic simulation of dynamic event trees. This will provide the candidate sequences that will be analyzed in detail in the Path Analysis module (Block E). The codes that are currently part of this block are: a simulation control code (BABIECA, ref [2]), the code for simulation of the operator crew following Emergency Operating Procedures (SIMPROC, ref [3]), the code describing the plant model (TH code like MAAP, ref [4], or TRACE, ref [5]) and the event scheduler (DENDROS, ref [2]).

- **Block E.** In the paths analysis module each sequence of interest obtained in block B is repeatedly simulated with different values of selected parameters and/or time delays (human actions or stochastic phenomena). Each such simulation is called a path. The region of parameter and/or time delays values that lead to damage paths is the damage domain of the sequence, and is determined by this tool. It must be noted that a sequence may contain a set of paths leading to damage and another set of paths leading to success.

- **Block A.** The probability and delay times quantification module provides the necessary information to calculate the probabilities and the exceedance frequency of damage of each sequence of interest which are calculated in Block D (Risk Assessment).

- **Block D.** The risk assessment module calculates the exceedance frequency of damage by integrating the probability distributions on the damage domain region obtained in Block E (Path Analysis module).

The analyses can be iterated to precisely define the damage domain border, also taking the complexity of the TH code used into account to limit computing time.
2 SEQUENCES GENERATION MODULE. DYNAMIC EVENT TREE SIMULATION

The objective of Block B of the ISA methodology, the details of which are shown in Fig. 2, is to simulate the dynamic event tree (DET) stemming from an initiating event. Dynamic event trees follow the evolution of the plant according to the occurrence or not of events that change the plant dynamics, i.e., the set of governing laws that determine the dynamic evolution of the accident.

The main components of this software package (Block B) are summarized as follows:

- **Thermal-hydraulic code (plant model):** This code performs the plant transient simulations, providing for the use of different thermal-hydraulic codes like MAAP or TRACE coupled through the Babieca driver.

- **SIMPROC (procedures simulator):** Simulates the operator interventions following emergency operating procedures (EOPs), and interacts with the plant simulator to control the transient evolution.

- **Dendros (event scheduler):** It is in charge of driving the unfolding of the Dynamic Event Tree, by opening branches based on the plant state. Dendros allows the parallelization of the tree generation. It also collects quantitative risk results by calls to the probability calculator, which is fed with the plant systems status.

- **Babieca (driver):** This driver code handles the communication among the modules above (Thermal hydraulic code with SIMPROC and Dendros). It is also provided with a library of lumped-parameter models, ref [6], implemented in a set of thermal hydraulic modules which allow simulating light water reactors in a simplified way.

- **Probability wrapper:** It connects the probability engine (block A) with Dendros to compute the probability of each sequence. Pruning rules can be implemented based on the results to avoid an excessive number of branches for the tree.

- **Global database:** The global database stores the simulation input and output decks for the DET structure and for the simulation results of each branch. It has enough information to be able to store a simulation at one time point and perform a restart of the simulation from that point on. Path Analysis module (Block E) takes the information stored in this database in order to obtain the damage domain of each sequence.

Figure 2: Sequence generation module (Block B).
Test simulations that include the DET generation by means of the connection/communications between MAAP, Babieca and Dendros have been performed. To this end, rules for event tree delineation, such as the branch opening and sequence truncation criteria have been established. Data from the Zion Probabilistic Safety Analyses (PSA), see ref [7], have been used to estimate the branch frequency results.

2.1 Application to Loss of CCW/SW Scenario

The loss of CCW and/or SW impacts the plant operation due to the loss of cooling of essential equipment as reactor coolant pumps and safeguard systems. After the loss of CCW/SW, the reactor coolant pumps are the components first affected by the loss of cooling. Operators are required to trip the reactor and stop the pumps upon activation of the high temperature alarm. At the same time, other equipment is affected. In particular, charging pumps may result inoperable because of high temperature. Important functions like reactor coolant pump seal injection or primary coolant inventory control are then lost or seriously degraded.

Even if the reactor coolant pumps are stopped, lack of water injection to the seals combined with loss of cooling water to the thermal barrier may lead to seal damage resulting in a seal LOCA.

The Auxiliary Feedwater System (AFW) plays a very important role in this kind of scenarios. It provides the means for cooldown and guarantees that severe core damage is prevented in non seal LOCA cases, even without CCW/SW recovery.

In the case that a seal LOCA occurs as a consequence of the loss of CCW, safety injection systems (SIS) are needed to compensate the loss of inventory. However, both High Pressure and Low Pressure Safety Injection (HPSI and LPSI) are unavailable while CCW is not recovered. Accumulators are the only available injection system under these circumstances. In our study, all the SIS have been considered, conditioned to the CCW recovery and with their corresponding failure probabilities.

Described below is the application of the sequence generation module for obtaining the DET.

2.1.1 Dynamic Event Tree for the Scenario of Loss of CCW/SW

A preliminary selection of the loss of CCW/SW headers has been performed. Sequences with reactor trip failure have not been included because they are transferred to the ATWS event tree. Sequences with failure of AFW have not been considered to reduce the scope of our analysis. Sequences without seal LOCA have not been analysed because do not have significant contribution to core damage since the intervention of AFW is enough to prevent damage, even without CCW recovery. Additionally, recirculation has been included in LPSI header because it is conditioned to availability of LPSI pumps.

Thus the analysis has been oriented towards a sequences with the following headers: SLOCA (RCP seals failure with a total leakage flow of 4.592E-02 m$^3$/s); RU (Recovery of CCW/SW and HPSI available); RL (Recovery of CCW/SW and LPSI available) which include the recirculation phase; S (Beginning of primary cooling at 55K/h); A (Accumulators discharge three out of four).

Simulations that include the DET generation by means of the connection/communications between MAAP, Babieca and Dendros have been performed. One DET obtained for the cases at 100% of power is shown in Fig. 4. Pressure in primary system of every sequence is shown in Fig. 5. From the analysis of the results it is found that there are some sequences in which the end state is not always success or damage. For those
sequences, it is necessary to obtain their damage domain, i.e. the time/parameter region where the damage condition is reached. Fig. 6 shows this classification graphically. In these sequences the damage or success end state depends on the starting time of the S header and the time of CCW/SW recovery, which are human actions with a given probability distribution (both probability distributions are described further below). The damage domains are obtained in the Path Analysis Module (Block E).

![Figure 3: Dynamic Event Tree of Seal LOCA with recovery of CCW/SW with power at 100%](image1.png)

![Figure 4: Pressure in the primary system of different sequences with power at 100%](image2.png)

![Figure 5: Event tree for seal LOCA with recovery of CCW/SW showing the sequences classified as: success, damage or damage domain.](image3.png)

In order to obtain the increase in damage exceedance frequency it must be taken into account that only the sequences with damage domain (S0 to S4) are susceptible to have different contribution in the cases of 100% and 110% power.

3 PATH ANALYSIS MODULE

Path Analysis Module (Block E) receives the sequence and parameter information of all branches of DET from the sequence generation module (block B) and determines the damage domain of the candidate sequence. In each sequence of the DET, it is possible that some headers have different completion timings (mainly operator actions but also events with stochastic phenomenology) within a time interval. These completion timings are related to a
probability distribution. In order to take into account this uncertainty a time sampling is performed for each non-deterministic header (NDH) inside the time interval.

As previously commented, in a sequence of the DET there is a set of paths and some of them could be damage paths and others non-damage paths. This is the reason why we need to obtain the damage domain of each sequence. If there are several non-deterministic headers and/or uncertain parameters, it will be necessary to perform a multidimensional time sampling.

3.1 Application to Loss of CCW/SW. Simulations Performed with MAAP and TRACE Codes

From the analysis of the Zion PSA it has been obtained that S1 is the sequence with damage domain that has the highest frequency and for this reason the damage domain will be calculated for this sequence. The calculation process performed in sequence S1 with MAAP code is explained below:

1. Failure of S header is assumed, with the result of no manual depressurization in secondary side. A transient (path) is simulated for each time of CCW/SW recovery considered. In these sequences, damage will arrive at a certain time $t_0$, which sets the maximum time for the (manual) start of depressurization. Starting depressurization later than $t_0$ time is not useful to avoid damage and no more analysis is required. These time points form the line of Previous Damage (PD) above the diagonal that is shown in Fig. 6.

2. Failure of header R is assumed, with the result of no SIS injection due to the lack of his cooling. A path is simulated for each time of initiation of manual depressurization in secondary side. In these sequences, damage will arrive at certain time $t_1$, which sets the maximum time for the recovery of CCW/SW. Recovering of CCW/SW later than time $t_1$ is not useful to avoid damage and no more analysis is required. These time points form the line of PD below the diagonal.

3. A set of paths are simulated with different times for the beginning of depressurization and CCW/SW recovery, always below the PD line. Some of the paths exceed the damage condition (red diamond) while other paths do not reach it (blue circle). The damage boundary line is drawn by joining every path that exceeds the damage condition that is beside to a path that does not.

4. The same process is followed for the power uprate of 10%.

In a second stage a similar analysis has been performed with TRACE. The TRACE model of Zion NPP, provided by Paul Scherrer Institute, was modified in order to obtain one with similar characteristics than the input model of MAAP. The necessary changes were those relatives to setpoints, and systems required in the sequences. Once the model was obtained, the same process was followed to obtain the damage domain. Results of sequence S1 with 100% and 110% of power obtained with MAAP and TRACE codes are shown in Fig. 7.
Figure 6: Damage Domain of sequence S1. Path analysis performed with MAAP code.

Figure 7: Damage Domain of sequence S1 with 100% and 110% of power. Comparison of the damage domains obtained with MAAP and TRACE codes.

The damage domain results show that, in general, results from MAAP are more conservative than those from TRACE.
4 PROBABILITY CALCULATION AND RISK ASSESSMENT

The damage exceedance frequency is obtained by integrating the equations of the Theory of Stimulated Dynamics (TSD) inside the damage domain of each sequence (to check the equations involved in this module, see ref. [8]). This integration module constitutes the Risk Assessment module (Block D). The equations of the TSD need several probabilistic data that can be obtained from several sources like pre-existent PSA’s, stochastic phenomena models and operator procedures (Block A).

4.1 Application to Sequence S1

The data needed are the frequency of the initiating event (Loss of CCW/SW), the failure probabilities of the headers (H, L, A) and the probability distribution functions (PDF) of the delays of stochastic headers that are shown in Table 1.

Table 1: Probability and frequency data

<table>
<thead>
<tr>
<th>Header</th>
<th>Type of header</th>
<th>Failure probability</th>
<th>PDF</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>Deterministic</td>
<td>2.2E-05</td>
<td>--</td>
</tr>
<tr>
<td>L</td>
<td>Deterministic</td>
<td>5.6E-04</td>
<td>--</td>
</tr>
<tr>
<td>A</td>
<td>Deterministic</td>
<td>9.4E-04</td>
<td>--</td>
</tr>
<tr>
<td>R</td>
<td>Stochastic</td>
<td>0.0</td>
<td>Lognormal (μ = 8.2319, σ = 0.8690)</td>
</tr>
<tr>
<td>S</td>
<td>Stochastic</td>
<td>0.0</td>
<td>Lognormal (μ = 8.2091, σ = 0.4338)</td>
</tr>
<tr>
<td>SLOCA</td>
<td>Stochastic</td>
<td>0.21</td>
<td>Lognormal (μ = 7.4955, σ = 0.4214)</td>
</tr>
</tbody>
</table>

Frequency of initiating event (y⁻¹) 1.88E-03

Taking into account the probability and frequency data, the TSD equations are integrated inside the damage domain to obtain the damage exceedance frequency of the sequence S1, see Table 2.

Table 2: Exceedance frequency of damage of the sequence S1

<table>
<thead>
<tr>
<th>Sequence</th>
<th>TH Code</th>
<th>Exceedance Frequency of Damage (y⁻¹) (Power 100/110%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>MAAP</td>
<td>8.35E-07/8.65E-07</td>
</tr>
<tr>
<td>S1</td>
<td>TRACE</td>
<td>4.82E-08/4.85E-08</td>
</tr>
</tbody>
</table>

The exceedance frequency of damage results show that results from MAAP are more conservative than those from TRACE.

5 CONCLUSIONS

The damage domain approach is a complement to uncertainty propagation methods. When applied to the calculation of exceedance frequencies, it allows to better focus the analysis on areas of interest and to concentrate the simulation resources on those cases where the limit is actually exceeded, i.e., on the contributors to the exceedance frequency. In addition, it allows for accounting of dynamic dependencies, difficult to handle (when possible) with propagation methods. This paper shows a practical example for the analysis of CCW/SW scenario treated with two different codes, MAAP and TRACE showing that, in general, results from MAAP are more conservative than those from TRACE.
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REFERENCES


