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**Abstract**

During the last decades, the Safety Analysis of Nuclear Power Plants has been shifting from conservative models and hypotheses to best estimate. Within this trend, the different safety analyses can be categorized depending on their associated conservatisms. The approach that includes Best Estimate model and conditions Plus Uncertainty avoiding any conservatisms in system availability can be referred as Extended BEPU. In this sense, an Extended BEPU safety analysis relies on Expanded Event Trees and Best Estimate models to study an accidental sequence. In the present paper, an EBEPU study is performed, using a loss of coolant accident in a pressurized water reactor simulated with the TRACE 5 code. A 5 % core power uprate is used as an example of this safety margin analysis. The paper presents parametric and non-parametric uncertainty analyses, and sensitivity analysis to study the sequence. Observing the results from all event tree sequences, it is seen that some of the branches that contribute to the core damage frequency are successful branches, with all systems available, and some core damage branches have a possibility of success.

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| Highlights.docx | [Highlights] |
| EET_LBLOCA_DD_v8.docx | [Manuscript File] |
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# Study of Expanded Event Trees using Extended Best Estimate Plus Uncertainty methodologies

César Queral, Kevin Fernandez-Cosials, Eneko Zugazagoitia, Carlos París, Javier Gómez-Magan, Rafael Mendizabal, José María Posada.

## Abstract

During the last decades, the Safety Analysis of Nuclear Power Plants, have been shifting from conservative models and hypotheses to best estimate. Within this trend, the different safety analyses can be categorized depending on their associated conservatisms. The approach that includes Best Estimate model and conditions Plus Uncertainty avoiding any conservatisms in system availability can be referred as Extended BEPU. In this sense, an Extended BEPU safety analysis relies on Expanded Event Trees and Best Estimate models to study an accidental sequence.

In the present paper, an EBEPU study is performed, using a loss of coolant accident in a pressurized water reactor simulated with the TRACE 5 code. A 5 % core power uprate is used as an example of this safety margin analysis. The paper presents parametric and non-parametric uncertainty analyses, and a sensitivity analysis to study the sequence. Observing the results from all event tree sequences, it is seen that some of the branches that contribute to the core damage frequency are successful branches, with all systems available, and some core damage branches have a possibility of success.

# 1. Introduction

Since the beginning of the nuclear industry, the Deterministic Safety Analysis (DSA) stood out as a remarkable tool in assessing the risk of nuclear power plants (NPP) for the different accidental sequences. More recently, the IAEA released updated guidelines for the use and licensing by DSA named “Deterministic Safety Analysis for Nuclear Power Plants Specific Safety Guide No. SSG-2” [1]. On these guidelines, four options are summarized and proposed to correctly use conservatisms in safety analyses. Options 1 and 2 involve the use of conservatisms on initial and boundary conditions of the sequence and were the first ones to be applied in NPP design and regulation.

The SSG-2 Option 3 was not used and fully developed until the last decades. It relies on Best Estimate (BE) codes to perform the sequences calculations with realistic initial and boundary conditions. In this option, given that most conservatisms are avoided, it is required to assess the uncertainties of the input data and their propagation through the code [2,3]. This approach is known as Best Estimate Plus Uncertainty (BEPU), and most of the regulatory bodies already accept this methodology for safety analysis [4].

However, BEPU methodologies still make use of conservatisms for the systems availability during the accidental sequence; they limit the analysis to success configurations of the safety systems, and therefore include conservatisms in the availability of the different safeguards systems (e.g. Safety Injection System, SIS). The different configuration system availabilities are not assessed, and substituted by conservative sequences. In this aspect, several NPPs have used SSG-2 Option 3 to assess a nominal power uprate for DBA, [5].

Finally, in order to avoid more conservatisms, the SSG-2 Option 4 for DSA was proposed. It is supposed to be a realistic analysis, on which most of conservative hypotheses are eliminated such as the systems availability or initial conditions, [1]. This approach is appropriate for realistic analysis of anticipated operational occurrences aimed at the assessment of control system capability and in general for best estimate analysis of design extension conditions

On the other hand, as stated in IAEA SSG-3, the PSA overall aim should be to calculate a best estimate of the core damage frequency while avoiding the introduction of excessive conservatisms wherever possible, since this may bias the results unnecessarily; this way, the Level 1 PSA should be based on best estimate models, assumptions and data, [6].

Accordingly, this approach can be based on Expanded Event Trees (EETs), which are similar to the classical PSA event trees, but considering all configurations of systems availability. If this approach also includes an uncertainty treatment, it can be referred as an Extended BEPU (EBEPU methodology). This option is not widely used yet, so different EBEPU approaches are still being studied and developed, [7], as well as its implications in licensing, [8].

One of the most important efforts made to study EBEPU approaches was performed in the SM2A exercise, [9], combining the PSA and the uncertainty assessment techniques developed in BEPU analyses, continuing the research of the SMAP framework. In this approach, organized by the OECD/CSNI, the safety systems availability is evaluated in all combinations, and an uncertainty analysis is performed for all of them. Depending on the sequence, different statistical methods were used to assess the uncertainties such as parametric statistics for the Medium Break Loss of Coolant Accident (MBLOCA), non-parametric for the Large Break LOCA or damage domains for Loss of Component Cooling/Service Water [5], [9]. This exercise analyzed the power uprate of the NPP and to what extent the Core Damage Frequency (CDF) of a sequence is modified by this uprate. It focused on a single acceptance criterion, the Peak Cladding Temperature (PCT). In this sense, it is worth commenting that most of the commented studies are focused solely on PCT as the Figure of Merit (FoM), but there are other CD-relative variables such as the Local Maximum Oxidation (LMO) which can be more limiting under some circumstances.

It must be commented, that this approach can be also interpreted as a risk informed DSA, [10,11] as it combines both approaches. It integrates PSA methods into DSA, to obtain deeper insights of a NPP sequence, [12,13]. Risk informed DSA methodologies have been proposed several times in order to avoid some conservatisms but at present they have not been applied in licensing cases.

There is a reduced number of examples in the literature of EBEPU approaches for safety analysis. Regarding DSA, the research of Martorell et al. studied a Loss Of Normal Feedwater (LONF) sequence in a PWR using its own developed methodology, [14,15]. For PSA, the Spanish regulator developed the Integrated Safety Assessment (ISA), which integrates methods suited for sequences where some events occur at uncertain times, [16,17]. A combination of PSA and BEPU is also found on [18], assessing the APR1400 against a Large Break Loss of Coolant Accident (LBLOCA).

In this context, the goal of the current research paper is to present a safety study of an LBLOCA in a PWR using an EBEPU approach, analyzing two FoM (PCT and LMO). The analysis will use EETs, and include a comparison between parametric and non-parametric statistics for the uncertainty analyses, and also a sensitivity analysis. The present study will the impact of this power uprate in the CDF of the sequence while using an EBEPU approach.

The remaining sections of the article are organized as follows. First, a description of the LBLOCA EET will be done, with the probability quantification of each branch. Then, different approaches to study the LBLOCA safety margins using Uncertainty Analysis will be exposed and compared. Next, a study of the LBLOCA safety margins using a sensitivity analysis will be made. Consequently, a discussion on the different results obtained is presented. Finally some conclusions are drawn.

## 2. LBLOCA Expanded Event Tree

This section describes the probability quantification of the different EET sequences corresponding to a cold leg LBLOCA initiating event.

The PSA information used in this analysis corresponds to a self-built generic PWR 3-loop Westinghouse model. This model has been implemented in Risk Spectrum ®, version 1.3.0, using system and equipment reliability data obtained from [19].

Figure 1 illustrates the EET depicted for a cold leg LBLOCA initiating event. Both *A* and *L* headers have been expanded in order to consider all possible configurations, whose probabilities are indicated in each branch of the EET: 0, 1 or 2 out of2 available Accumulators (ACC) and 0, 1 or 2 out of 2 Low Pressure Safety Injection (LPSI) trains injecting to at least 1 out of 3 cold legs. 1. The success criteria used for PSA regarding the systems actuation during the LBLOCA is 2/2 Accumulators and 1/2 LPSI injection. In this case, only the sequences 1 and 3 are considered successful. Moreover, the following considerations have been taken into account:

1. The LBLOCA is located at cold leg 1, and as a consequence, the injection of the ACC 1 is always considered failed as well as the LPSI injection to cold leg 1 so for the sequences there will be a maximum of two available ACCs.
2. The cold leg recirculation header, LR, has not been expanded. A success criterion has been considered to estimate its failure probability, which consists of at least 1 LPSI train recirculating from containment sumps to at least 1 out of 2 intact cold legs through the RHR heat exchangers. As can be checked in Figure 1, there is a strong dependence between the LR failure probability and the L configuration.
3. It is assumed that every sequence either with 0 out of 2 LPSI trains injecting to cold legs or with failed LR header leads to a Core Damage (CD) end state.

The occurrence probabilities of all 15 sequences of the EET have been obtained and are shown in Table 1. The statistically dominant MCS for each sequence are presented. It is worth analyzing the MCS of the most likely sequences:

- Sequence 1: this is the default case where no equipment failures have happened, corresponding to a 2 out of 2 ACCs and 2 out of 2 LPSI trains successfully injecting to cold legs. Its occurrence probability conditional to the occurrence of a LBLOCA in cold leg 1 is equal to 9.62E-01
- Sequence 3: The ACCs of cold legs 2 and 3 are available but an event has occurred so only 1 out of 2 LPSI train successfully injects to the cold legs, while the recirculation phase is still successful (success criterion is still matched). Its probability is equal to 3.78E-02. The most likely events leaving one LPSI train unavailable are:
    - A Service Water System (SWS) train is unavailable due to maintenance or testing procedures. This would prevent the corresponding Component Cooling Water System (CCWS) train from dissipating the heat from the low-head pump of the corresponding LPSI train, which is required to keep the pump working during the accident duration.
    - A CCWS or SWS train fails to start.
- Sequence 5: The ACCs of cold legs 2 and 3 are available, but no LPSI train can discharge into at least 1 intact cold leg. The CD cannot be prevented, despite the state of the LPSI recirculation header. Its probability is equal to 1.58E-04. The most likely events leading to this sequence are:
    - Both LPSI pumps fail to start due to a Common Cause Failure (CCF)

    - One of the LPSI trains cannot operate because a maintenance or testing procedure is being performed on the corresponding SWS train, while the recirculation line of the pump of the other LPSI train fails to close. These lines are designed to close as soon as the flow discharged by the pumps reaches a set-point value. It is assumed that the flow lost though a pump recirculation line which fails to close would be enough to prevent the LPSI train to accomplish its cooling function.
- Sequence 4: The ACCs of cold legs 2 and 3 are available, but an event has occurred so only 1 out of 2 LPSI train successfully injects to cold legs and the recirculation phase has failed. Its probability is equal to 4.13E-05. The most likely combination of events leading to this sequence is the following:
    - A SWS train is unavailable due to maintenance or testing procedures leaving the corresponding LPSI also unavailable, while the other LPSI train successfully injects to cold legs
    - When the RWST reaches the low level set-point, the suction of the available LPSI train switches from the RWST to the containment sump. However, a mechanical failure prevents a sump valve from opening, which leads to the recirculation phase failure and to a CD end state.

After the EET configurations probabilities are obtained, the different simulations required for the EBEPU can be developed.

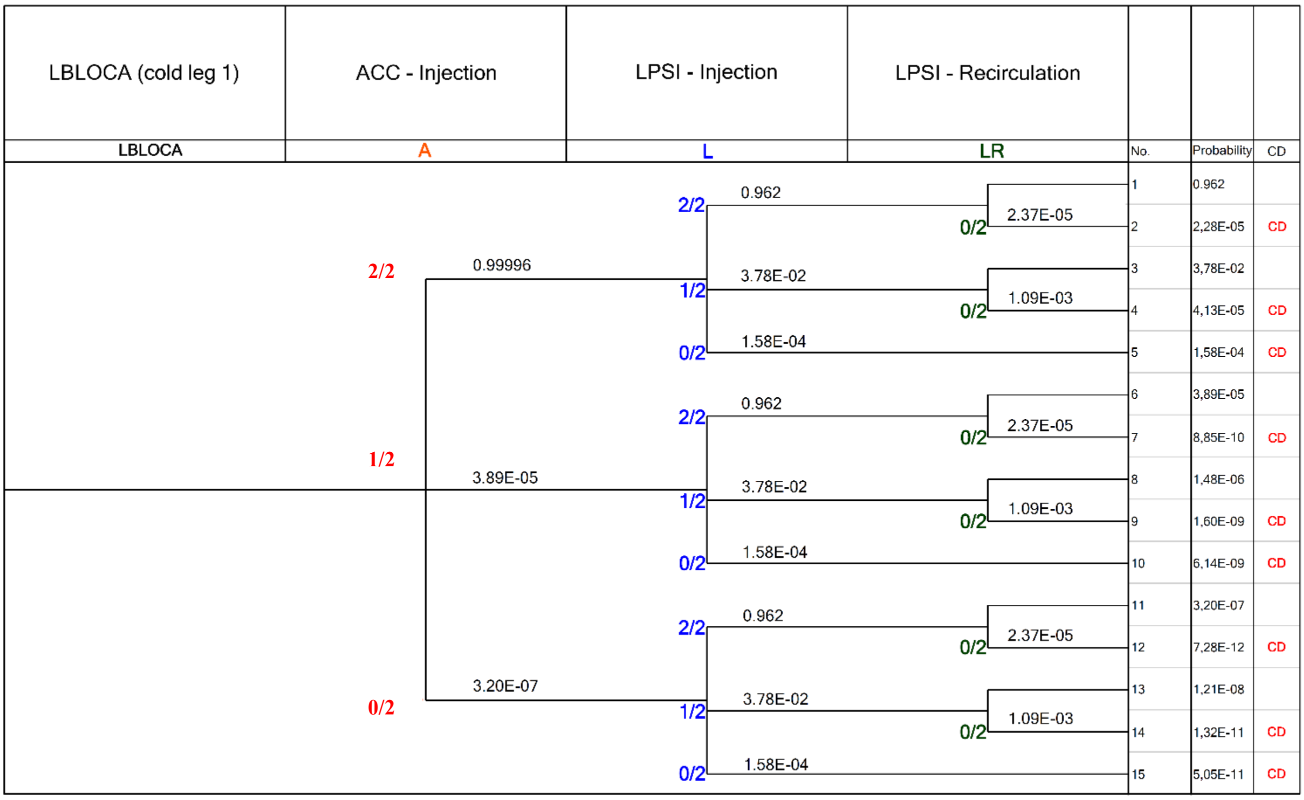

*Figure 1. Probability quantification of the 15 EET sequences corresponding to a cold leg LBLOCA.*

| **Seq.** | **A** | **L** | **LR Success** | **Probability** | **Minimal cut-sets** |
|---|---|---|---|---|---|
| 1 | 2/2 | 2/2 | Yes | 9.62E-01 | **Default case** |

| | | | | | |
|---|---|---|---|---|---|
| 2 | | | No | 2.28E-05 | **(1)** CCF to open of sump isolation valves,<br>**(2)** RWST isolation valves fail to close |
| 3 | 2/2 | 1/2 | Yes | 3.78E-02 | **(1)** Test/Maintenance of a SWS train,<br>**(2)** One CCWS train fails to start,<br>**(3)** One SWS train fails to start |
| 4 | | | No | 4.13E-05 | **(1)** sump isolation valve of train A/B fails to open + Test/Maintenance of SWS train B/A |
| 5 | 2/2 | 0/2 | - | 1.58E-04 | **(1)** CCF to start of the LPSI pumps,<br>**(2)** Test/Maintenance of SWS train A/B + failure to close of the valve in the LPSI pump recirculation line of train B/A (I&C failure) |
| 6 | 1/2 | 2/2 | Yes | 3.89E-05 | **(1)** A check valve of the ACC 2 or 3 fails to open,<br>**(2)** a motor operated valve of ACC 2 or 3 fails to remain open |
| 7 | | | No | 8.85E-10 | **(1)** A check valve of the ACC 2 or 3 fails to open + CCF to open of sump isolation valves |
| 8 | 1/2 | 1/2 | Yes | 1.48E-06 | **(1)** Test/Maintenance of a SWS train + a check/motor operated valve of ACC 2 or 3 fails to open/remain open |
| 9 | | | No | 1.60E-09 | **(1)** Test/Maintenance of SWS train A/B + sump isolation valve of train B/A fails to open + a check/motor operated valve of ACC 2 or 3 fails to open/remain open |
| 10 | 1/2 | 0/2 | - | 6.14E-09 | **(1)** CCF to start of the LPSI pumps + a check valve of ACC 2 or 3 fails to open |
| 11 | 0/2 | 2/2 | Yes | 3.20E-07 | **(1)** CCF to open of check valves of ACC 2 and 3,<br>**(2)** Combination of failures to open of check valves of ACC 2 and 3 |
| 12 | | | No | 7,28E-12 | **(1)** CCF to open of check valves of ACC 2 and 3 + CCF of sumps isolation valves |
| 13 | 0/2 | 1/2 | Yes | 1,21E-08 | **(1)** Test/maintenance of a SWS train + CCF to open of check valves of ACC 2 and 3,<br>**(2)** one CCWS pump fails to start + CCF to open of check valves of ACC 2 and 3 |
| 14 | | | No | 1,32E-11 | **(1)** Test/maintenance of SWS train A/B + sump isolation valve of train B/A fails to open + CCF to open of check valves of ACC 2 and 3 |
| 15 | 0/2 | 0/2 | - | 5,05E-11 | **(1)** CCF to start of both LPSI pumps + CCF to open of check valves of ACC 2 and 3 |

*Table 1. Probability and minimal cut-sets obtained for each EET sequence of cold leg LBLOCA initiating event*

## 3. LBLOCA EET Base Cases

This section will cover the description of the model used for the different analyses, as well as the development of the Base Cases of the different configurations of systems availability commented in Section 2.

### 3.1. PWR-W Trace Model

The NPP model corresponds to a PWR-W with 3 loops and a nominal power of 2900 MWt. The Reactor Coolant System (RCS) nodalization is shown in Figure 2. The core data correspond to the beginning of the cycle, under Xenon equilibrium, with all the control rods out, operating at full power and with a burn-up of 1000MWd/tU. The version of the code used for the present study is TRACE V5.0 Patch 4, [20].

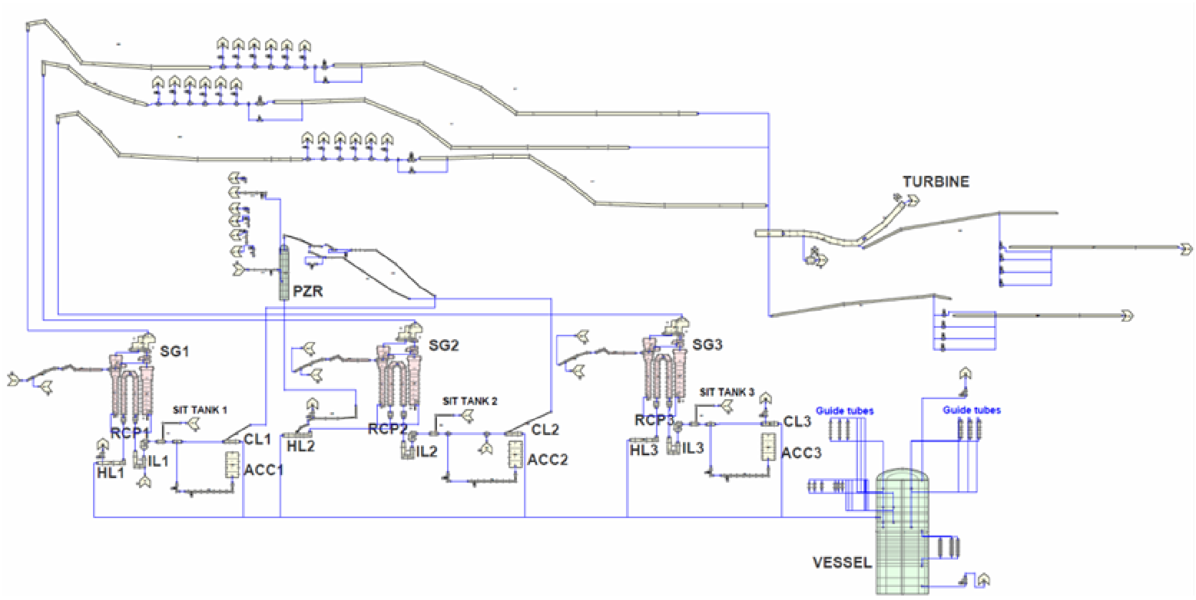

*Figure 2. PWR-W TRACE model Reactor Coolant System Nodalization*

The present model has been validated against steady state, SCRAM transients and an extensive set of transients; for a detailed review of the model performance see [16,21–23].

### 3.2. LBLOCA 100-105 % Power Base Cases

The Base Cases consist of an LBLOCA in the cold leg covering all the branches of the EET shown in Section 2 for 100 and 105 % power.

The PCT and LMO evolution of all Base Cases can be seen in Figure 3 to 6, on which the legend makes reference to the number of available LPSI trains or ACC. Comparing all cases, the behavior of the PCT and the LMO is qualitatively similar. The PCT starts with an initial peak during the blowdown phase, followed by another peak during the reflood phase caused by the uncovering of the core until the quenching is reached and the temperature finally decreases. The LMO increases mainly during the reflood phase because of the core uncover. For the PCT, only in the case with no ACC and one LPSI train, the acceptance criteria (1477 K) is surpassed for both 100% and 105% power, all the remaining cases do not surpass this limit. For LMO, none of the 100% power cases surpass the acceptance criteria (17%), and only the case with no ACC and one LPSI train exceeds it for 105 % power.

While comparing the PCT and LMO values of the 100 and 105 % it is seen that the qualitative behavior of these variables is mostly the same, but the 105 % cases tend to reach higher values.

Comparing the different behaviors in terms of ACCs and LPSI trains availability, it is seen that a reduction in the number of LPSI trains with 2/2 ACC available provokes little to no change in the PCT behavior. However, the combined effect of neglecting the ACC and having only one LPSI train provokes a high non-linear peak of both PCT and LMO. This is, if the ACC are available, there are no large differences in having 1 or 2 LPSI trains, but those become more relevant as the ACC availability decreases.

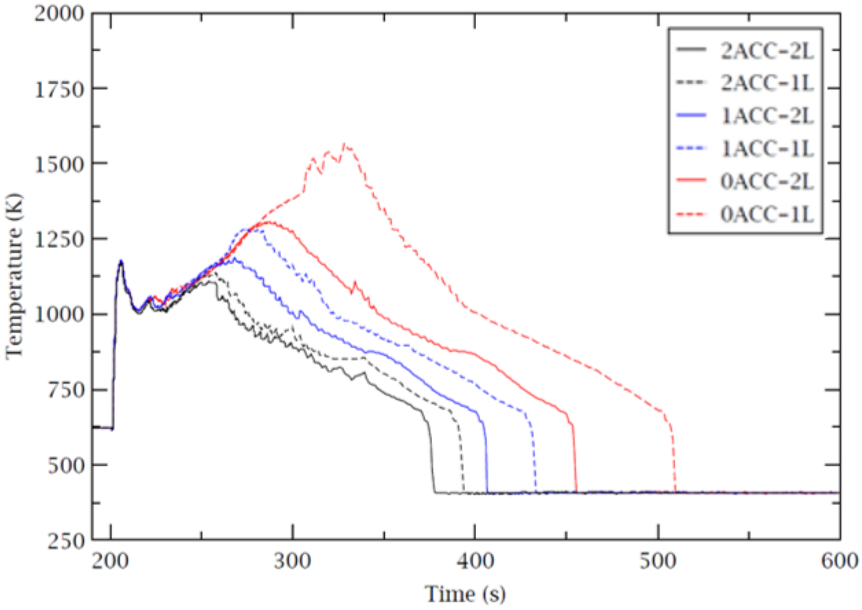

*Figure 3. PCT of the 100 % power Base Cases*

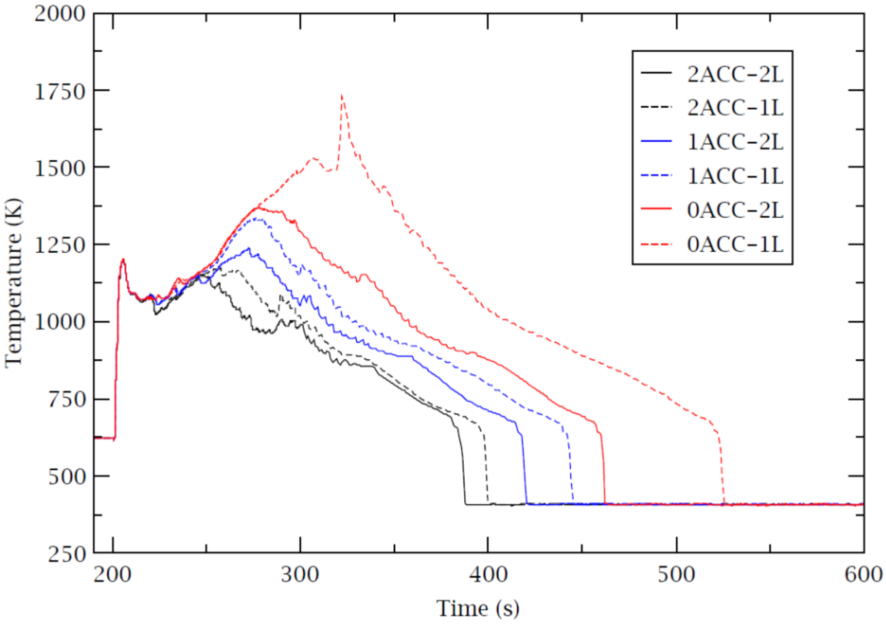

*Figure 4 PCT of the 105 % power Base Cases*

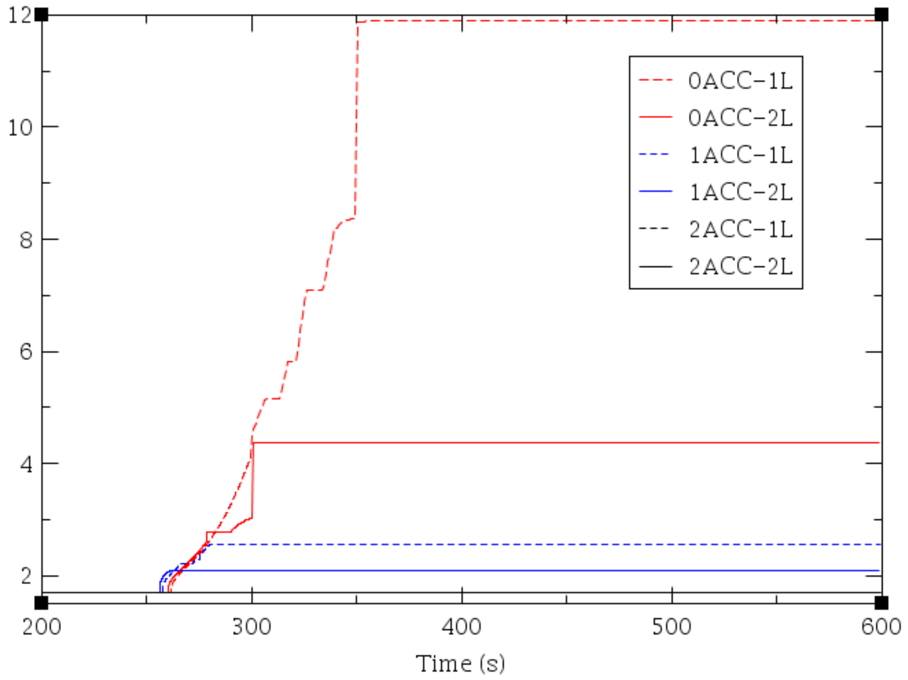

*Figure 5 LMO of the 100 % power Base Cases*

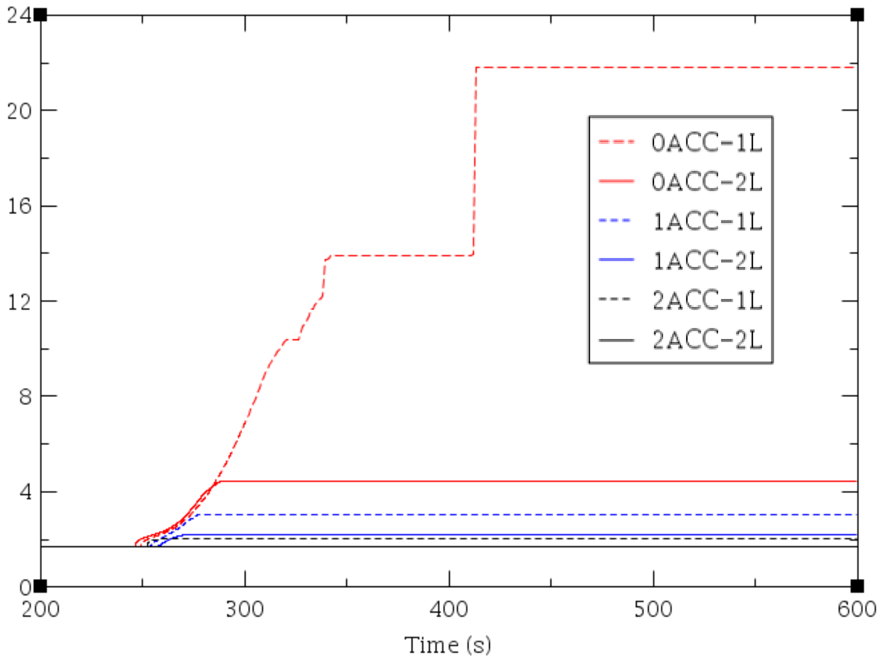

*Figure 6 LMO of the 105 % power Base Cases*

## 4. Study of the LBLOCA safety Margins using EET Uncertainty Analysis

In this section, the EBEPU approach will be studied via uncertainty analyses of the LBLOCA EET. Different approaches of uncertainty analysis will be used and compared: parametric and non-parametric methods. The uncertainty analysis will be developed generating 100 Monte Carlo simulations of each branch of the EET for 100% and 105% core power using the TRACE code.

### 4.1. Monte-Carlo Sampling

As previously commented, once the Base Cases are created, in order to perform an Uncertainty Analysis, a Monte-Carlo sampling of different input parameters will be developed, creating a set of 100 cases for each EET branch.

In order to select the different input parameters, several references have been used, such as the LOCA Phenomena Identification Ranking Table (PIRT) [24,25]. Additionally, recent studies of uncertainty and sensitivity analysis have been also considered, [14,26–29]. For a complete and comprehensive record of the input parameters, its variability range and PDF associated, see [30].

### 4.2. Parametric UA study

In this section, the results of the EETs Monte Carlo simulations will be presented and analyzed using parametric statistics. In this sense, a PDF will be reconstructed from the results, and the sequence will be analyzed by studying this PDF. This Uncertainty Analysis method is used in the BEPU TRACG methodologies (SSG-2 Option 3), which apply this approach to verify that certain variables are below the acceptance criteria (e.g. PCT) by testing the results against normality, and if succeed, the confidence intervals are obtained using properties of the normal distribution, [31,32].

In the present paper, each set of 100 Monte Carlo simulations is tested against more than 60 PDF distributions with Anderson-Darling goodness of fit test using the tool EasyFit, [33]. The distribution with the best adjustment is selected for each case and will be used to calculate the acceptance criteria exceedance probability.

The PDFs for PCT and LMO can be seen in Figure 7-10. Within this method, the probability of exceeding the acceptance criteria is obtained by integrating the PCT and LMO beyond the limit, and the comparison is made based on the distributions shape. This approach is similar to the one used in the SM2A project to study EBEPU methodologies for MBLOCA [5].

Observing the different PDFs, it is seen that in terms of both PCT and LMO, the case with no ACCs and just a single LPSI train available, has a higher kurtosis than the remaining cases; the tails are more weighted, meaning that the results are strongly dispersed. As shown in Figure 7 to 10, the PDFs kurtosis is highly dependent on the number of ACCs available, being lower with 2/2 ACCs. Additionally, it is seen that in all 100% power cases, the median is below the limit, similarly to the 105 % except for the 0 ACCs, 1 LPSI train.

The differences observed relative to the 100-105 % cases are similar to the Base Cases. It is seen, however, that the PDF tails of the 105 % cases have more weight than the 100% cases. This implies that elevating the reactor power to 105 % causes a stronger dispersion of the results, increasing the median values and the probability of exceeding the acceptance criteria.

Summarizing and attending at Table 2, it is observed that the probability of exceeding the acceptance criteria increases by a large factor with the uprate to 105 % in the sequences where the majority of the systems are available for both PCT and LMO. In other words, the damage probability increment for the 105 % power uprate is lower with less availability of the LPSI and ACCs. Additionally, the damage increase due to the unavailability of the systems ranges between a factor 5.0E+02 and 1.0E+06.

It is remarkable that the obtained probability of exceeding the acceptance criteria is not provided together with a confidence level, as required by the current methods of the SSG-2 Option 3, [3,34]. Obtaining a confidence interval for these values and comparing them comes together with some problematic, as seen in [30]. First, the region of interest of the simulations is near the acceptance criteria limit, which is normally a region where little to no information is obtained from the simulations. Second, given the small sample (100) a Bootstrap confidence interval [35] cannot be easily constructed, as there would be several Bootstraps samples which will not adjust to the selected PDF.

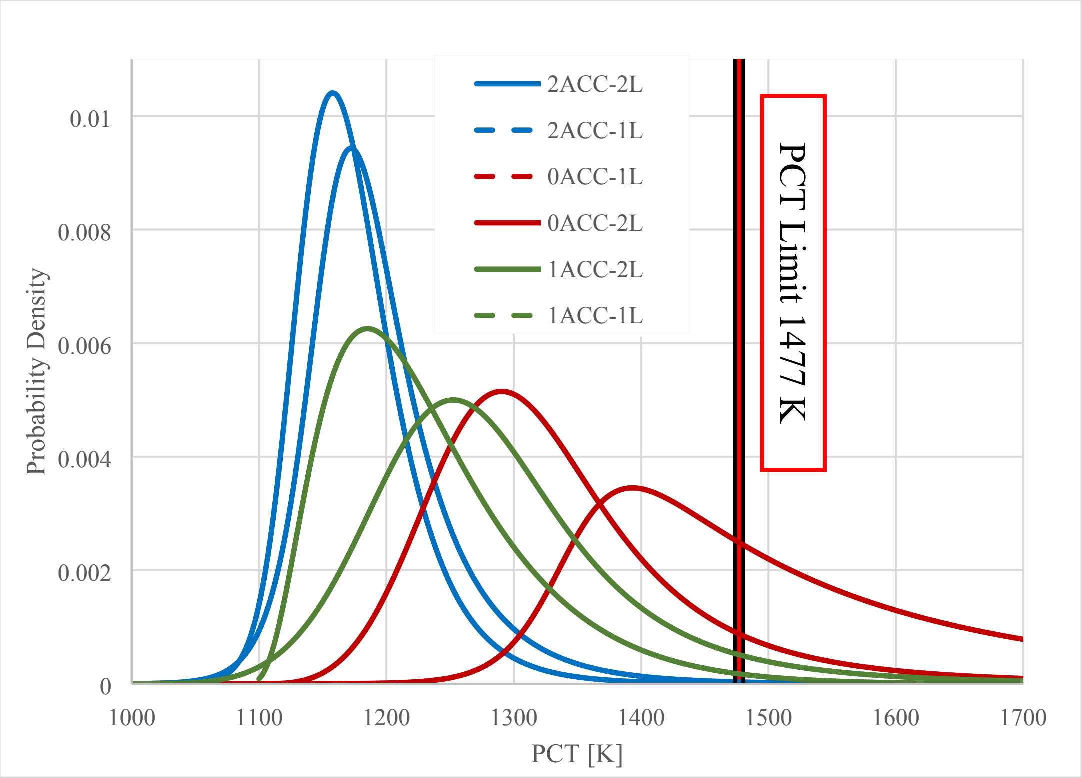

*Figure 7. PDFs reconstructed using the PCT for 100 % power.*

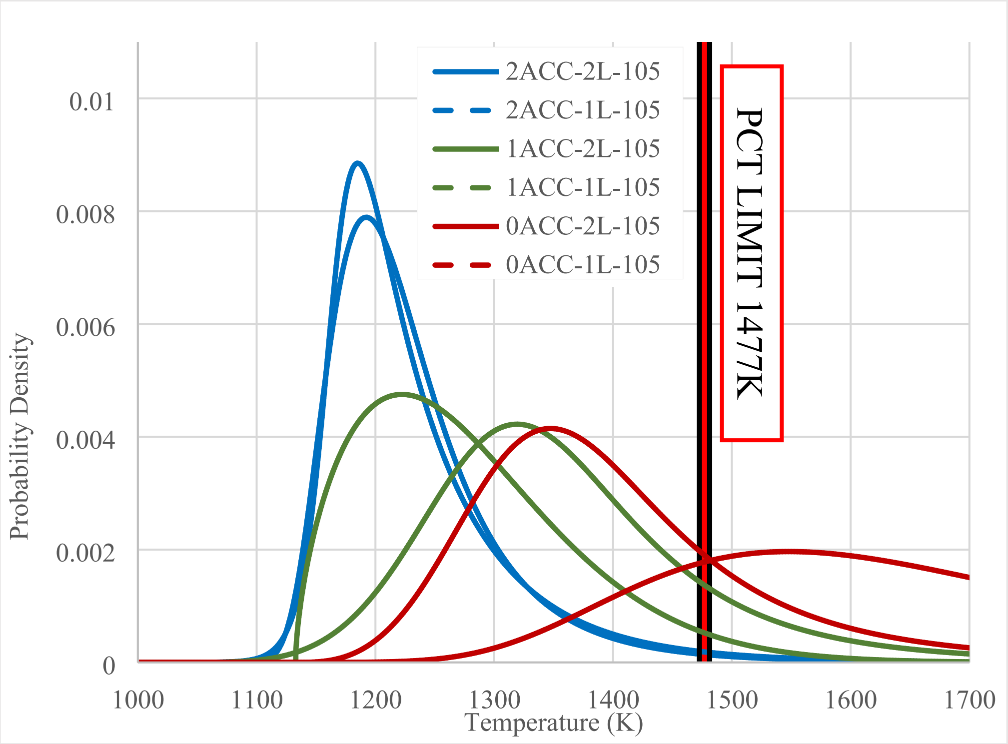

*Figure 8. PDFs reconstructed using the PCT for 105 % power.*

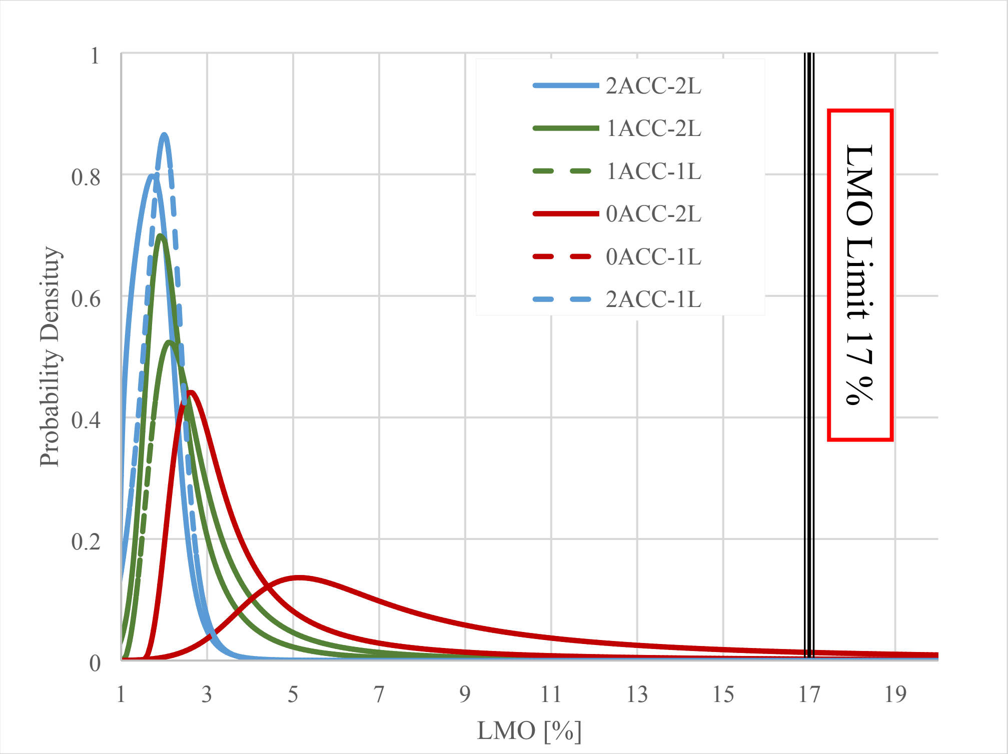

*Figure 9. PDFs reconstructed using the LMO for 100 % power.*

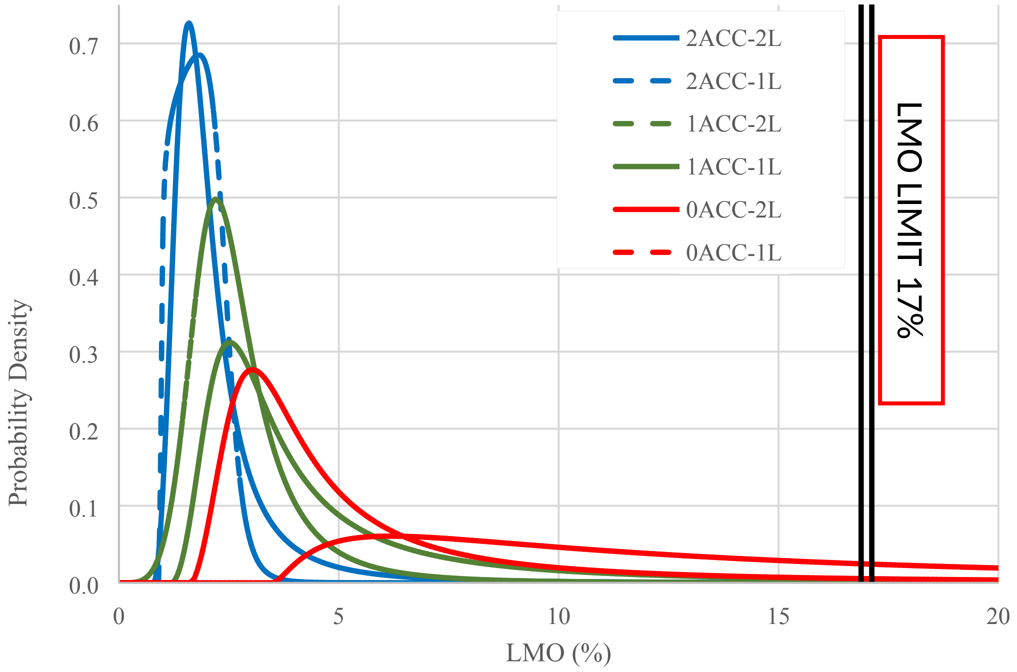

*Figure 10. PDFs reconstructed using the LMO for 105 % power.*

| | Probability (PCT>1477K) | | Probability (LMO >17%) | |
|---|---|---|---|---|
| | **100 % Power** | **105 % Power** | **100 % Power** | **105 % Power** |
| **2ACC-2L** | 1.10E-03 | 1.03E-02 | 3.13E-08 | 1.07E-03 |
| **2ACC-1L** | 1.77E-03 | 1.57E-02 | 3.77E-10 | 6.54E-04 |
| **1ACC-2L** | 9.52E-03 | 3.23E-02 | 5.12E-04 | 7.32E-04 |
| **1ACC-1L** | 4.81E-02 | 1.40E-01 | 4.70E-03 | 6.46E-02 |
| **0ACC-2L** | 8.72E-02 | 2.19E-01 | 2.74E-02 | 7.14E-02 |
| **0ACC-1L** | 5.08E-01 | 8.09E-01 | 1.68E-01 | 4.38E-01 |

*Table 2. Probability of exceedance the acceptance criteria using parametric statistics*

### 4.3. Non-parametric UA study

In order to continue the study with non-parametric statistics, the authors have evaluated the data as a binomial distribution with two states (acceptance criteria meet/not meet) with a confidence interval, [36]. On each case, the resulting PCT and LMO values are compared against the associated acceptance criteria, and only two possible outcomes can be obtained: failure or success. This approach is similar to the one used in the SM2A project to study EBEPU methodologies for LBLOCA [5].

This technique can be visualized in Figure 11 to 14, on which every dot inside the acceptance criteria boundaries is a success case while the outside points represent cases where the criteria are not meet. Then, the probability of exceeding the acceptance criteria is obtained by means of the Clopper-Pearson confidence interval. A one sided 95 % confidence has been selected, similar to the usual regulatory requirements.

Observing Figure 11-14, it is seen that the results obtained are similar to those reported by the literature, in the sense that a higher PCT is correlated with a higher LMO with a strong dispersion of values at the highest values of PCT, [37]. Additionally, as seen in the previous section, the 105 % results show a higher non-linear behavior against the input values, reaching high values in terms of both PCT and LMO.

The probabilities of CD using the binomial approach are summarized in Table 3. In this case, the differences found between the 100 and 105 % cases are in the range of a factor 2, and the differences in CD probability provoked by the availability of the LPSI and ACCs ranges between a 10 and 100 factor, lower than the values obtained in the parametric analysis.

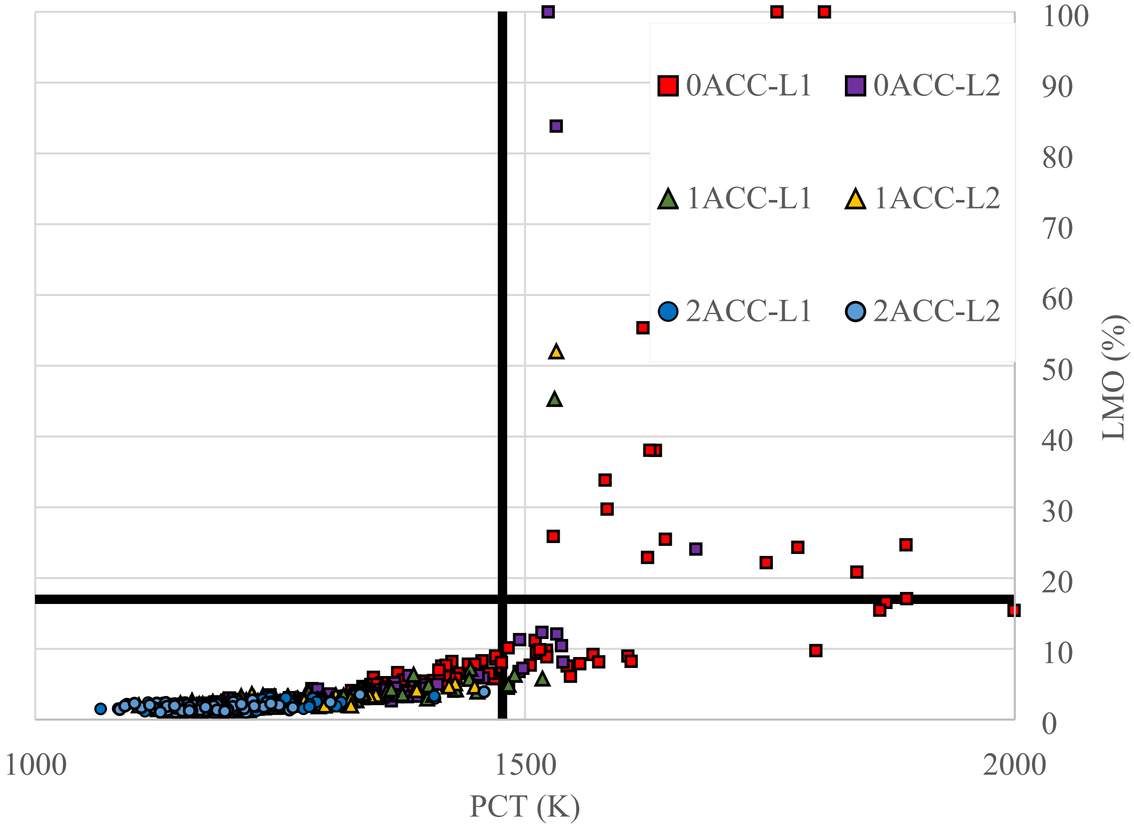

*Figure 11. PCT and LMO for the 100 % Power Cases.*

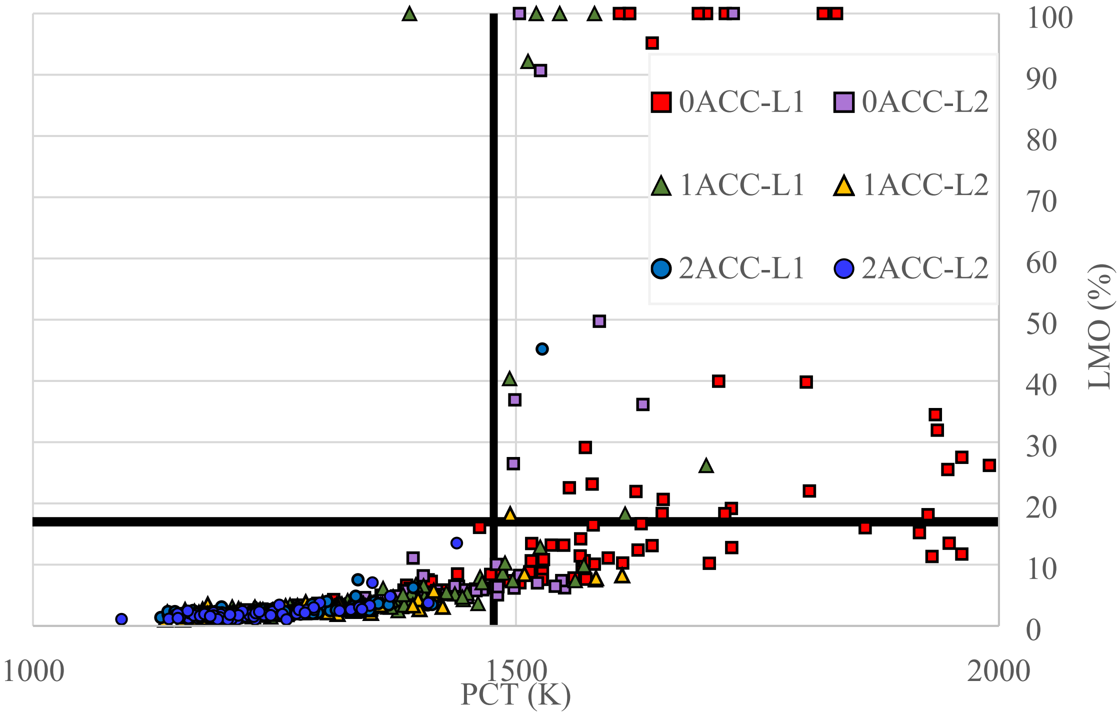

*Figure 12. PCT and LMO for the 105 % Power Cases*

| | Core Damage Probability | | Classical PSA State |
|---|---|---|---|
| | **100 % Power** | **105 % Power** | **-** |
| **2ACC-2L** | 2.95E-02 | 1.03E-02 | Success |
| **2ACC-1L** | 2.95E-02 | 1.57E-02 | Success |
| **1ACC-2L** | 4.66E-02 | 8.96E-02 | Core Damage |
| **1ACC-1L** | 1.02E-01 | 2.33E-01 | Core Damage |
| **0ACC-2L** | 1.8E-01 | 3.10E-01 | Core Damage |
| **0ACC-1L** | 5.4E-01 | 8.55E-01 | Core Damage |

*Table 3. Core Damage Probability using binomial approach with 95 % Clopper-Pearson Confidence interval*

## 5. Study of LBLOCA safety margins using EET Sensitivity Analysis

In this section, the EBEPU approach for LBLOCA is studied by means of a Sensitivity Analysis. Sensitivity Analyses are considered useful tools that should complement an uncertainty analysis, [38]. In the present paper, they are used for a study of the input space of the different EET branches, and to quantify the CD probabilities based on its results.

In this section, as a first step, the correlation coefficients between the inputs and outputs are calculated using the Monte Carlo simulations of Section 4. Then, after selecting the two most influential variables, a detailed study of the input space is performed by simulating 121 cases varying these two variables.

## 5.1. Global Sensitivity Analysis (PRCC).

To perform a sensitivity analysis, different techniques and approaches can be found in the literature involving increasing levels of complexity and number of code runs associated. In this work, a global sensitivity analysis has been performed in order to consider all input parameters simultaneously. The indicator used for the present research is the Partial Rank Correlation Coefficient (PRCC), [39,40], which is a common coefficient used in Option 3 and BEPU studies, [3].

The PRCC is similar to the Ranked Correlation Coefficient (RCC), but canceling the effects of the other inputs on each correlation. Additionally, it is suitable for the present research, as the number of simulations required to obtain a reasonable statistical accuracy is in the order of 100, [39].

In order to establish a threshold on the correlated variables, the values of Table 4 are used, then the PRCC for PCT and LMO for all EET sequences are found in Table 5 and Table 6, colored accordingly.

From these tables, it is seen that the parameters that are influent for 100 % power, are also correlated for 105 % power conditions such as the decay heat or the fuel thermal conductivity. Additionally, it is observed that some parameters become non-influential or vice versa depending on the systems availability. For example, parameters such as the Critical Heat Flux are correlated with PCT with a very high level of confidence but only for cases with 2 available ACCs. It is also seen that for the case with no ACC and one LPSI train available, fewer correlations are found, because of the spread of the results. Taking into account this data, it can be concluded that the most influential parameters for all simulations, for different nominal power levels and for PCT and LMO are the Forced Convection Heat Transfer Coefficient (HTC), and the Film Boiling HTC. These findings agree with previous results found in the literature, [30,41].

| **Confidence Level (%)** | **PRCC Limit (abs)** |
|---|---|
| **99.98** | 0.35 |
| **99.9** | 0.31 |
| **99** | 0.23 |
| **95** | 0.16 |

*Table 4. Confidence level and PRCC threshold values for 100 simulations*

| | **100 % Power** | | | | | | **105 % Power** | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **2ACC-1H-2L** | **2ACC-1H-1L** | **1ACC-1H-2L** | **1ACC-1H-1L** | **0ACC-1H-2L** | **0ACC-1H-1L** | **2ACC-1H-2L** | **2ACC-1H-1L** | **1ACC-1H-2L** | **1ACC-1H-1L** | **0ACC-1H-2L** | **0ACC-1H-1L** |
| Break discharge coefficient | 0.69 | 0.70 | 0.46 | 0.54 | 0.64 | 0.39 | 0.57 | 0.58 | 0.35 | 0.56 | 0.62 | 0.32 |
| Initial Core Power | 0.26 | 0.43 | 0.27 | 0.37 | 0.13 | 0.26 | 0.54 | 0.44 | 0.44 | 0.20 | 0.45 | 0.30 |
| Decay Heat | 0.31 | 0.26 | 0.55 | 0.73 | 0.73 | 0.54 | 0.31 | 0.40 | 0.61 | 0.64 | 0.64 | 0.47 |
| Power peaking factors | 0.49 | 0.57 | 0.54 | 0.46 | 0.53 | 0.43 | 0.71 | 0.67 | 0.53 | 0.43 | 0.60 | 0.30 |
| Forced Convection HTC | -0.72 | -0.70 | -0.81 | -0.86 | -0.90 | -0.88 | -0.80 | -0.81 | -0.83 | -0.82 | -0.82 | -0.80 |
| Film Boiling HTC | -0.60 | -0.69 | -0.91 | -0.90 | -0.90 | -0.77 | -0.66 | -0.78 | -0.83 | -0.89 | -0.86 | -0.70 |
| Transition Boiling HTC | -0.07 | -0.01 | 0.00 | 0.12 | 0.12 | -0.10 | -0.11 | 0.04 | -0.16 | 0.10 | -0.15 | -0.16 |
| Critical Heat Flux | -0.65 | -0.49 | -0.11 | 0.27 | 0.11 | 0.13 | -0.68 | -0.42 | -0.04 | 0.00 | -0.02 | -0.02 |
| Accumulator Pressure | 0.15 | 0.10 | 0.07 | 0.15 | 0.11 | -0.01 | 0.02 | 0.13 | 0.19 | -0.08 | 0.12 | -0.04 |
| LPSI mass flow factor | 0.13 | 0.20 | -0.41 | -0.03 | -0.30 | -0.31 | 0.03 | -0.09 | -0.30 | -0.10 | -0.05 | -0.18 |
| RCP broken loop speed | -0.08 | -0.04 | 0.09 | 0.14 | -0.18 | -0.13 | -0.10 | 0.02 | 0.09 | 0.09 | 0.13 | 0.13 |
| RCP intact loop speed | 0.08 | -0.07 | -0.05 | 0.10 | -0.09 | 0.05 | 0.04 | 0.34 | -0.05 | -0.06 | -0.24 | -0.09 |
| Gas Gap HTC | -0.01 | -0.09 | -0.09 | 0.07 | -0.37 | 0.00 | 0.10 | 0.00 | -0.26 | -0.24 | -0.13 | -0.12 |
| Cladding inner radius | -0.15 | 0.32 | 0.02 | 0.36 | 0.25 | 0.05 | 0.10 | 0.18 | 0.17 | 0.17 | -0.01 | 0.13 |
| Cladding thickness | -0.15 | -0.05 | -0.08 | -0.11 | -0.16 | -0.14 | 0.03 | -0.08 | 0.06 | -0.20 | -0.42 | -0.22 |
| Pellet radius | -0.22 | -0.15 | -0.03 | 0.03 | -0.13 | -0.04 | -0.15 | -0.06 | -0.13 | -0.06 | -0.10 | -0.05 |
| Pellet dish depth | 0.09 | 0.02 | -0.02 | 0.13 | -0.08 | -0.09 | -0.07 | 0.01 | -0.07 | 0.02 | 0.18 | -0.29 |
| Pellet shoulder | -0.02 | 0.10 | -0.18 | -0.02 | 0.10 | 0.21 | 0.11 | -0.10 | -0.16 | -0.06 | -0.16 | -0.13 |
| Rod spring volume | 0.16 | -0.09 | -0.02 | -0.35 | -0.04 | 0.05 | 0.08 | -0.03 | -0.08 | 0.11 | -0.14 | 0.14 |
| Rod plenum height | 0.03 | 0.04 | -0.02 | -0.02 | -0.02 | -0.16 | -0.05 | -0.03 | -0.25 | -0.05 | 0.00 | -0.08 |
| Fuel density | -0.36 | -0.07 | -0.20 | -0.19 | 0.03 | -0.16 | -0.05 | -0.12 | 0.06 | -0.21 | -0.44 | -0.09 |
| Fuel thermal conductivity | -0.78 | -0.77 | -0.75 | -0.60 | -0.58 | -0.24 | -0.78 | -0.81 | -0.56 | -0.39 | -0.54 | -0.40 |
| Burst temperature coefficient | -0.01 | 0.05 | -0.07 | -0.21 | 0.15 | 0.02 | -0.14 | -0.05 | -0.17 | -0.16 | -0.02 | -0.02 |
| Metal-water reaction coefficient | 0.12 | 0.04 | 0.05 | 0.19 | -0.04 | 0.13 | 0.02 | -0.05 | 0.16 | -0.05 | -0.04 | 0.02 |
| Containment pressure | 0.00 | -0.04 | -0.17 | -0.15 | -0.14 | -0.34 | 0.07 | -0.05 | -0.14 | 0.10 | -0.02 | -0.03 |
| Accumulator Temperature | -0.09 | -0.13 | -0.12 | 0.05 | -0.11 | -0.03 | -0.04 | -0.05 | 0.05 | -0.11 | 0.15 | -0.04 |
| Gap pressure | -0.06 | 0.03 | -0.05 | 0.14 | 0.10 | -0.05 | -0.03 | 0.09 | 0.06 | 0.17 | 0.06 | 0.09 |
| Burst Strain | -0.27 | -0.11 | -0.18 | -0.26 | -0.03 | -0.14 | 0.01 | -0.28 | -0.10 | -0.36 | -0.43 | -0.12 |
| Oxide layer | -0.05 | -0.12 | 0.02 | -0.11 | -0.09 | 0.02 | -0.14 | -0.36 | -0.11 | -0.05 | -0.07 | -0.05 |

*Table 5. PRCC values for PCT*

| | **100 % Power** | | | | | | **105 % Power** | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **2ACC-1H-2L** | **2ACC-1H-1L** | **1ACC-1H-2L** | **1ACC-1H-1L** | **0ACC-1H-2L** | **0ACC-1H-1L** | **2ACC-1H-2L** | **2ACC-1H-1L** | **1ACC-1H-2L** | **1ACC-1H-1L** | **0ACC-1H-2L** | **0ACC-1H-1L** |
| Break discharge coefficient | 0.16 | 0.41 | 0.46 | 0.53 | 0.46 | 0.41 | 0.36 | 0.28 | 0.43 | 0.44 | 0.59 | 0.14 |
| Initial Core Power | 0.16 | 0.36 | 0.04 | 0.39 | 0.04 | 0.43 | 0.25 | 0.18 | 0.46 | 0.05 | 0.42 | 0.06 |
| Decay Heat | 0.27 | 0.25 | 0.44 | 0.62 | 0.44 | 0.45 | 0.32 | 0.34 | 0.52 | 0.50 | 0.60 | 0.45 |
| Power peaking factors | 0.16 | 0.07 | 0.31 | 0.26 | 0.31 | 0.47 | 0.38 | 0.46 | 0.39 | 0.29 | 0.48 | 0.31 |
| Forced Convection HTC | -0.24 | -0.48 | -0.81 | -0.77 | -0.81 | -0.79 | -0.57 | -0.69 | -0.74 | -0.67 | -0.79 | -0.63 |
| Film Boiling HTC | -0.55 | -0.61 | -0.82 | -0.80 | -0.82 | -0.78 | -0.71 | -0.78 | -0.77 | -0.83 | -0.86 | -0.60 |
| Transition Boiling HTC | -0.14 | -0.06 | -0.10 | 0.12 | -0.10 | -0.06 | -0.14 | 0.15 | -0.16 | 0.02 | -0.29 | -0.07 |
| Critical Heat Flux | -0.13 | 0.09 | -0.01 | 0.09 | -0.01 | 0.06 | -0.32 | -0.17 | 0.00 | -0.09 | 0.02 | -0.05 |
| Accumulator Pressure | 0.16 | 0.01 | 0.12 | 0.30 | 0.12 | 0.04 | -0.08 | 0.17 | 0.24 | -0.04 | 0.10 | -0.12 |
| LPSI mass flow factor | 0.16 | -0.15 | -0.19 | -0.01 | -0.19 | -0.27 | -0.11 | -0.17 | -0.16 | -0.04 | -0.08 | -0.04 |
| RCP broken loop speed | -0.16 | 0.08 | 0.09 | 0.06 | 0.09 | 0.02 | -0.20 | -0.12 | 0.05 | -0.03 | 0.23 | -0.06 |
| RCP intact loop speed | -0.01 | -0.23 | -0.02 | 0.28 | -0.02 | 0.04 | -0.01 | 0.20 | 0.07 | -0.19 | -0.19 | 0.01 |
| Gas Gap HTC | 0.10 | -0.03 | -0.17 | 0.03 | -0.17 | -0.14 | -0.01 | 0.06 | -0.02 | -0.20 | -0.07 | -0.03 |
| Cladding inner radius | -0.17 | 0.19 | 0.06 | 0.30 | 0.06 | 0.11 | 0.16 | 0.00 | 0.23 | 0.15 | 0.05 | 0.25 |
| Cladding thickness | -0.43 | -0.42 | -0.27 | -0.41 | -0.27 | -0.08 | -0.25 | -0.34 | -0.29 | -0.29 | -0.52 | -0.08 |
| Pellet radius | -0.05 | -0.10 | 0.06 | -0.10 | 0.06 | -0.08 | -0.23 | 0.09 | -0.24 | -0.11 | -0.04 | 0.06 |
| Pellet dish depth | 0.16 | 0.05 | 0.01 | 0.03 | 0.01 | -0.02 | 0.09 | 0.12 | -0.16 | 0.08 | 0.31 | -0.07 |
| Pellet shoulder | -0.02 | -0.13 | 0.07 | -0.06 | 0.07 | 0.26 | 0.00 | -0.23 | -0.04 | -0.11 | -0.14 | -0.02 |
| Rod spring volume | 0.11 | 0.03 | -0.12 | -0.28 | -0.12 | 0.09 | -0.05 | 0.00 | -0.05 | 0.00 | -0.10 | -0.02 |
| Rod plenum height | 0.15 | -0.20 | -0.18 | 0.05 | -0.18 | 0.00 | -0.06 | -0.02 | -0.07 | -0.05 | 0.01 | 0.00 |
| Fuel density | -0.09 | -0.07 | -0.04 | -0.17 | -0.04 | -0.04 | 0.23 | -0.06 | 0.09 | -0.10 | -0.21 | -0.06 |
| Fuel thermal conductivity | -0.29 | -0.46 | -0.46 | -0.47 | -0.46 | -0.13 | -0.30 | -0.42 | -0.40 | -0.31 | -0.47 | 0.03 |
| Burst temperature coefficient | -0.22 | -0.31 | -0.49 | -0.55 | -0.49 | -0.18 | -0.48 | -0.40 | -0.61 | -0.43 | -0.39 | -0.05 |
| Metal-water reaction coefficient | -0.08 | 0.22 | 0.00 | 0.30 | 0.00 | 0.20 | 0.19 | 0.07 | 0.13 | 0.14 | 0.12 | -0.01 |
| Containment pressure | -0.03 | -0.16 | -0.23 | 0.00 | -0.23 | -0.12 | 0.04 | 0.02 | -0.06 | 0.01 | -0.13 | 0.02 |
| Accumulator Temperature | 0.20 | -0.24 | -0.07 | -0.14 | -0.07 | -0.05 | -0.11 | -0.04 | 0.03 | -0.02 | 0.09 | -0.01 |
| Gap pressure | -0.20 | 0.21 | 0.02 | 0.19 | 0.02 | -0.06 | -0.03 | 0.04 | 0.13 | 0.17 | -0.06 | -0.04 |
| Burst Strain | -0.18 | 0.25 | 0.41 | 0.24 | 0.41 | 0.22 | -0.19 | 0.13 | 0.27 | 0.04 | 0.00 | -0.05 |
| Oxide layer | 0.94 | 0.89 | 0.61 | 0.63 | 0.61 | 0.26 | 0.80 | 0.73 | 0.71 | 0.39 | 0.27 | 0.01 |

*Table 6 PRCC values for LMO*

## 5.2. Local Sensitivity Analysis (Damage Domain)

In the previous section, a global sensitivity analysis was made in order to identify which parameters were more influent for all sequences, for different nominal power and regarding the PCT and LMO. These two parameters were the Forced Convection HTC and the Film Boiling HTC. Once those parameters are found, a local sensitivity analysis of the input space can be performed in order to search for a Damage Domain, i.e. a region of the input space where a combination of specific values of those parameters leads to CD by surpassing PCT or LMO acceptance criteria. This approach is similar to the one used in the SM2A project to study EBEPU methodologies for LCC/SW [5].

Observing Figure 13 and 14, it is seen that a damage domain appears when the values of Film Boiling HTC and Forced Convection HTC are both very low, reaching a PCT higher than 2000 K in the worst cases. As expected, the cases with 105 % power, reach higher PCT values and the damage domain is more extended. Attending at Figure 15 and 16, it can be seen that the LMO has a similar behavior, reaching CD for low HTC values. It is notable that in all simulations at least one case leads to CD, remarking the importance of correctly identifying the uncertainties in the input parameters. Additionally, although the behavior is mostly monotonic, there are some peaks for PCT and LMO that reveal non-linear behavior, which may indicate that future sensitivity analyses should take this into account.

The quantification of CD probability using the damage domains is obtained calculating the probabilities of the inputs values that lead to damage. Forced Convection HTC and Film Boiling HTC values distributions were considered as normal distributions truncated at their extremes, see [30]. The probabilities obtained are shown in Table 7; it can be seen that there is an increase of a factor 1000 while decreasing the availability of the systems for 100% power, and a factor 50 for 105% power, which is an intermediate value between the parametric and the non-parametric analysis.

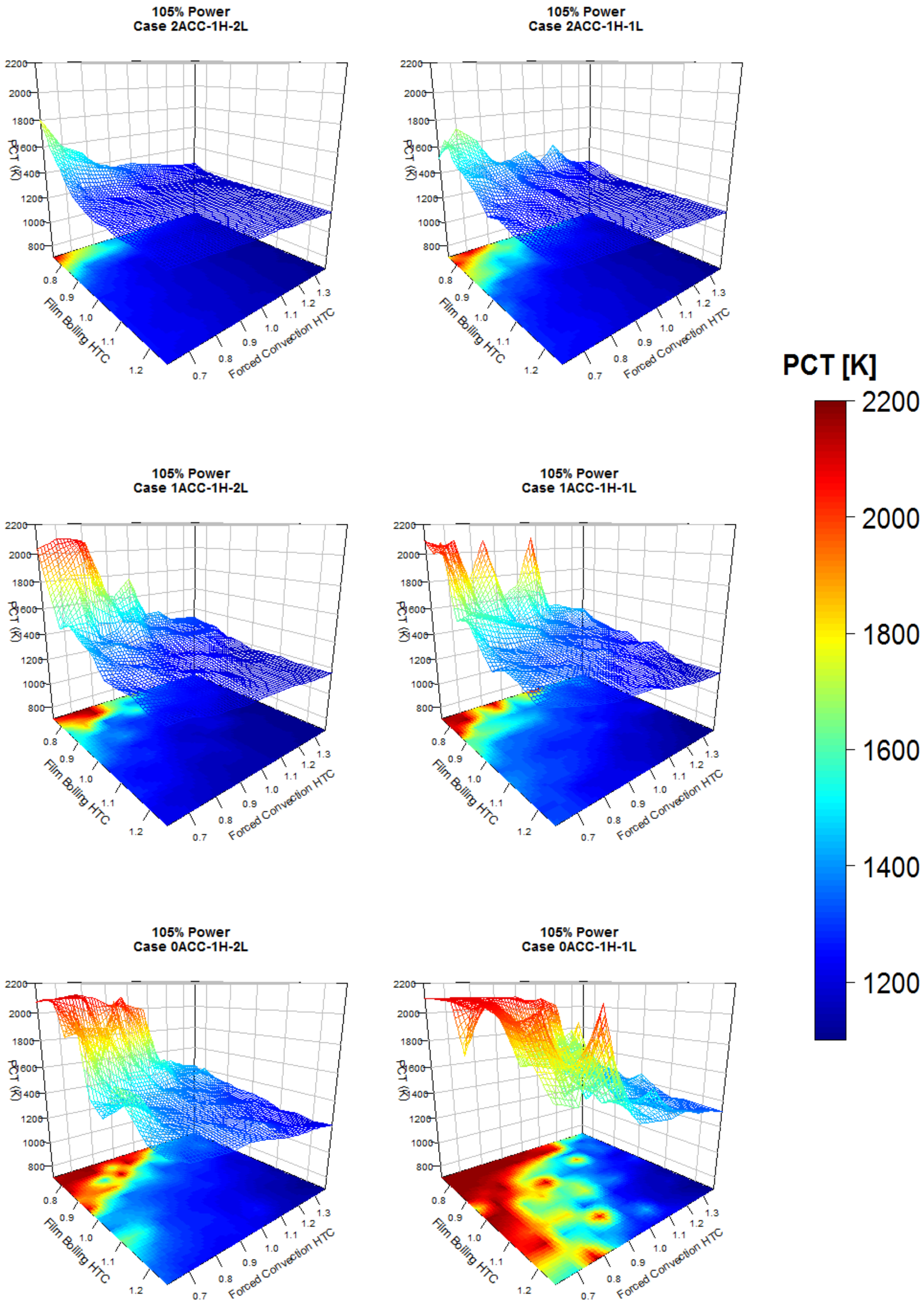

*Figure 13. Damage Domain Search for PCT for 105 % Nominal Power*

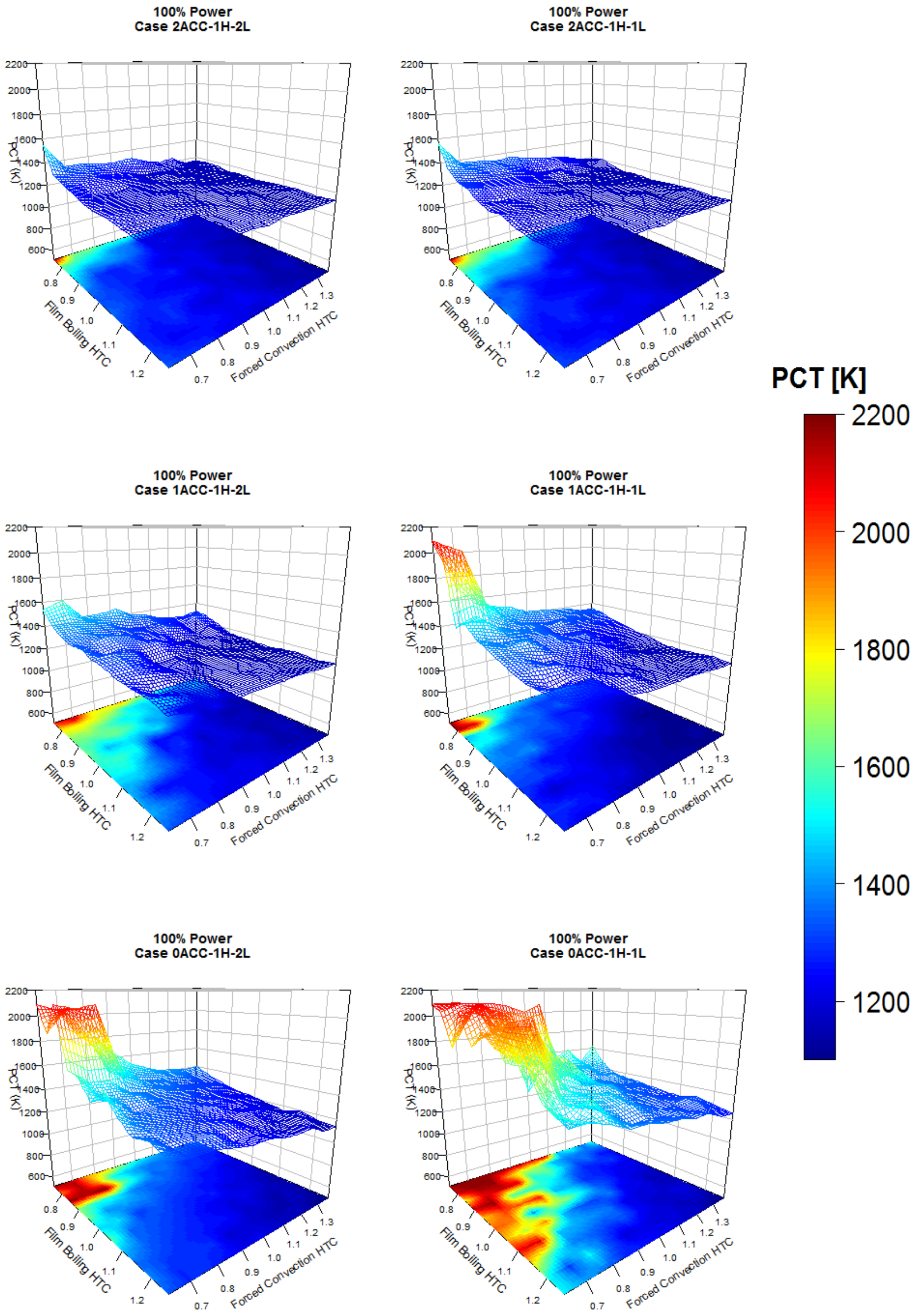

*Figure 14. Damage Domain Search for PCT for 100 % Nominal Power*

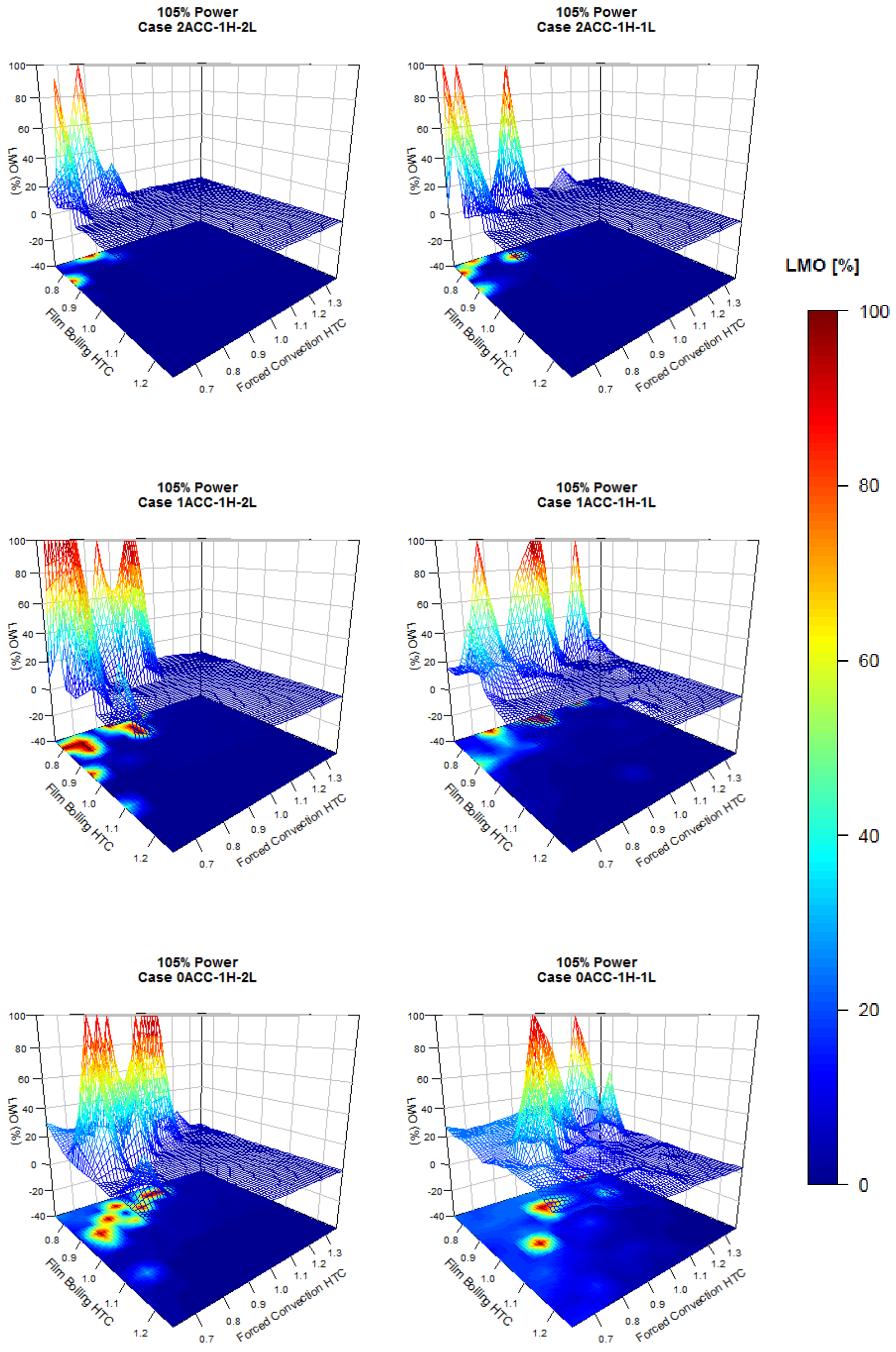

*Figure 15. Damage Domain Search for LMO for 105 % Nominal Power*

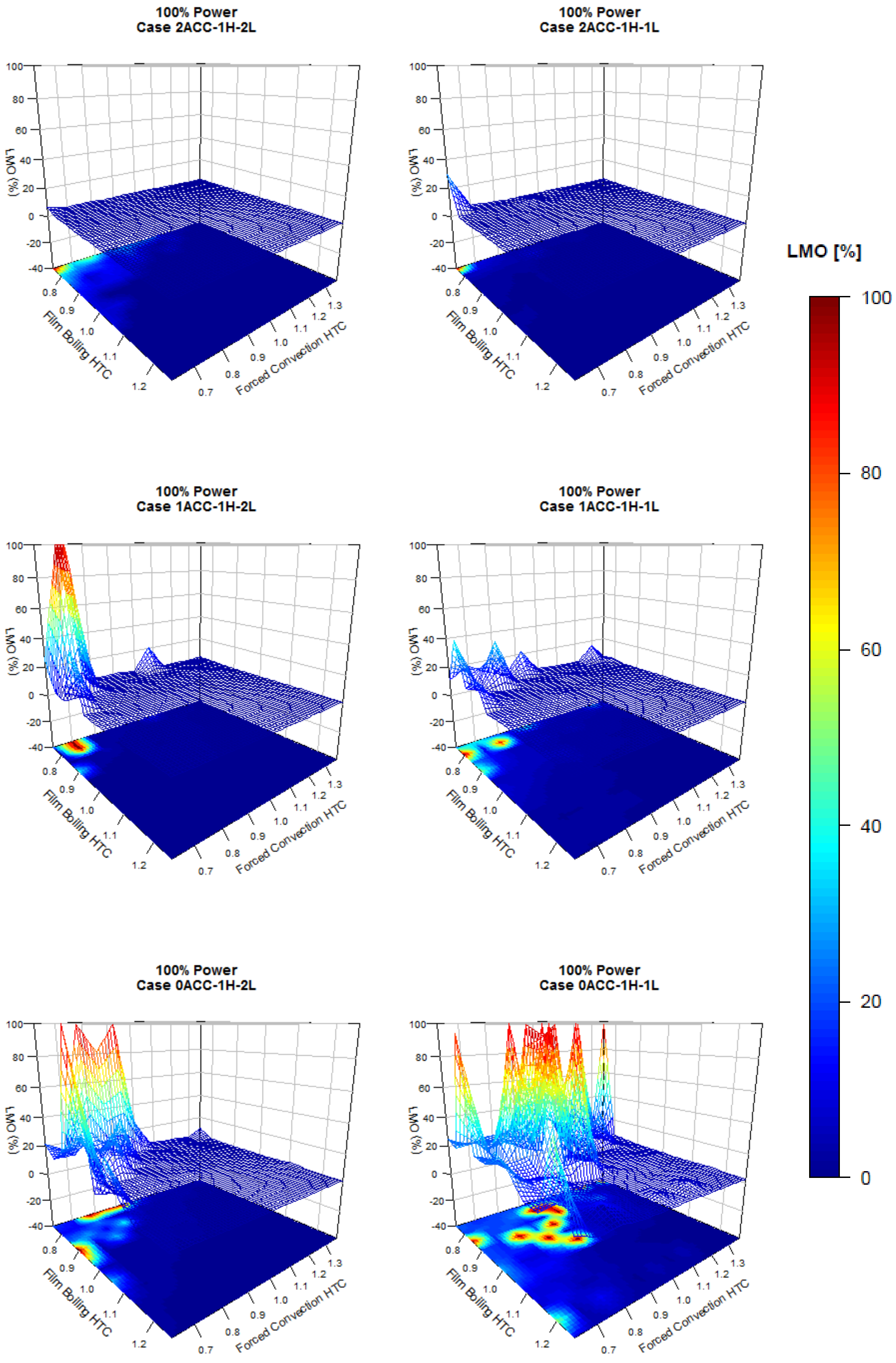

*Figure 16. Damage Domain Search for LMO for 100 % Nominal Power*

|  | Core Damage Probability |  |
|---|---|---|
|  | **100 % Power** | **105 % Power** |
| **2ACC-2L** | 3.09E-04 | 1.36E-02 |
| **2ACC-1L** | 7.70E-04 | 1.88E-02 |
| **1ACC-2L** | 9.58E-03 | 5.81E-02 |
| **1ACC-1L** | 2.77E-02 | 9.98E-02 |
| **0ACC-2L** | 7.81E-02 | 1.80E-01 |
| **0ACC-1L** | 4.79E-01 | 7.59E-01 |

*Table 7. Core Damage probability using Damage Domains of Film Boiling and Forced Convection HTC*

# 6. Results discussion

## 6.1. Uncertainty and Sensitivity Analyses Comparison and Discussion

Summarizing and comparing the CD probabilities of Table 2, 3 and 7, it is seen that the most conservative values are obtained using the binomial approach. This was expected, as the binomial approach is in fact equivalent to a Wilks approach with a single variable, and the information loss in the non-parametric methods induces conservatism [42]. At the same time, the probability obtained using damage domains does not take into account all the inputs uncertainty, and this reduces the CD probabilities.

It is remarkable that all CD probabilities obtained from the damage domains are lower than the ones obtained with the binomial approach, but it must be remarked that it is not correct to compare a standard probability (obtained with PDFs or damage domains) with the upper limit of a 95 % confidence interval of a probability (obtained with Clopper Pearson). The current regulation for uncertainty treatment requires a confidence level for the probabilities obtained, [1], so in order to use PDFs as valid methods, a confidence interval should be calculated. Accordingly, to study the EETs, it is recommended to use a binomial approach; because the PDFs obtained do not have the necessary amount of simulations to develop the confidence interval, and the damage domains only cover few parameters, neglecting the uncertainty propagation of the rest. These drawbacks could be partially solved if the number of simulations for each sequence is increased, but then the computational effort can become excessive.

## 6.2. EET CDF using the Binomial Non-parametric Results Discussion

In this section, the results obtained in section 3.5 will be discussed and used to analyze EBEPU approach using the information of Section 2.

As a first step, the probability of CD will be considered together with the sequence probability and the initiator event probability. The CDF is obtained by multiplying the CD probability acquired with the binomial approach with confidence interval and the sequence frequency obtained in Section 2 of the article.

The summary of the CDFs obtained using the binomial approach with confidence interval can be seen in Table 8, on which *Pseq* is the probability of the sequence, and *IE* is the frequency of the initiating event, in this case a LBLOCA in the cold leg 1, (1.14E-03 year $^{-1}$). All sequences with the recirculation header failed are merged under “No-recirc” wording.

Comparing the 100% and 105% nominal powers, it can be seen that the total CDF increase is 1.97E-05 year $^{-1}$, which represents a 156% increase. This result is similar to the one obtained in SM2A exercise for LBLOCA sequences [9].

As a relevant observation, it is also seen that the main contribution to the CDF for the LBLOCA sequence comes from a success sequence, on which both ACC and LPSI trains are fully available; this is provoked because, even though the CD probability is the lowest of all sequences, the occurrence probability of the sequence itself is the highest. This occurs for both 100 % and 105 % power cases, and the main contributor to the CDF increase is the “success” sequence 2ACC-2L.

The results of the EBEPU study using uncertainty analyses suggest that the best strategy to reduce the sequence CDF involves working on the “success” sequence 2ACC-2L, reducing the CD probability of this sequence. In this sense, an increase in the success sequence (*Pseq*) barely changes the total CDF of the LBLOCA. This result, somehow confronts the philosophy of soma PSA options for safety analyses, because their end states are either “CD” or “Success”, and the main strategy to reduce the CDF of a sequence is to make the success sequences more likely. This aspect will require further discussion in the future.

As commented in Section 1, the nature of this analysis makes possible to interpret it both for a PSA or a risk informed DSA. In this sense, as a final comparison, the CDF that would have been obtained using different approaches is shown in Table 9, and commented below:

- **Classical PSA**: This approach only takes into account 2ACC-2L and 2ACC-1L sequences as successful, as explained in Section 2, and its probability solely depends on the headers failure probability.
- **Base Estimate PSA**: As observed in Section 3, if the Base Cases would have been used as indicatives of success or CD similar to a PSA with Best Estimate conditions, the CDF would have been reduced, as solely 0ACC-1L reaches CD.
- **BEPU 95/95 like**: If the success criteria would have been determined by a “95/95” criteria similar to a DSA BEPU without single failure, [1] and regarding the results of Section 4.3, the CDF would be higher than the Best Estimate PSA and lower/equal than the Classical PSA.
- **EBEPU**: Finally, employing an EBEPU approach, the CDF increases mainly because of the damage probability in the successful sequences. It must be commented that these results is particular of just some sequences such as LBLOCA or MBLOCA. In this sense, this approach seems particularly interesting for sequences with several uncertainties where a clear and sharp separation between CD and success is nonexistent. This kind of situations are not exclusive of the nuclear industry and are perfectly applicable to other industries with risk-informed decisions such as the chemical or aerospace industries.

|  |  |  | 100 % Power |  | 105 % Power |  |  |
|---|---|---|---|---|---|---|---|
| Sequence | Pseq | IE ·Pseq [year $^{-1}$] | P damage | CDF [year $^{-1}$] | P damage | CDF [year $^{-1}$] | ΔCDF [year $^{-1}$] |
| 2ACC-2L | 9.69E-01 | 1.11E-03 | 2.95E-02 | 3.29E-05 | 4.66E-02 | 5.19E-05 | 1.90E-05 |
| 2ACC-1L | 3.00E-02 | 3.45E-05 | 2.95E-02 | 1.02E-06 | 4.66E-02 | 1.61E-06 | 5.90E-07 |
| 2ACC-0L | 9.00E-04 | 1.03E-06 | 1.00E+00 | 1.03E-06 | 1.00E+00 | 1.03E-06 | 0.00E+00 |
| 1ACC-2L | 2.58E-04 | 2.97E-07 | 4.66E-02 | 1.38E-08 | 8.96E-02 | 2.66E-08 | 1.28E-08 |
| 1ACC-1L | 8.00E-06 | 9.20E-09 | 1.02E-01 | 9.41E-10 | 2.33E-01 | 2.14E-09 | 1.20E-09 |
| 1ACC-0L | 2.40E-07 | 2.76E-10 | 1.00E+00 | 2.76E-10 | 1.00E+00 | 2.76E-10 | 0.00E+00 |
| 0ACC-2L | 2.91E-05 | 3.34E-08 | 1.8E-01 | 5.87E-09 | 3.10E-01 | 1.04E-08 | 4.49E-09 |
| 0ACC-1L | 9.00E-07 | 1.04E-09 | 5.4E-01 | 5.56E-10 | 8.55E-01 | 8.85E-10 | 3.29E-10 |
| 0ACC-0L | 2.70E-08 | 3.11E-11 | 1.00E+00 | 3.11E-11 | 1.00E+00 | 3.11E-11 | 0.00E+00 |
| No-recirc | 6.41E-05 | 7.31E-08 | 1.00E+00 | 7.31E-08 | 1.00E+00 | 7.31E-08 | 0.00E+00 |
| Total | 1.00E+00 | 1.38E-06 |  | 3.49E-05 |  | 5.46E-05 | 1.97E-05 |

*Table 8. Core Damage Frequency obtained using the binomial approach with 95% confidence level for each of the EET branches.*

|  | **Classical PSA** | **Best Estimate PSA** | **BEPU 95/95 like** | **EBEPU** |
|---|---|---|---|---|
| **Core Damage Frequency (100%/ 105%)** | 1.38 E-06/<br>1.38E-06 | 1.1E-06/<br>1.1E-06 | 1.15E-06/<br>1.38E-06 | 3.49E-05/<br>5.46E-05 |

*Table 9. Comparison of Core Damage Frequency using different Approaches*

## 7. Conclusions

In this paper, a study of the EBEPU approach for safety analysis is performed. This option relies on Expanded Event Trees and Best Estimate models, avoiding conservatism in the systems availability to analyze sequences. The present research makes use of a LBLOCA in a PWR-W simulated with the TRACE code to develop the analysis.

This EBEPU is made through an uncertainty and sensitivity analysis, using a 105% power uprate as an example. From the results obtained, it is seen that parametric and non-parametric uncertainty analyses, and the sensitivity analysis all provide similar results; they show an increase of a large factor in the CD probability depending on the systems individual availability, and a similar increase in CDF is found with the 105 % power uprate.

Then, analyzing the EBEPU approach with non-parametric statistics, it is strongly remarkable that if we take into account the systems availability probability, the sequence that contributes the most to the CDF of a LBLOCA is a “success sequence”; this is, the sequence with all the systems available, also the most probable, contributes in more than 90 % to the CDF taking into account all EET sequences. This may be an indicator that the best strategy to reduce the sequence CDF involves working on that successful sequence, reducing consequences, i.e. the CD probability of this sequence. This result, somehow confronts the philosophy of soma PSA options for safety analyses, because their methodologies result in end states that are either “CD” or “Success”, and the main strategy to reduce the CDF associated to an initiating event is to make the success sequences more likely. It is certain that this aspect will require further discussion in the future.

Finally, it is worth commenting that the EBEPU approach seems particularly interesting for accidental sequences with great uncertainties associated, where the separation between CD and success is not perfectly clear.

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