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Demonstration of the E-BEPU Methodology for LB-LOCA in NPP with PWR Reactor

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ABSTRACT

The paper presents preliminary results for the application of the new Extended Best Estimate Plus Uncertainty (E-BEPU) methodology developed in the framework of the Horizon-2020 NARSIS project. The approach is risk-informed combined deterministic and probabilistic methodology dedicated to Nuclear Power Plant (NPP) systematic design verification and to enhance Defence-in-Depth (DiD). It assumes application of the best-estimate computer code, realistic input data for initial and boundary conditions and plant systems availability based on Probabilistic Safety Analysis (PSA). It extends the scope of the uncertainty analysis to include the availability of safety systems as an additional uncertain item. The generic large Generation III Pressurized Water Reactor (PWR) design with core thermal power of 4500 MW defined in the NARSIS project was applied. The surge line LB-LOCA, a postulated initiating event, was studied as an example of design basis type event. This study is the first practical application of the E-BEPU methodology, which is under development in the NARSIS Project.

1 INTRODUCTION

The essential reference for the Deterministic Safety Analysis (DSA) is the IAEA Safety Standards Deterministic Safety Analysis Specific Safety Guide-2 (SSG-2) Revision-0 published in 2009 [1] and its recent update Revision-1 published in 2019 [2]. Both revisions of the IAEA document defines four options for performing DSA analysis. The Option-1 is simple conservative analysis with conservative assumptions, data and computer codes. The Option-2 covers usage of the Best Estimate (BE) computer code with conservative data and assumptions. The Best Estimate Plus Uncertainty (BEPU) methodology is considered as the Option-3 with conservative assumptions on the availability of safety systems, best estimate codes, initial and boundary conditions. In the SSG-2 Rev-0, Option-4 is an extension of Option-3 with reduction of the conservatism, with no limitation set on studied transient type. Availability of systems is derived from probabilistic analysis (i.e. PSA), and the whole option is referred as risk-informed with realistic input data and realistic quantification of uncertainties, when possible and conservative when no proper data available [1]. On the contrary, in the new revision of the SSG-2, Option-4 is defined in more general terms. It is defined as a realistic approach with best estimate computer codes, best estimate assumptions and best estimate initial and boundary conditions. There is also no explicit demand for quantification of uncertainties. In the Rev-1, Options 1-3 are 'conservative analysis', where Option-4 is considered as a realistic analysis. What is important, it is explicitly limited to Anticipated Operational Occurrences (AOO) and Design Extension Conditions (DEC) [2]. It should be highlighted that the Rev-1 Option-4 is a different concept than presented in Rev-0.

There are only a few publicly available research reports related to the possible realisation of the Option-4 or E-BEPU. The first E-BEPU was proposed by Dusic et al. in 2014 paper [3],[4]. In principle, it can be applied to any Plant Condition; it was initially intended for Design Basis Accidents and AOO, but an application to DEC is also possible. The alternative E-BEPU was proposed by Martorell et al. in 2017 and published in two papers [5],[6].

The E-BEPU methodology presented in this work is being developed in the framework of the Horizon 2020 NARSIS Project [7]–[9], and it is an extension of the idea proposed in [3],[4]. What is important, it corresponds to the Option-4 presented in the SSG-2 Rev-0, but it does not correspond to the Option-4 in SSG-2 Rev-1. The basic motivation and purpose of this work are to test the new E-BEPU methodology.

2 METHODOLOGY

2.1 E-BEPU Overview

The E-BEPU procedure is depicted in Figure 1, and it is composed of 15 blocks, each representing a set of complex activities to be executed. The procedure starts with Blocks#1-2, which are dedicated to defining Postulated Initiating Event (PIE), classify it in terms of Plant Condition (PC), define Regulatory Acceptance Criteria (RAC) and screen sequences to be analysed. Block#3 is similar to the typical BEPU, and it covers uncertainty analysis for non-screened sequences. The BEPU results are assessed in Block#4, which is a branching point which splits the work-flow into two different parts.

Blocks #4-to-7 form a path for the situation when uncertainty analysis shows that all non-screened sequences fulfil RAC with Standard Tolerance Level (STL) 95/95. In the next step, in Block #5-6 RAC criteria for the next accident class are defined and tested with Increased Tolerance Level (ITL) (99/95). If this test is positive, the design is acceptable. The additional design verification with ITL (99/95), for both branches, is dedicated to confirming that there are no cliff-edge effects [10].

The path with Blocks #4-to-14 is dedicated to a situation when there is at least one non-screened sequence failing to fulfil RAC with STL. In this case, a whole PIE demands verification if the considered PIE, being a set of different sequences, fulfils RAC with STL. If the test fails, the design is not acceptable (Block#9). In case of success, each sequence is assessed separately. Sequences which succeeded test with STL are transferred to the left branch (Block #5). Failed sequences are reclassified (Block #11), and if their conditional probability met proper criteria, they are tested with ITL for the next class RAC (Blocks #12-13). Success ensures design acceptance; otherwise, if the ITL test or reclassification test fails, the design is not acceptable.

2.2 Test Case and Details

In this work, the PIE is a double-ended pressuriser surge line break at the point of connection with the hot leg. The surge line break belongs to the LB-LOCA type of accidents considered as DBA for the studied design and is classified as Design Basis Condition 4 (DBC-4). For simplicity, the Peak Cladding Temperature (PCT) 1204°C was selected as the only RAC (Figure 1, Block#1) [11].

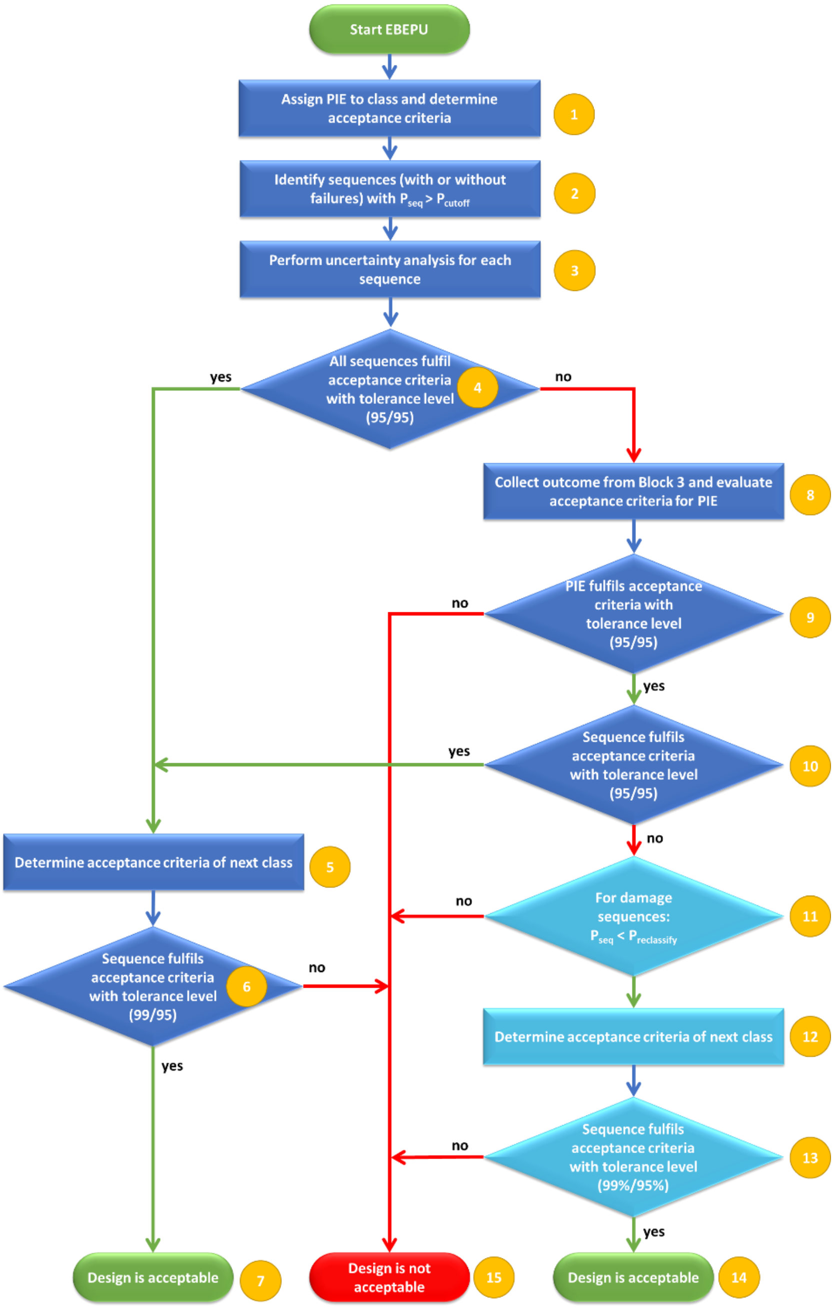

Figure 1 Flow Diagram of E-BEPU. Based on [7].

The deterministic plant model was developed with system code RELAP5 Mod3.3 (Figure 2), and it was used to predict plant response. Moreover, the standard PSA model, for the considered PIE, was developed by the project partners in Risk-Spectrum and Sapphire codes

[12]. The E-BEPU allows to use of PSA models in Block#2, but modifications are necessary. It is mainly because probabilistic part of the E-BEPU has a different purpose than a typical PSA. In consequence, the Multiple-Path Event Tree (MPET) approach was proposed, where event trees are not designated to studying success/failure, but they have multiple branches at each branching point regardless of the outcome. It allows estimation of the conditional probabilities for each sequence with different systems availability. Fault Trees were used to obtain proper configurations of systems to be quantified in each branching vertex of the MPET. Probabilistic results are used in the sequence screening process, which demands that the sum of all conditional probabilities for non-screened sequences has to be lower than a threshold value equal to $5 \cdot 10^{-4}$. In this study, thirteen different sequences were identified (Table 1). The conditional probability of screened sequences is $4.76 \cdot 10^{-4}$, and it is below the limit.

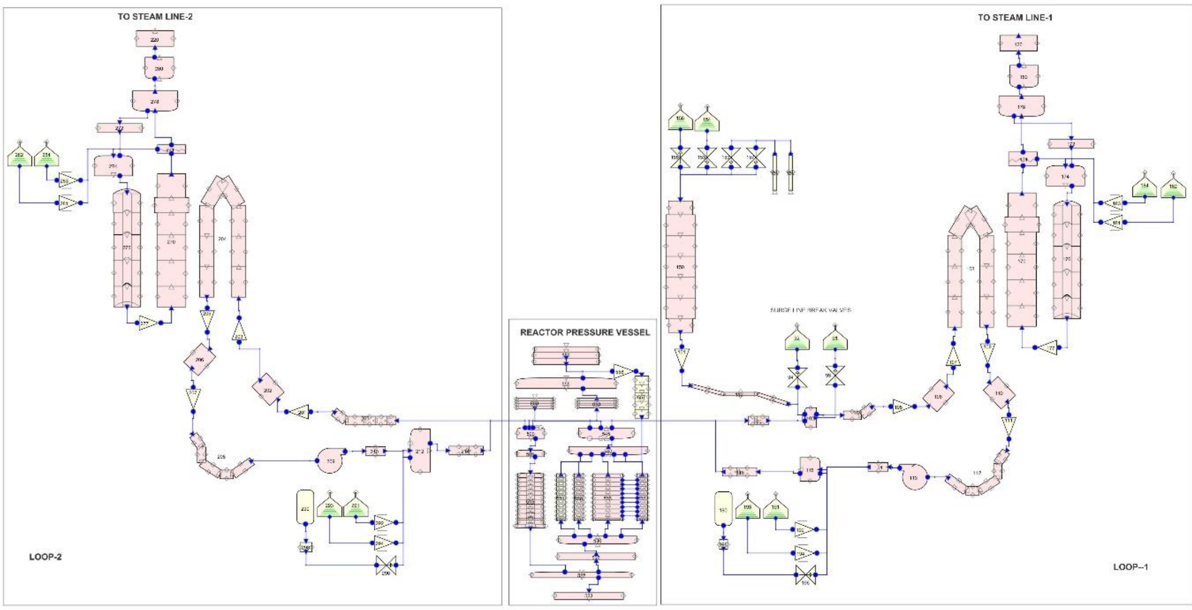

Figure 2 RELAP5 model of the NPP, RPV and Loop-1 and Loop-2 (2/4 loops).

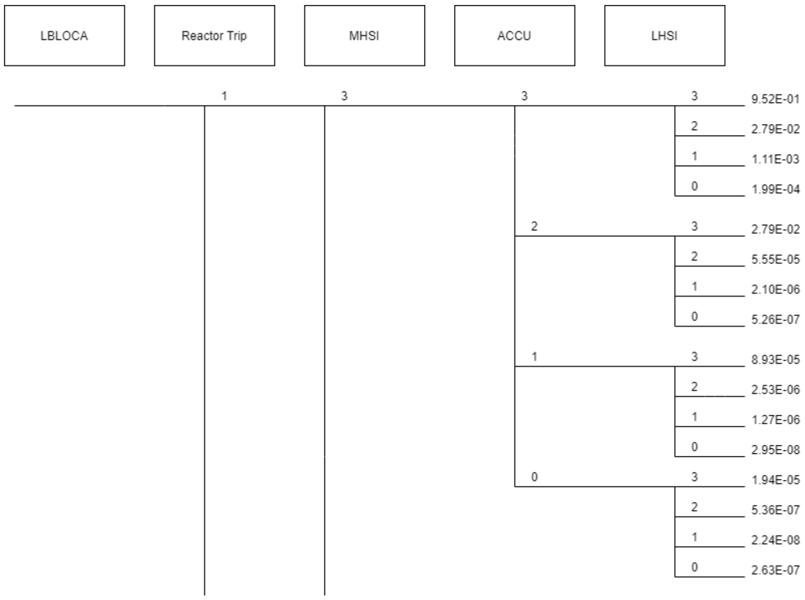

Figure 3 Part of the Multiple-Path Event Tree (MPET) for the studied PIE.

Sequences selected in Block #2 were analysed in the further part of the procedure. Block #3 is analogous to the BEPU (see [13]), and the Wilks based (GRS) approach was applied [10]. A set of fifteen uncertainty parameters, being significant for the Figure of Merit (FoM) and typical for LB-LOCA BEPU were selected – see Table 2. List of parameters with distributions is preliminary and is based on [14],[15]. Values were sampled with Simple Random Sampling. For each sequence with one-sided STL limit, 59 input decks were generated, and it resulted in 13x59=780 system code runs [10]. Transients were simulated for 1800 seconds only because long-term plant stabilisation was not considered, and all important events occur within this time interval.

In the current version of the methodology [7],[8], DBC-4 is a special case, the "last class". The approach is simplified, and Blocks #5-6 and Blocks #12-13 can be omitted, as there are "no next" class for the last class. It has to be mentioned that the research is ongoing to extend this part and use DEC criteria for the last class in Blocks #5,6,12,13, and it will be a matter of current research activities [9].

Table 1 Sequences which were not screened in Block #2. MHSI – Medium Head Safety Injection, ACCU – Accumulators, LHSI – Low Head Safety Injection.

No.	Code	MHSI	ACCU	LHSI	Conditional Probability
1	1333	3	3	3	9.52E-01
2	1332	3	3	2	2.79E-02
3	1331	3	3	1	1.11E-03
4	1330	3	3	0	1.99E-04
5	1323	3	2	3	2.55E-03
6	1233	2	3	3	1.59E-02
7	1232	2	3	2	8.98E-03
8	1231	2	3	1	4.00E-04
9	1133	1	3	3	5.45E-04
10	1313	3	1	3	8.93E-05
11	1131	1	3	1	1.76E-04
12	1130	1	3	0	9.25E-05
13	1222	2	2	2	5.95E-05

Table 2 Uncertainty parameters with probability distributions.

No	Uncertainty Parameter	Nominal value	Unit	Type	Distribution	Min	Max	Mean	Std. Dev
1	Break discharge coefficient	1.0	---	multiplicative	normal	0.95	1.05	1	0.025
2	Initial power	4500	MWth	multiplicative	normal	0.98	1.02	1	0.01
3	Fuel thermal conductivity	correlations	---	multiplicative	normal	0.9	1.1	1	0.05
4	UO2 specific heat	correlations	---	multiplicative	normal	0.98	1.02	1	0.01
5	Fuel gap size (diametric gap)	0.17	mm	multiplicative	normal	0.8	1.2	1	0.1
6	power after scram decay power multiplier	Maximum Decay + 2sigma	---	multiplicative	normal	0.92	1.08	1	0.04
7	I&C signal delay start pumps – MHSI, LHSI	15	s	Additive	uniform	15	40	---	---
8	initial conditions: primary loop flow	27185	m^3/h	multiplicative	normal	0.96	1.04	1	0.04
9	initial cold leg temperature	295.6	°C	additive	normal	-2	2	0	1
10	accumulator initial pressure	4.5	MPa	additive	normal	-0.2	0.2	0	0.1
11	accumulator line friction form losses	8.65	---	multiplier	log-normal	0.5	2	1.25	0.75
12	accumulator temperature	50	°C	additive	normal	-10	10	0	10
13	MHSI - flow characteristics	table	kg/s	multiplier	normal	0.95	1.05	1	0.05
14	LHSI - flow characteristics	table	kg/s	multiplier	normal	0.95	1.05	1	0.05
15	hot channel peaking factor	2.82	1	multiplier	normal	0.95	1.05	1	0.025

3 RESULTS AND DISCUSSION

Maximum output values of the PCT (FoM), for hot fuel rod for all 13 sequences are presented in Figure 4. Additionally, for example, hot rod results with uncertainty bands, for arbitrarily selected sequence number 12 are presented in Figure 5. These are results for the version of the E-BEPU for DBC-4 and with the omission of Blocks #5,6,12,13.

It can be observed that RAC was not violated in any run. It shows that the studied PIE is successful from the point of view of the E-BEPU methodology. We can clearly see that the presented demonstration case follows the left branch of the procedure (Figure 1).

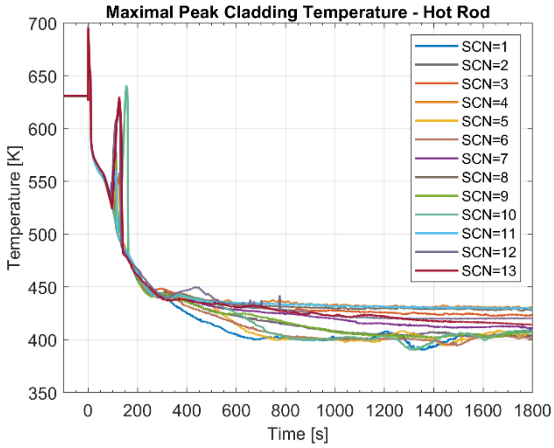

Figure 5 PCT for single realisations with the highest observed hot rod temperature at the peak for all 13 sequences.

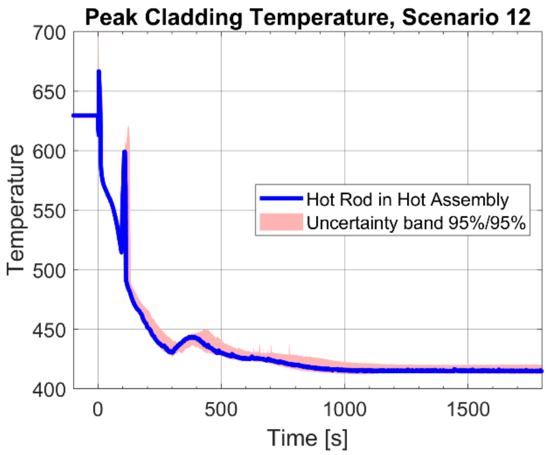

Figure 4 PCT temperatures with uncertainty bands for sequence no. 12 with 1xMHSI, 3xACCU and no LHSI.

4 CONCLUSIONS

This paper demonstrates, the preliminary results, for the first practical application of the novel Extended Best Estimate Plus Uncertainty methodology. In this paper, only part of the procedure, namely the "left branch" for the last design basis category (DBC-4) was tested. It is, in fact, the simplest possible E-BEPU situation. The considered design successfully passed the verification procedure for the LB-LOCA (surge line) type PIE for all considered sequences. It is thanks to the fact that the considered NPP design is very robust. LOCAs are usually design basis accidents, and a lot of focus is present during the plant design process to cope with it. Moreover, the considered accident is the surge line break, which is substantially less severe, in terms of PCT, than a typical LB-LOCA for hot leg or cold leg. What is more, it can be observed that the variation of ACCU and LPSI availability has low importance for PCT. It has to be highlighted that the qualification of the presented RELAP5 model is still ongoing, and results should be treated with a proper margin of confidence. It is worth mentioning that the alternative results for SL-LOCA can be found in the literature [16],[17]. What is also important, the list of uncertainty parameters (Table 2) does not consider RELAP5 modelling parameters, and it should be considered in the final analysis.

We can conclude that the, presented outcomes suggest that the E-BEPU methodology is applicable to Light Water Reactors with available thermal-hydraulic system codes and PSA codes and can be executed with reasonable computational resources. However, additional research is a necessity.

Further research activities will focus on studying other details and parts of the methodology, i.e. testing situations when some sequences are failed in Block #4 or when in general design is not acceptable. What is more, future activities will cover the application of the methodology for DEC, lower DBC classes and possible improvements for the last class analysis.

The E-BEPU is the next step in Nuclear Safety and opens the possibility to decrease the conservatism in the assumptions for safety systems availability. It extends the scope of the uncertainty analysis to include the availability of safety systems as an additional uncertain item and allows to include risk insights in deterministic analysis framework. It avoids or detects possible cliff-edge effects by comparison with next-class criteria and allows reclassification of low probability sequences. It can also reduce potential problems with "apparently" conservative assumptions. Finally, the E-BEPU provides a systematic approach to study NPP safety and allows to strengthen Defence-in-Depth.

The application of the E-BEPU as a risk-informed combined probabilistic-deterministic approach is a relatively new approach, and it is an active area of research. The methodology presented in this paper can potentially be an alternative to BEPU and possible realisation of the E-BEPU. The necessary trade-off of using E-BEPU and reducing the conservatism is the substantial increase in necessary computational effort.

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