ASSOCIAÇÃO BRASILEIRA DE ENERGIA NUCLEAR – ABEN
2019 International Nuclear Atlantic Conference - INAC 2019
Santos, SP, Brazil, October 21-25, 2019

Agência Brasileira do ISBN
ISBN 978-85-99141-08-3

AN ANGRA 2 LBLOCA SIMULATION MODEL FOR RELAP5MOD3.3 CODE WITH UNCERTAINTY ANALYSIS

Alzira A. Madeira[1], Luiz Carlos M. Pereira[1] and Gaianê Sabundjian[2]

[1] Comissão Nacional de Energia Nuclear – Coordenação de Reatores (CNEN / CODRE – RJ)
Rua General Severiano, 90, Botafogo
22290-040, Rio de Janeiro, RJ, Brazil
alzira@cnen.gov.br and lpereira@cnen.gov.br

[2] Instituto de Pesquisas Energéticas e Nucleares (IPEN / CNEN - SP)
Av. Professor Lineu Prestes 2242
05508-000 São Paulo, SP, Brazil
gdjian@ipen.br

ABSTRACT

This paper describes the activities related to the work planned within Project BRA3.01/12 between CNEN and the European Community, relatively to its Task 2.1 (independent uncertainty quantification and sensitivity analysis utilizing the computational tool SUSA for the calculus related to LOCA simulation for licensing matter). SUSA software has been applied to the reference case, a double-ended LBLOCA in Angra 2, simulated with a RELAP5 code nodalization developed by the thermal hydraulic technicians of CNEN and its research institutes. This original nodalization has been improved for the development of the main objective of Task 2.1. The recommendations that our European counterparts provided on the last workshop, held at CNEN in Rio de Janeiro from January 28th to February 2nd, 2018, have been implemented as far as feasible.

1. INTRODUCTION

This report aims at the description of final status of the uncertainty studies using SUSA software [1], associated to the simulation of a large break loss of coolant accident (LBLOCA) in Angra 2 NPP with RELAP5 [2]. The mentioned accident consists of a double-ended break on the cold leg of the loop where the pressurizer is located (loop 20). This accident is thoroughly discussed on the FSAR of Angra 2 [3] and on [4], where it is called the base case. On the present application, this simulation presented on [4] will be considered our reference case. However, the work here presented will refer mainly to the application of SUSA software.

2. DESCRIPTION OF THE ANGRA-2 PLANT DESIGN

The Central Nuclear Almirante Alvaro Alberto (CNAAA) site, where units Angra 1 and Angra 2 are located, is at an elevation of 5.00 m above the sea level. Eletrobras Eletronuclear is the owner of the Nuclear Power Plants (NPPs). The plants are located on the Itaorna beach in Angra dos Reis, Rio de Janeiro, Brazil. Angra 2 achieved full power operation in 2001, and it is a PWR design. It was built by Siemens-KWU (currently Areva), resulting from an agreement between Brazil and Germany in 1975. Angra 2 is a four-loop NPP with 1350 MWe capacity. It has four pumps to control the water flow, one pump for each loop.

Fig. 2.1 shows the arrangement of the components of Angra 2 NPP.

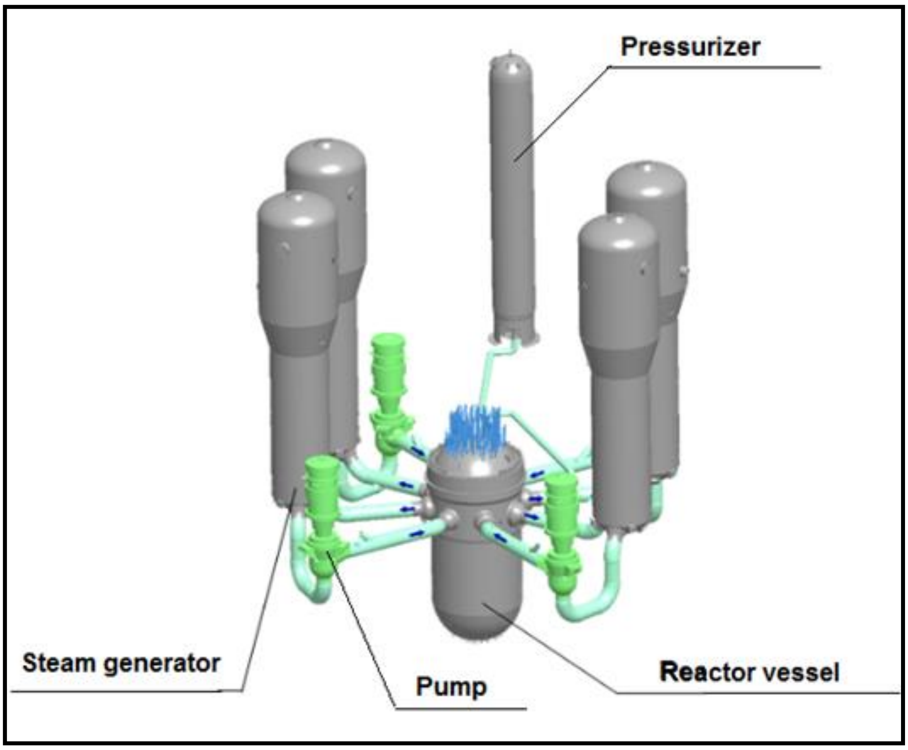

Figure 2.1: Arrangement of Angra 2 components

To guarantee the safety of this NPP, in case the steam generators of the plant secondary side are not at proper conditions to provide suitable cooling for the plant primary side, two branches of the Emergency Core Cooling System (ECCS) are provided, respectively connected to the hot and cold legs of each primary side loop [3]. The ECCS, actuating during loss of coolant accidents, and the Residual Heat Removal (RHR), in case of plant shutdown, are performed by the same system, the Residual Heat Removal System (RHRS). The RHRS consists of four independent trains allocated to the four reactor coolant loops. The trains, designed JN10 to JN40 (loop 10 to loop40), are identical but differ from trains JN20 and JN30, which have additional operational and safety functions; they are connected with the fuel pool.

3. COMPUTATIONAL SOFTWARE

3.1. RELAP5 Code

The Idaho National Laboratory developed the RELAP5/MOD3.3 [2] code for the analysis of thermal hydraulic transients in several NPP design and research reactors. RELAP5 is also able to model experimental facilities of nuclear reactors.

The program uses the non-homogeneous, non-equilibrium two-fluid models and considers the mass, momentum and energy equations for the liquid and gaseous phases. RELAP5 also offers two additional equations to calculate non-condensable gases and soluble boron. Onedimensional models are used to describe the fluid flow and the heat conduction at the structures However, in some special cases such as the crossflow in the reactor core and the rewetting region in flooding model, two-dimensional models are used.

3.2. SUSA Software

SUSA (Software for Uncertainty and Sensitivity Analyses) [1] is a PC-software running under Windows. It can be used for any simple or complex application. There are, in principal, no limitations concerning the number of uncertain parameters, output quantities, and computer code runs.

SUSA guides through the main steps of a probabilistic uncertainty and sensitivity analysis. These steps can be summarized as follows:

(a) Identification of all phenomena, modeling assumptions, and parameters that are potentially important contributors to the uncertainty of the computational result and representation of all uncertainty sources by uncertain parameters;
(b) Quantification of the state of knowledge on the uncertain parameters in terms of probability distributions and dependence measures;
(c) Generation of a sample of values for the uncertain parameters according to a multivariate probability distribution which satisfies the input given in step b;
(d) Performance of computer code runs for each set of values sampled for the uncertain parameters (random sample from the unknown probability distribution of the computational result);
(e) Quantification of the uncertainty of the computational result on the basis of the sample resulting from step d;
(f) Ranking of the parameters with respect to their contribution to the overall uncertainty of the computational result;
(g) Comprehensive documentation of the analysis steps for scrutinizing the analysis results.

4. RELAP5 ANGRA2 MODELING

As a reference case for this work to estimate the uncertainty bands of a LBLOCA best estimate analysis, an accident in the cold leg of the loop 20 (which is the loop connected to the pressurizer) was considered, next to the pressure vessel of the reactor, thus isolating the ECCS for this loop. It is a double-ended rupture, the worst LBLOCA case considered at the Final Safety Analysis Report [3].

4.1. Angra 2 Nodalization

Angra 2 nodalization [5], improved in the frame of the mentioned national technical cooperation [4], presents the main components (reactor vessel and reactor core) which were modified to obtain the reference LBLOCA case. The final nodalization of these components are shown respectively in Fig. 4.1 and Fig. 4.2. The final nodalization models all the NPP primary system (the reactor being modeled with seven hydrodynamic channels and nine core active heat structures) and part of the secondary system, whose boundary conditions are the turbine, relief and safety valves of the steam generator (SG) and main and emergency feedwater valves.

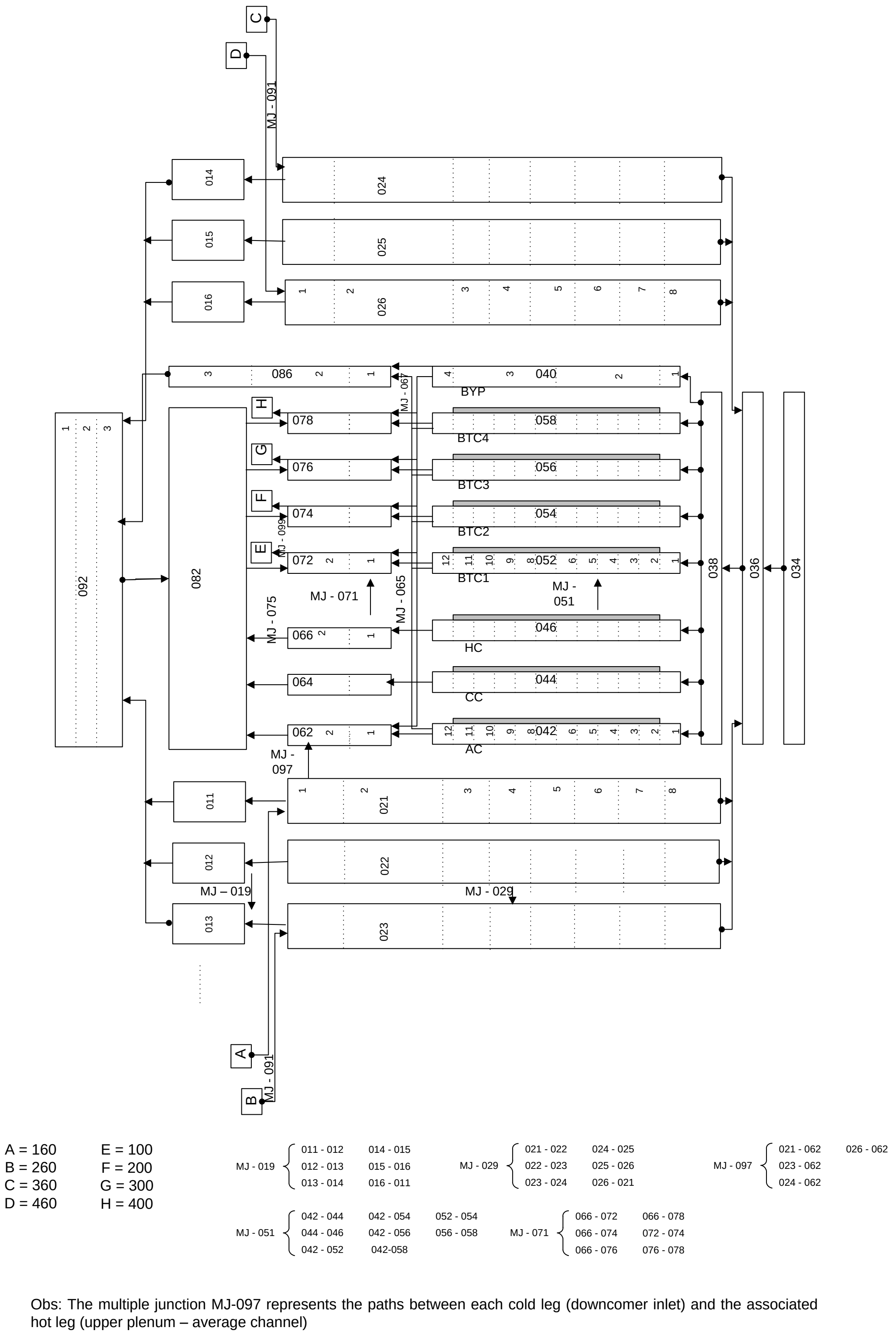

Figure 4.1: Reactor pressure vessel nodalization

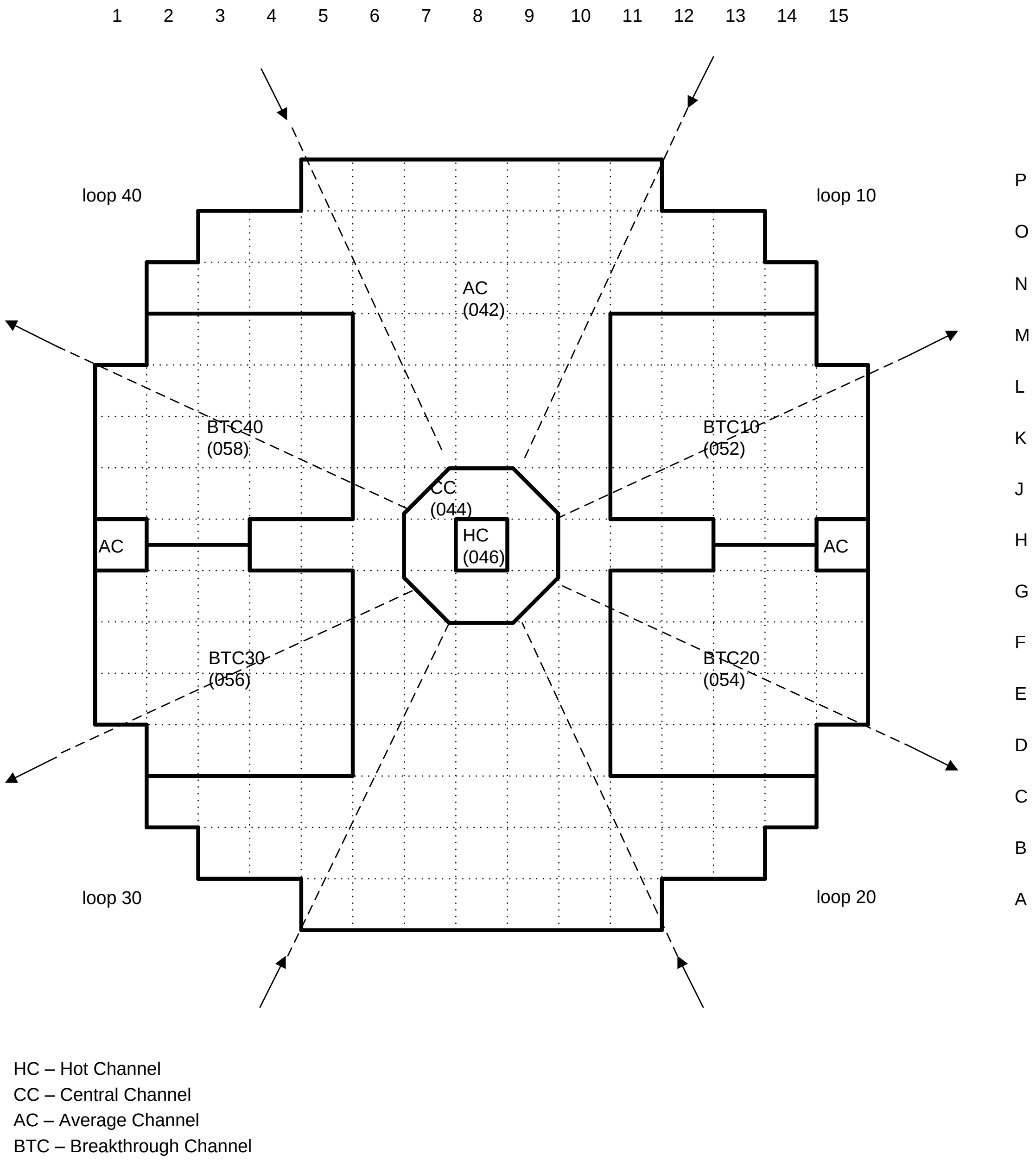

Figure 4.2: Reactor core – schematic view

4.2. LBLOCA Implementation

The double-ended LBLOCA is simulated starting from the introduction of three valves (258, 991 e 993) in the nodalization (see Fig. 4.3). For the initiation of the accident, valve 258, which is opened for steady state, being part of the pressurized boundary (primary circuit 20), is closed. Simultaneously, valves 991 and 993, which connect the pressurized boundary to the containment and are closed for steady state, are opened.

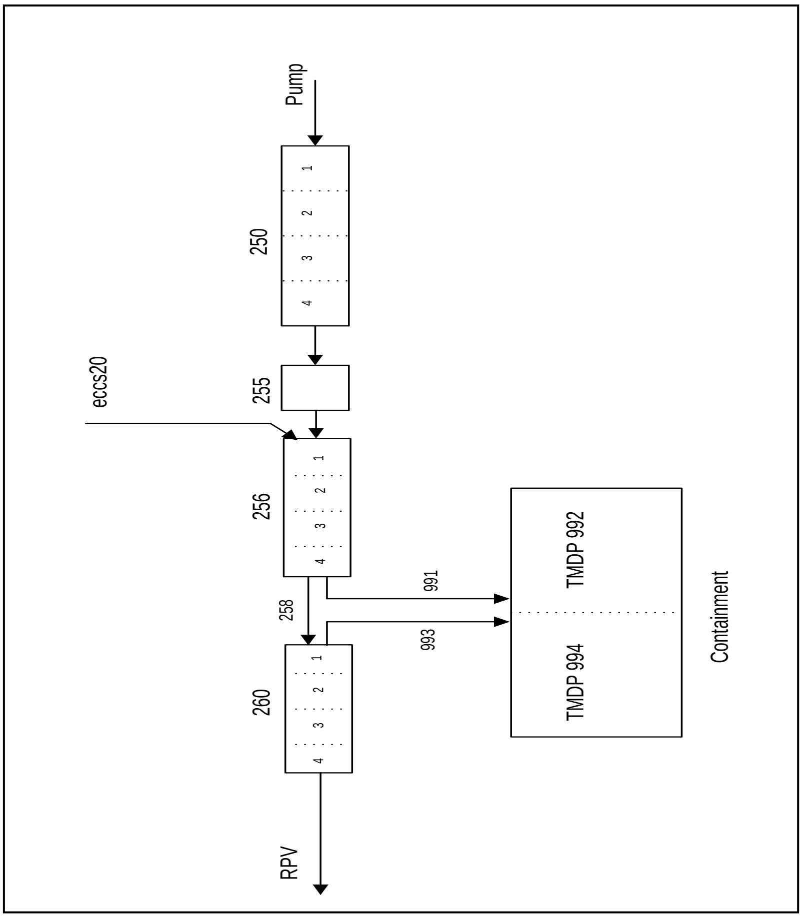

Figure 4.3: Cold leg break nodalization

The realistic conditions considered for the LBLOCA at Angra 2 FSAR are nominal power at 100% (3765 Thermal MW) and the nominal pump mass flow in each loop is 4896 kg/s.
The conservative conditions (or licensing requirements) related to the availability of ECCS components are presented in Table 4.1. These conditions were also introduced on the nodalization input.

Table 4.1: Injection from ECCS for a cold leg LBLOCA

ECCS Components	Loop 10		Loop 20		Loop 30		Loop 40	
	Hot	Cold	Hot	Cold	Hot	Cold	Hot	Cold
Safety Injection Pumps	1	-	SF	-	1	-	1	-
Accumulators	1	1	SF	Break	RC	1	1	1
Residual Heat Removal Pumps	1	1	SF	Break	1	1	1	1

Break – Injected coolant lost via the break
SF – Single Failure of Isolation Valve
RC – Repair Case

The Angra 2 reactor power axial profile adopted is “top skewed”, and reactor core is represented in the nodalization by nine heat structures, which are concisely described in Table 4.2.

Table 4.2: Reactor core heat structures

Heat Structure	Nº of Rods	$F_{\Delta h}$	Average Linear Heat Generation Rate (W/cm)	Maximum Linear Heat Generation Rate (W/cm)
Hot Fuel Assembly	234	1.6	339	473
Hot Rod 1 (Realistic)	1	1.60472	340	475
Hot Rod 2 (Conservative)	1	1.80295	382	533
Central Core Channel	6 * 236	1.448	307	429
Average Core Channel	106 * 236	≈1.0	208	291
Breakthrough Channel 1	20 * 236	≈1.0	208	291
Breakthrough Channel 2	20 * 236	≈1.0	208	291
Breakthrough Channel 3	20 * 236	≈1.0	208	291
Breakthrough Channel 4	20 * 236	≈1.0	208	291

The other boundary conditions adopted, according to the stated at FSAR [3] are the following:

- **Decay heat:** RELAP5 input by 1.01*ANS 79-1. The reference value for the decay heat is the assumed reactor power of 100% immediately before accident initiation;
- **Reactor shutdown:** For LB-LOCA, safe shutdown of the reactor is performed in the plant inherently by the void reactivity immediately after the start of the accident, and in the long term by the boron reactivity. Therefore, in the plant an additional control rod insertion is not necessary to shut off the fission power in the core after the occurrence of a large break. However, the option to use the control rod insertion was used in addition to the void reactivity, according to the assumption also adopted at FSAR [3];
- **Operation of the RCPs:** The reactor coolant pumps are shut down either from ECCS criteria or the pressurizer level < 2.28 m signal;
- **Availability of offsite power:** For the realistic analysis, the availability of offsite power is assumed.

4.3. Steady State Qualification

Table 4.3 summarizes the steady state qualification process. It presents, for the main Angra 2 parameters, the code simulation results with this nodalization, obtained through the so-called null-transient, compared with simulated results presented at FSAR. The last column of Table 4.3 refers to the acceptable errors for the parameters considered, according to the methodology [6] adopted in the frame of steady state qualification.

Table 4.3: Angra 2 steady state results

Properties	Unit	FSAR	R5m33 LBLOCA	Parameter	R5m33 Error (%)	Acceptable Error (%)
Core thermal power	MW	3765.00[a]	3769.84	rktpow_0	0.128	2.00
RPV pressure loss	bar	3.20[b]	2.80	cntrlvar_155	12.636	10.00
Core pressure loss	bar	1.50[b]	1.49	cntrlvar_160	0.925	10.00
Core inlet temperature	ºC	292[a]	292.2	tempf_26006	0.069	0.50
Core outlet temperature	ºC	325.4[a]	326.12	tempf_20003	0.220	0.50
Core coolant flow rate (active region)	kg/s	18409.00[a]	18407.87	cntrlvar_181	0.006	2.00
Core bypass flow rate (LP-UP)	kg/s	881.00[a]	877.34	mflowj_03808	0.416	10.00
Downcomer-Upper Head	kg/s	98.00[a]	100.48	cntrlvar_181	2.534	10.00
Cold Leg to Hot Leg Path	kg/s	196.00[a]	197.64	cntrlvar_181	0.838	10.00
PS total mass inventory	ton	287.00[e]	291.64	cntrlvar_355	1.616	2.00
PS hot leg pressure	bar	158.00[a]	158.03	p_20003	0.096	0.10
PS total loop coolant flow rate	kg/s	4896.00[a]	4895.85	mflowj_20003	0.003	2.00
PS total loop pressure loss	bar	6.50[c]	6.35	cntrlvar_365	2.316	2.00
RCP head	bar	6.50[c]	6.52	pmphead_245	0.352	2.00
RCP speed	rpm	1190.0[c]	1192.9	pmpvel_245	0.241	1.00
SG inlet plenum temperature	ºC	326.1[d]	325.57	tempf_22002	0.162	0.50
SG outlet plenum temperature	ºC	291.1[d]	291.92	tempf_23001	0.282	0.50
SG SS mass inventory	ton	193.00[e]	x	x	x	5.00
SG downcomer liquid level	m	12.20[a]	12.21	cntrlvar_478	0.01m	0.10m
SG thermal power (4 loops)	MW	3782.00[a]	3780.46	cntrlvar_520	0.034	0.50
SG exit pressure	bar	64.50[a]	64.53	p_65001	0.039	0.10
SG feedwater temperature	ºC	218.0[a]	217.99	tempf_600	0.002	0.50
SG feedwater mass flow rate	kg/s	513.00[a]	511.93	mflowj_601	0.208	2.00
SG steam mass flow rate (4 loops)	kg/s	2052.00[a]	2050.73	mflowj_981	0.062	2.00
SG recirculation flow rate	kg/s	1026.00[e]	1023.80	mflowj_62502	0.208	10.00
SG recirculation ratio	-	2.00[e]	2.00	-	0.000	2.00
PZR – liquid level	m	8.00[a]	7.98	cntrlvar_253	0.02m	0.05m

a. FSAR [3] - Table 15.6.4.2-6
b. FSAR [3] – Fig. 15.0.1(approximated and considered as total loss)
c. FSAR [3] – Table 5.1-1 [05]
d. FSAR [3] – Table 5.0-3a
e. Not explicit in FSAR (assumed values in [9])

The free volumes against height and pressure along the position of the primary circuit had already been checked on [7], [8], [9] in the frame of the geometric calculation for this Angra 2 independent RELAP5 nodalization.

Table 4.3 data slightly changed in the last revision of the previous report [10], concerning RELAP5 results, due to the implementation of some nodalization junctions' corrections, as well as derived of some adjustments of plant nodalization recommended by Task 2.1 European Union leader. The "hutze" has been differently modeled in Angra 2 nodalization, with ECCS injection only to the hot legs and not to the RPV upper plenum, according to the recommendation of our GRS counterpart for this work.

4.4. On-Transient Qualification

Any nodalization must be qualified at the 'steady-state' level and at the 'on-transient' level. The meaning of nodalization qualification can be found, for instance, in [6] and [11]. Among the other things, the 'Kv-scaled' calculation may be useful in connection with the 'on-transient' qualification process. The Kv-scaled calculation means to reproduce computationally, through the use of an advanced code nodalization, and with reasonable agreement, the results verified on a similar accident on a suitable Integral Test Facility, scaled down to a specific NPP design. In order to develop this code simulation, the accident initial and boundary conditions of the Kv scaled test is scaled up to the full scale NPP, according to existent technics [12]. Within the present framework, the qualification at the steady state level was completed to a reasonable extent (section 4.3 above and [6]). However, due to restrictions associated to time, technical resources and number of specialists available to perform Task 2.1, the qualification at the 'on-transient' level was not fully demonstrated, being replaced by a process for achieving the reference 'transient-system-performance' (see section 5.2.1)., as described below (see also [13]). The final result from this process is identified as 'reference nodalization' and the related output as 'reference calculation'. It is described on the following section.

The 'on-transient' qualification process allows the demonstration of the correctness of a number of boundary and initial conditions (BIC - e.g., the pump homologous curves that could not be tested within the qualification process at the steady-state level) and the acceptability of a number of user options (e.g. choice of the CCFL correlation and of connected empirical factors).

On section 4.4.2, the results of the 'reference calculation' and the comparison with relevant ETN associated results, shown at FSAR Angra 2 [3], are briefly presented. The comparison of some of these results is evaluated, especially concerning the on-transient qualification restrictions.

4.4.1. Sequence of Events

Table 4.4 presents the time sequence of relevant key phenomena data for the simulation

Table 4.4: Sequence of events (RELAP5 x SRELAP5)

Event	Time (s)	
	SRELAP5 (KWU)	**RELAP5 (CNEN)**
Break initiation	0.0	0.0
Reactor trip Turbine trip	0.1	0.1
ECCS criteria meet	0.7	0.7
Safety injection pump start	5.7	5.7
Accumulator injection starts	20.0	21.5
Peak containment pressure*	23.0	23.0
Collapsed water level at lower plenum starts do rise	23.5	28.3
RHR pumps start	31.0	34.4
End of blowdown	34.0	34.0
Beginning of core recovery	35.5	50.0
Hot Rod PCT – Blowdown	4.7 (782 ºC)	15.7 (893ºC)
Hot Rod PCT – Reflood	43.0 (920ºC)	28.9 (901ºC)
Average channel rewetted	80.0	101.0
Hot rod rewetted	122.0	116.0
Accumulators empty	130.0-160.0	130.0-160.0
Calculation terminated	250.0	250.0

* – Containment pressure curve assumed the same as provided at FSAR

4.4.2. Representative Simulation Results

Fig. 4.4 to Fig. 4.10 below represent some relevant results obtained with the independent Angra 2 nodalization at the present simulation status, compared with results presented at FSAR.
The convention in all the figures is the following: All results in blue color were obtained by KWU/Siemens with SRELAP5, as presented in FSAR, while all results in orange color were those obtained by CNEN with RELAP5/MOD3.3.

After introducing some modifications on our Angra 2 nodalization, as pointed out on section 4.3 above, a number of sensitivity analysis were carried out in order to obtain a new reference case for SUSA application. We could observe that some ‘on-transient’ simulated results have changed somewhat and/or become more stable, what in turn yielded better SUSA results (see section 5 for more details).

As verified on the preliminary reference case, the primary and secondary side pressures, as well as the reactor thermal power (respectively Fig. 4.4, Fig. 4.5 and Fig. 4.6)., presented rather similar results in comparison with Angra 2 FSAR.

Also as obtained before the last nodalization changes, the break mass flow rate, RCP, side (Fig. 4.7), presented quite similar time behavior for both simulations being compared, while the break mass flow rate, RPV side (Fig. 4.8), calculated with our Angra 2 nodalization, is underestimated in comparison with FSAR results.

However, the results of some key phenomena on our last simulation, shown on Table 4.4 (Sequence of Events), which have been checked by our counterparts, present values closer to the ones verified at FSAR. The temperature difference for the blowdown PCT, which was 189 C higher for our Angra 2 nodalization, is now 111 C higher relatively to FSAR results (see Table 4.4 and Fig. 4.10). The difference for the rewetting time of the average channel, which was 50 s later in our preliminary LBLOCA simulation, decreased for 21 s (see Table 4.4) in comparison with FSAR results. Concerning the rewetting time of the hot rod, preliminarily the difference of the two simulation results was 44 s, but this time was reduced for only 6 s (see Table 4.4).

The initial and boundary conditions for ECCS actuation were assessed, and the FSAR values were adopted as far as they could be identified.

Certainly, a suitably rigorous on-transient qualification for our LBLOCA analysis could give us some clues and better indication of changes that could improve the corresponding simulating results. Not only the Kv-Scaled simulation mentioned on section 4.4, but also the simulation of separated effect tests, especially for a similar RPV test facility. Some additional work for the on-transient qualification of Angra 2 LBLOCA nodalization, still limited by the lack of technical resources, may also improve uncertainty calculation results.

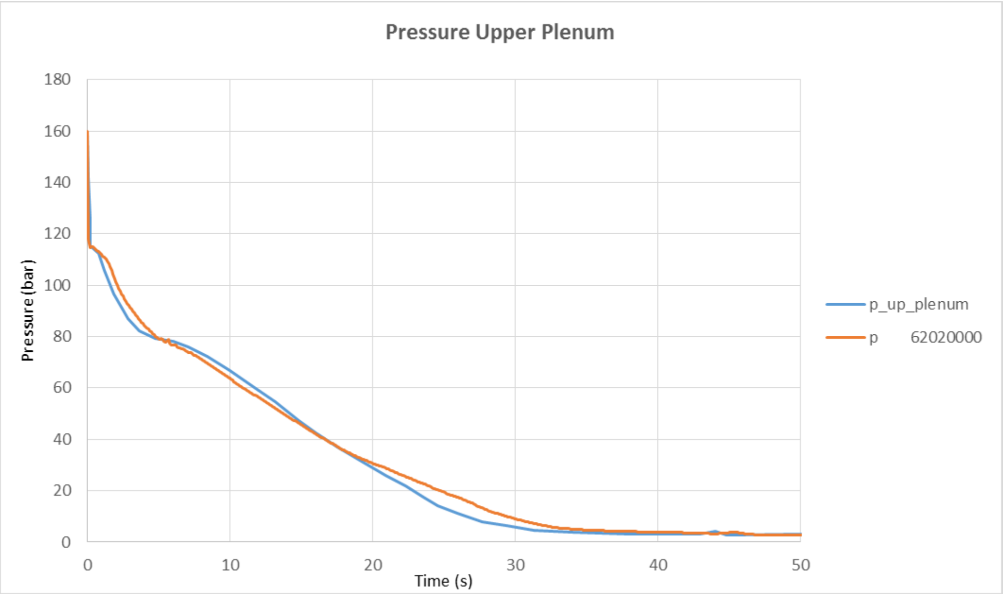

Figure 4.4: Primary circuit pressure

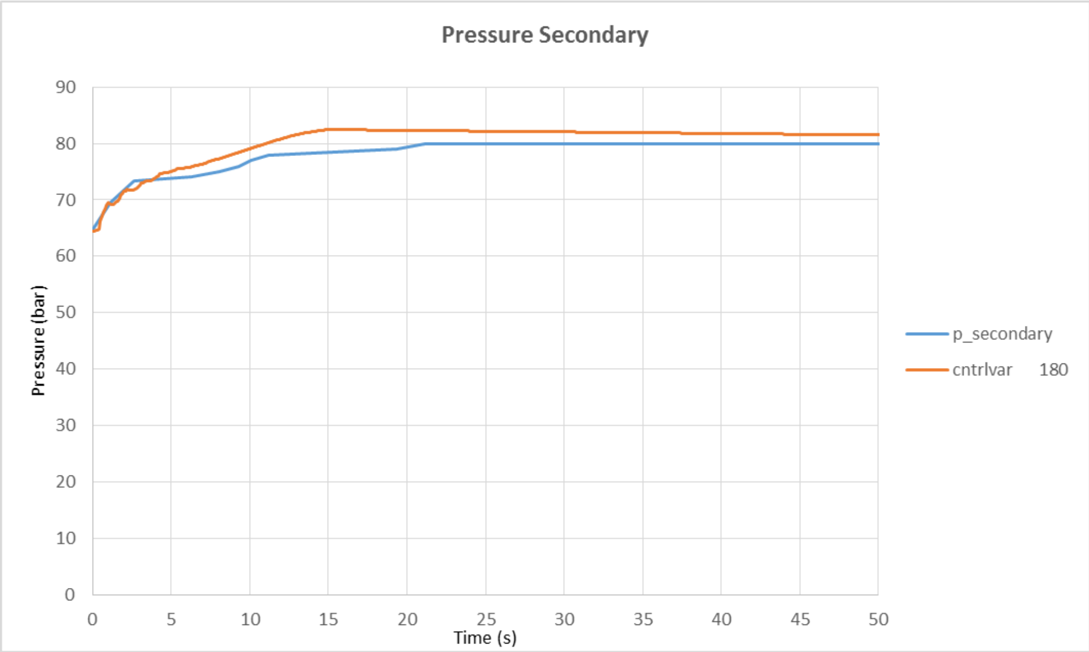

Figure 4.5: Secondary circuit pressure

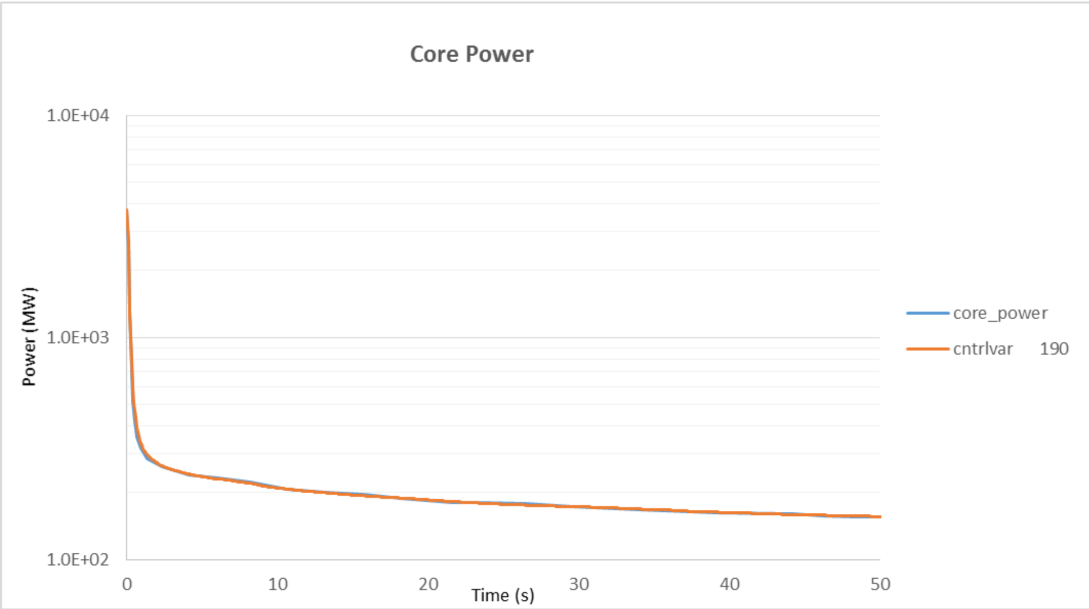

Figure 4.6: Reactor thermal power (kinetics)

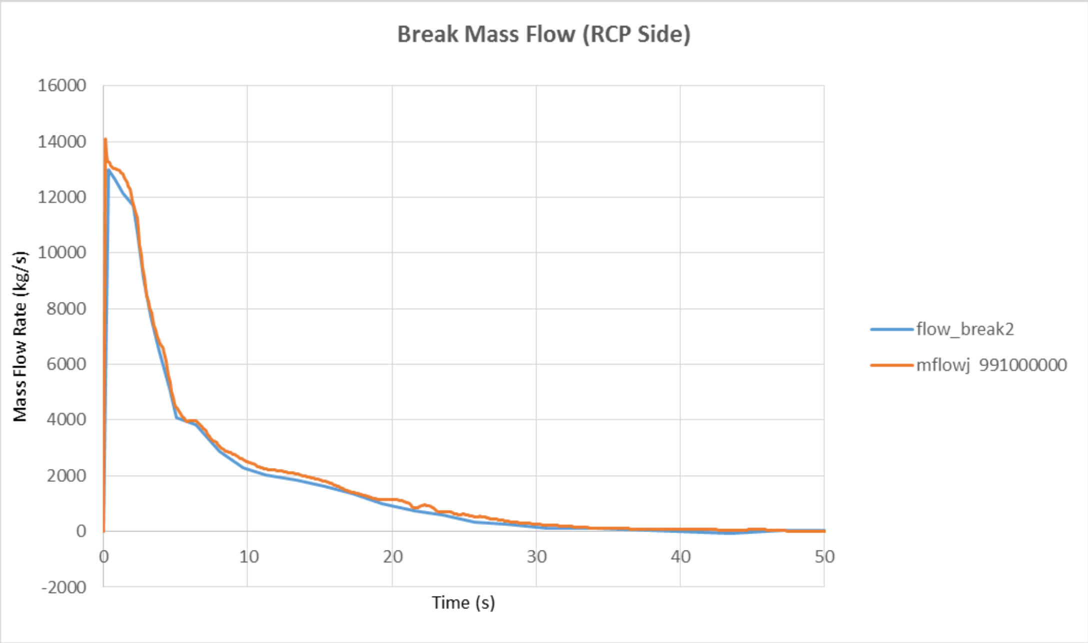

Figure 4.7: Break mass flow rate (RCP Side)

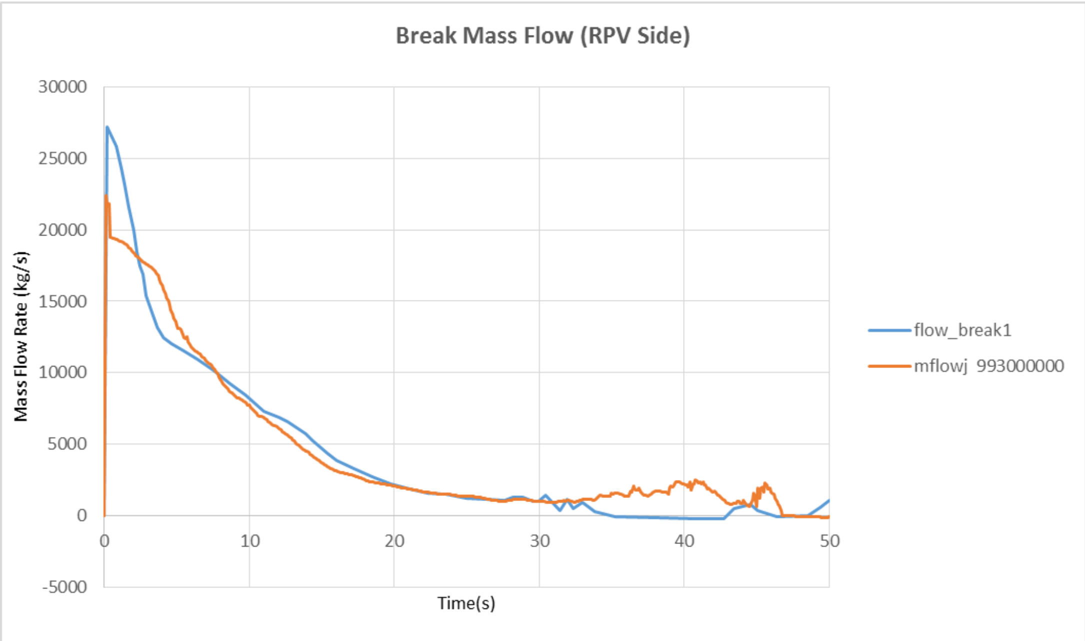

Figure 4.8: Break Mass Flow Rate (RPV Side)

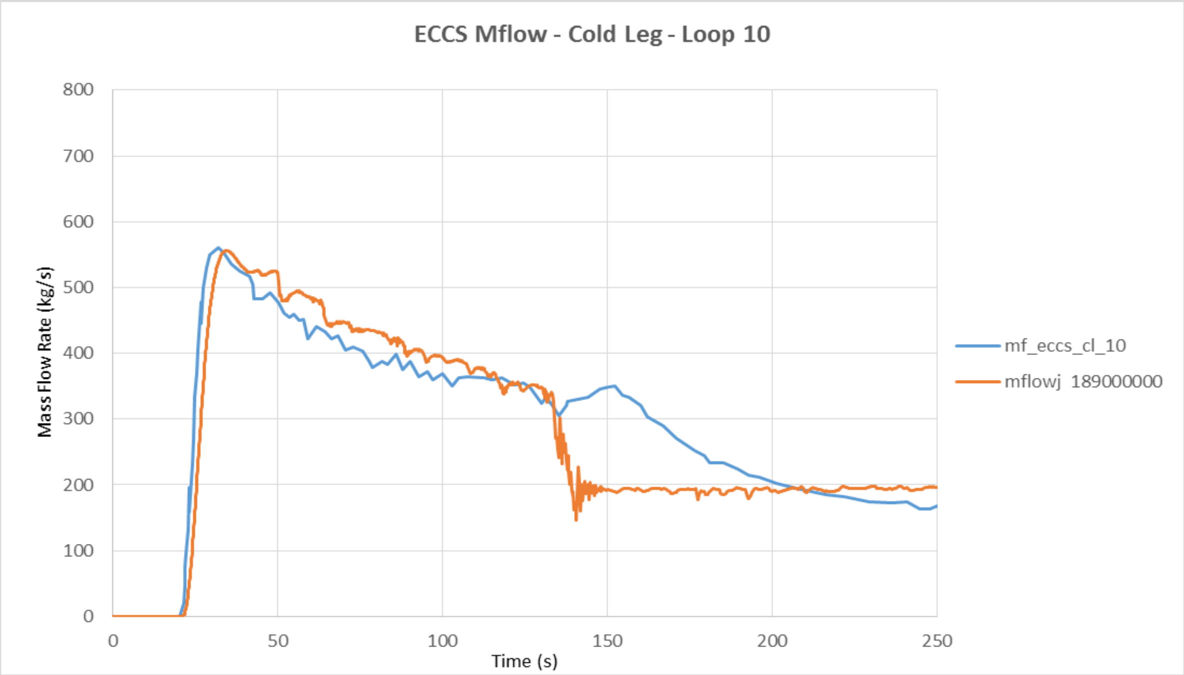

Figure 4.9: ECCS injection to loop 10 cold leg

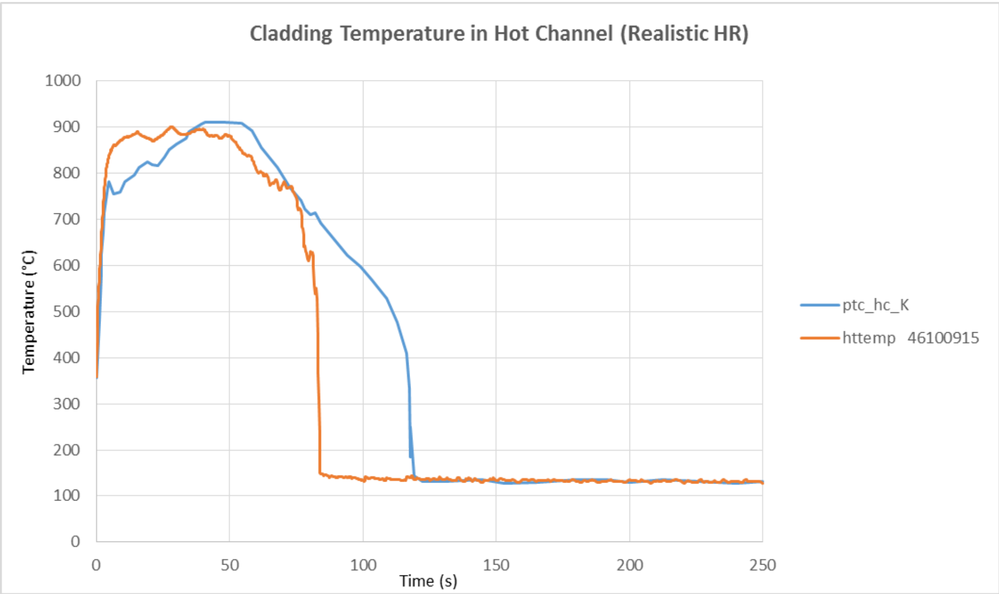

Figure 4.10: Cladding temperature in hot spot of realistic hot rod

5. UNCERTAINTY ANALYSIS WITH SUSA

Hereafter, the activities related to the main goal of Task 2.1, which is to achieve the skills using SUSA tool, will be presented.

5.1. Introduction

SUSA will be used coupled to code RELAP5 controlling its run. Thirty parameters were considered relevant, thus selected. They are shown on section 5.2 below. The SUSA execution process was performed with the automatic generation of RELAP5 input files and the automatic execution of eight instances of RELAP5 simultaneously.

5.2. Relevant Uncertainty Parameters

In this work, the following relevant uncertainty parameters were considered:

5.2.1. RELAP5 Code Uncertainties

According to Mr. Skorek presentation [14], the uncertainties related to RELAP5 code, which should be considered, are estimated through the following parameters:

- Interfacial drag model (EPRI or Bestion);
- CFFL correlations (Wallis or Kutateladze) and c/m correlation coefficients;
- Break discharge coefficient at saturated region;
- Critical heat flux multiplier;
- Heat transfer fouling factor;
- Reflood model (on/off);
- Entrainment model (on/off).

5.2.2. Power Uncertainties

According to Angra 2 FSAR [3], the uncertainties power related, which should be considered, are estimated through the following parameters:

- Total core power;
- Total peaking factor;
- Fuel fabrication uncertainty;
- Decay heat.

5.2.3. Fuel Material Uncertainties

According to BEMUSE [15], uncertainties related to the fuel material, which should be considered, are estimated through the following parameters:

- Fuel thermal conductivity;
- Fuel calorific capacity.

5.2.4. Plant Related Uncertainty

Finally, according to FSAR [3], uncertainties related to the plant, which should be considered, are estimated through the following parameters:

- Containment backpressure;

- Reactor coolant system initial mass flow rate;
- Reactor coolant system initial temperature;
- Reactor coolant system initial pressure;
- Pressurizer initial level;
- Accumulator initial temperature, pressure and level.

An additional plant related uncertainty, associated to the plant operation conditions is considered on BEMUSE [15]:

- Upper Head mean temperature.

5.3. Selection of Uncertainty Parameters

On the initiation of this work, when selecting the parameters to be effectively used for the uncertainty analysis to be developed with the aid of SUSA, we considered the parameters presented on section 5.1, as long as they could be automatically implemented (i.e., with placeholders for code input files).

Table 5.1 shows the thirty parameters effectively used for the uncertainty analysis with SUSA. In this table, the 15th parameter (pump speed) was used to obtain the variation of the primary loops initial mass flow; the 16th parameter (secondary pressure) was used to obtain the variation of the primary loops initial temperature; and the 20th parameter (local pressure drop: core path-upper head) was used to obtain the initial upper head temperature.

5.3.1. Bases for the Selected Parameters

When this work was initiated, we made analyses based on what was presented at BEMUSE [15], and this influenced our choice on parameters, limit values for parameters variation and distributions. Afterwards, the analyses were based also on information provided from GRS technicians and on data found on Angra 2 FSAR.
For the 30 used parameters, presented on Table 5.1, we used 21 normal, 4 discreet, 2 triangular, 2 log-normal and 1 uniform distributions. They will be discussed below, as well as the limits and the used distribution parameters.

- **Normal Distribution**

This was the preferred distribution here adopted. For 21 of the parameters presented, we used distributions so that 95% of the samples were comprehended in an 80% interval of the delimited region by the lower and upper limits. The lower and upper limits, for each case, were obtained from BEMUSE and FSAR. When these values were not available, we considered a 10 to 20% variation.

- **Discreet Distribution**

Cases in which parameter variation at RELAP5 input deck is given by a integer variable (parameters 24, 28, 29 and 30), a discreet distribution was naturally adopted, where the values are some, or all, the options made available by the code.

- **Log Normal Distribution**

In the case of parameters as friction form loss multiplier (parameters 9 and 14), log-normal distributions were applied, with values varying from 0.5 to 1.5, again following BEMUSE approach.

Table 5.1: SUSA uncertainty parameters for Angra 2 calculation

Par. No.	Parameter ID	Parameter Name	Reference Value	Distribution Type	Distribution Parameter 1	Distribution Parameter2	Minimum	Maximum
1	PCONT	Containment pressure (multiplier)	1	Uniform	0.85	1.15	0.85	1.15
2	IPOWER	Initial core power (multiplier)	1	Triangular	1		0.97	1.06
3	PFHROD	Peaking factor hot rod (multiplier)	1	Normal	1	0.022427	0.95	1.05
4	UO2TC1	UO2 conductivity until 2000 K (multiplier)	1	Normal	1	0.044854	0.9	1.1
5	UO2TC2	UO2 conductivity above 2000 K (multiplier)	1	Normal	1	0.089708	0.8	1.2
6	U02SH1	UO2 Specific heat below 2000 K (multiplier)	1	Normal	1	0.008971	0.98	1.02
7	U02SH2	UO2 Specific heat above 2000 K (multiplier)	1	Normal	1	0.05831	0.87	1.13
8	IACCP	Initial accumulator pressure	2650000	Normal	2650000	89708	2450000	2850000
9	FFLACL	Friction form loss in the accumulator line (multiplier)	1	Log. Normal	0.14407	0.29724	0.5	2
10	IACCT	Accumulators initial liquid temperature	308.15	Normal	308.15	4.4854	298.15	318.15
11	FCHALP	Flow characteristic of LPIS (multiplier)	1	Normal	1	0.022427	0.95	1.05
12	PZRIP	Pressurizer initial pressure	1.58E+07	Normal	1.58E+07	44854	1.57E+07	1.59E+07
13	PZRILV	Pressurizer initial level	0	Normal	-6.89E-07	0.044854	-0.1	0.1
14	FFLSUL	Friction form loss in the surge line (multiplier)	1	Log. Normal	0.14407	0.29723	0.5	2
15	PMPVEL	Pump Speed (factor)	1	Normal	1	0.017942	0.96	1.04
16	SECP	Secondary pressure (factor)	5450000	Normal	5445000	122114	5172750	5717250
17	DCPOW	Decay Heat Factor	1.01	Normal	1.01	0.035715	0.94	1.08
18	DHGAP1	Variation of gap length - all rods except hot rod	0	Normal	-1.44E-08	8.52E-06	-1.90E-05	1.90E-05
19	DHGAP2	Variation of gap length - hot rod	0	Normal	-3.00E-08	8.53E-06	-1.90E-05	1.90E-05
20	UHKFLO	Local drop pressure in path core - upper head	3.963	Triangular	3.963		0.963	10.963
21	CHFFAC	Heated Length as a CHF Factor		Normal	5	2.2427	0	10
22	FOULFA	Foul factor		Normal	1	0.089709	0.8	1.2
23	DISCOE	Discharge Coefficient		Normal	1	0.089707	0.8	1.2
24	CCFLCO	CCFL Correlation		Discrete			0	1
25	CCFLF1	CCFL Factor 01 (c)		Normal	0.79964	0.071497	0.8	1.2
26	CCFLF2	CCFL Factor 02 (m)		Normal	1	0.089708	0.8	1.2
27	IACCLV	Initial Accumulators Level (multiplier)	1	Normal	1	0.026912	0.94	1.06
28	IFDRAC	Interfacial Drag Correlation	0	Discrete			0	19
29	REFLOD	Reflood Option	2	Discrete			0	2
30	ENTRA	Entrainment Option – RPV In and Out	3	Discrete			0	3

- **Triangular Distribution**

In the case of asymmetric limits, relatively to the reference value, triangular distributions were used. For the case of nuclear power (parameter 2), an asymmetric distribution from 97% to 106% was used, according to GRS expert recommendation. For the case of local drop pressure in path core-upper head (parameter 20), an asymmetric distribution for the pressure coefficient was used to assure a symmetric distribution for the upper head temperature.

- **Uniform Distribution**

For the containment pressure (parameter 1), calculated by COCO code, BEMUSE choice was followed, which was a uniform distribution varying from 85% to 115%.

Table 5.2 presents the quantile and probabilities, which were added as input for SUSA program, on the normal and log-normal distribution cases.

5.4. Coupled SUSA-RELAP5 Runs

We run SUSA for 100 RELAP5 input files with the selected parameters randomly generated, according to the considerations on section 5.2 above. The simulation time for each RELAP5 file was 750 s (250 s of transient), because no other relevant phenomena are expected after the chosen 750 s period.

Initially, we had execution errors on nine files, four of them occurring on the beginning of the accident simulation. We run again these four files with a smaller Δt between 498s and 502s, and two of them run for all the simulation time.

For this report section, we are going to present the following relevant LBLOCA time trends for all 100 runs:

- Hot rod maximum cladding temperature;
- Upper plenum pressure;
- Primary mass inventory;
- Break mass flow (RPV side); and
- ECCS injection in cold leg of loop 10.

Table 5.2: Normal and log-normal qualities and probabilities

Par Num	Par ID	Reference	Inferior Limit	Superior Limit	Quantile 1	Quantile 2	Prob 1	Prob 2
3	PFHROD	1.000	0.950	1.050	0.96	1.04	0.025	0.975
4	<u>UO2TC1</u>	1.000	0.9	1.1	0.92	1.08	0.025	0.975
5	<u>UO2TC2</u>	1.000	0.8	1.2	0.84	1.16	0.025	0.975
6	UO2SH1	1.000	0.98	1.02	0.984	1.016	0.025	0.975
7	UO2SH2	1.000	0.87	1.13	0.896	1.104	0.025	0.975
8	IACCP	2650000	2450000	2850000	2490000	2810000	0.025	0.975
9	FFLACL	1.000	0.500	2.000	0.65	1.85	0.025	0.975
10	IACCT	308.15	298.150	318.150	300.15	316.15	0.025	0.975
11	FCHALP	1.000	0.950	1.050	0.96	1.04	0.025	0.975
12	PZRIP	1.5835E+07	1.5735E+07	1.5935E+07	15755000	15915000	0.025	0.975
13	PZRILV	0.000	-0.1	0.1	-0.08	0.08	0.025	0.975
14	FFLSUL	1.000	0.500	2.000	0.65	1.85	0.025	0.975
15	PMPVEL	1.000	0.960	1.040	0.968	1.032	0.025	0.975
16	SECP	5445000	5172750	5717250	5227200	5662800	0.025	0.975
17	DCPOW	1.010	0.940	1.080	0.954	1.066	0.025	0.975
18	DHGAP1	0.000E+00	-1.900E-05	1.900E-05	-0.0000152	0.0000152	0.025	0.975
19	DHGAP2	0.000E+00	-1.900E-05	1.900E-05	-0.0000152	0.0000152	0.025	0.975
21	CHFFAC	5.000	0	10	1	9	0.025	0.975
22	FOULFA	1.000	0.8	1.2	0.84	1.16	0.025	0.975
23	DISCOE	1.000	0.8	1.2	0.84	1.16	0.025	0.975
25	CCFL1	0.800	0.6	1	0.64	0.96	0.025	0.975
26	CCFL2	1.000	0.8	1.2	0.84	1.16	0.025	0.975
27	IACCLV	1.000	0.940	1.060	0.952	1.048	0.025	0.975

As a demonstration of significant obtained results, Fig. 5.1 to Fig. 5.3 show the time trends of the above relevant variables for the mentioned 100 RELAP5 runs.

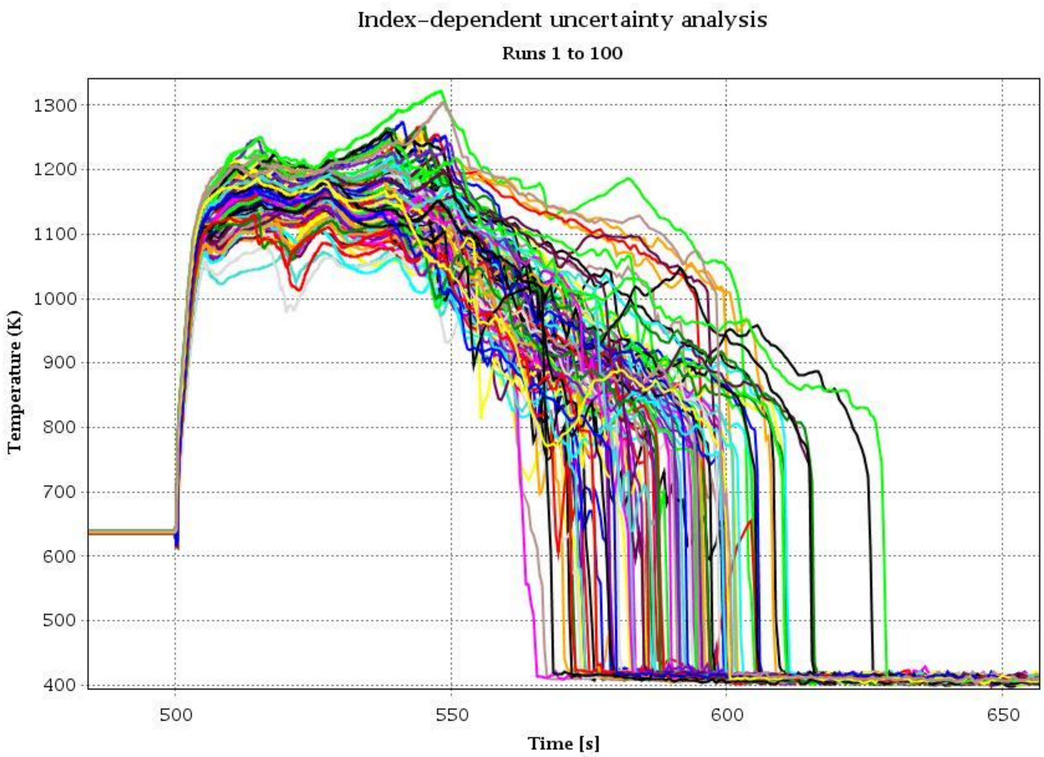

Figure 5.1: RELAP5 results - maximum cladding temperature

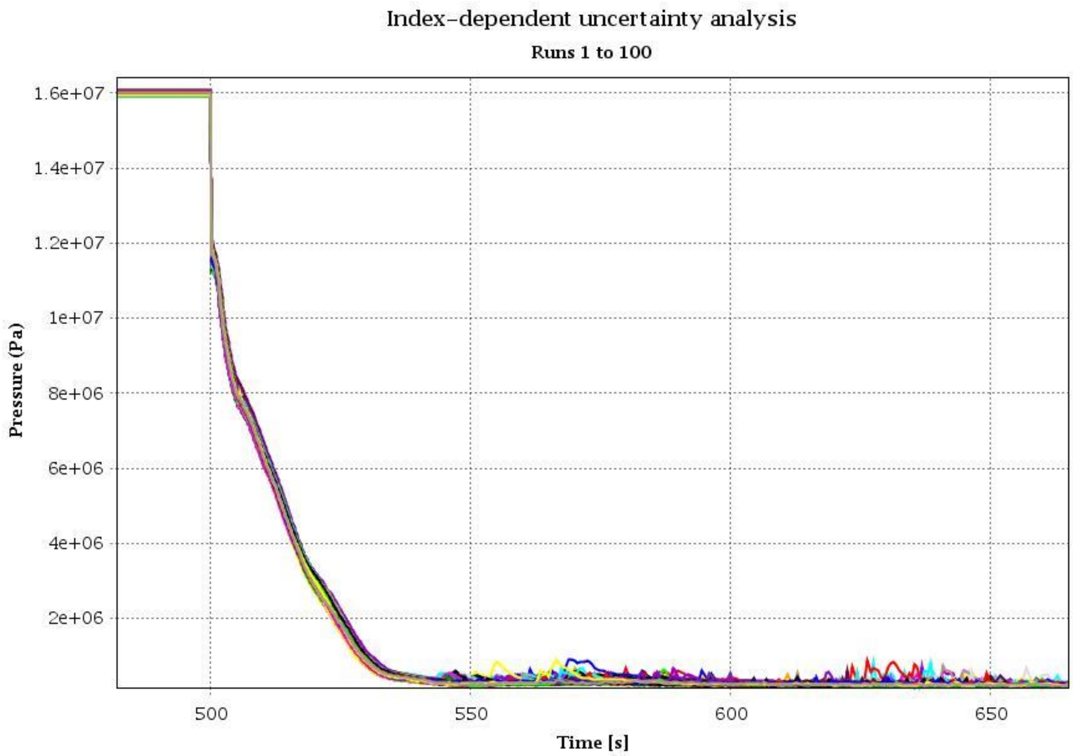

Figure 5.2: RELAP5 results - upper plenum pressure

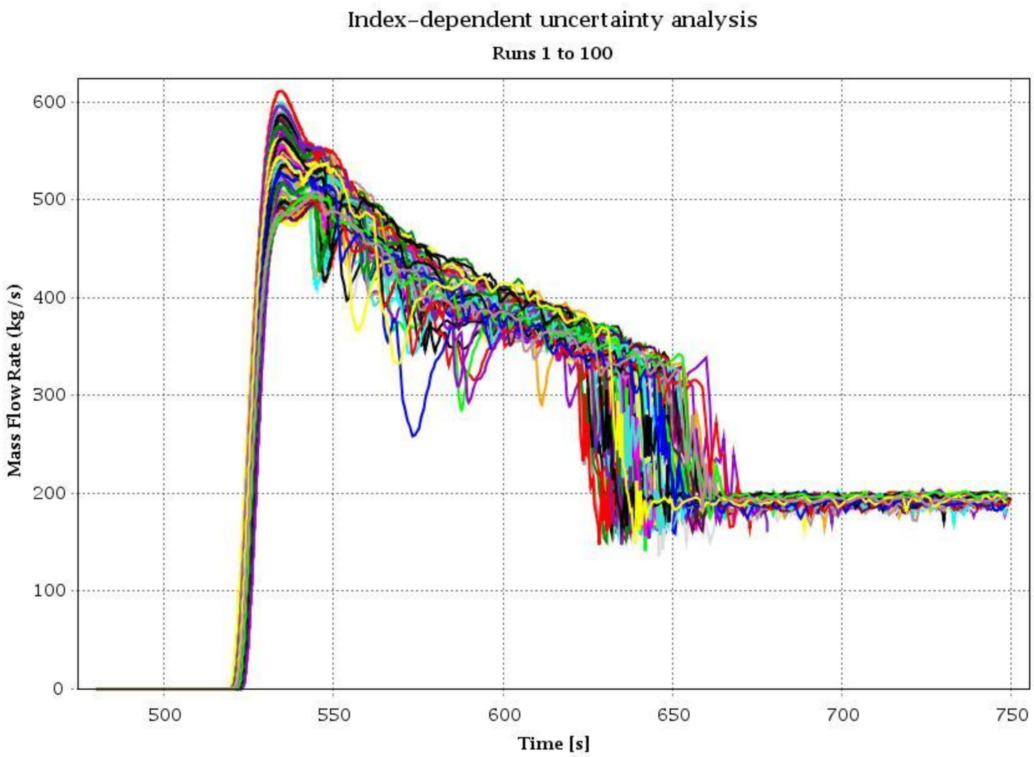

Figure 5.3: RELAP5 results - ECCS injection cold leg loop 10

5.5. Uncertainty results – Time Trends

The uncertainty bands and associated ranking of six time trends mentioned in section 5.4 will be presented:

5.5.1. Uncertainty Bands

Fig. 5.4 to Fig. 5.6 present the reference case results for the above mentioned time trends, as well as the associated upper and lower uncertainty bands and medians. The maximum and minimum curves represent for the each time step the largest and smallest values among the 93 runs, not generally representing a given run result The same is valid for the median curve.

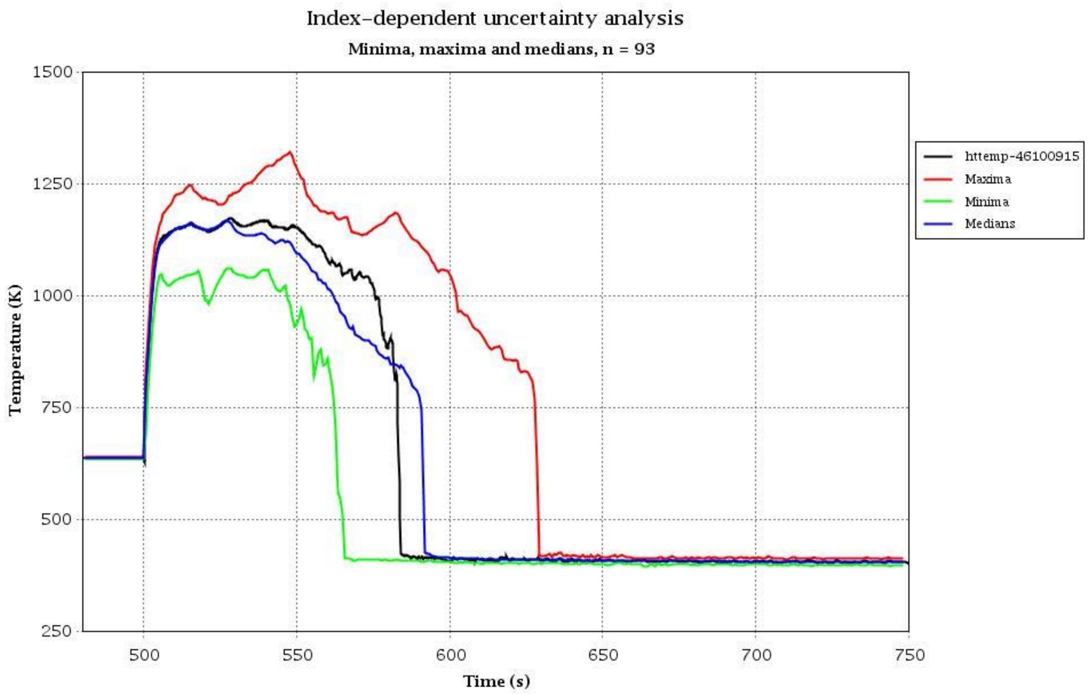

Figure 5.4: Uncertainty result - maximum cladding temperature

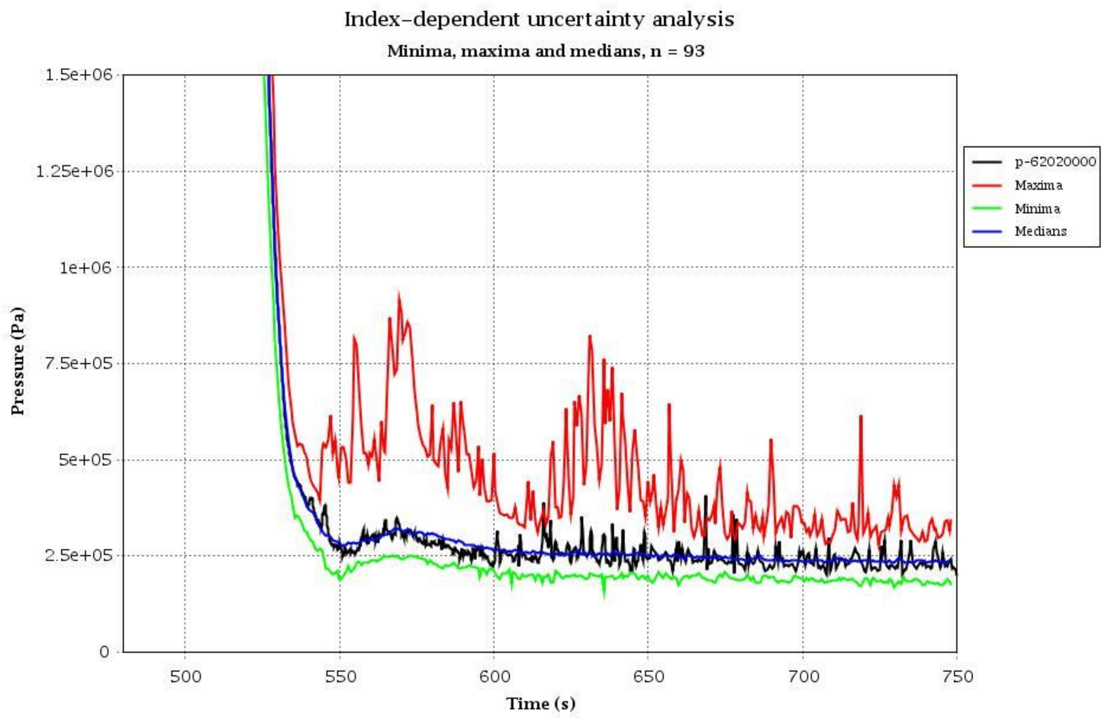

Figure 5.5: Uncertainty result – upper plenum pressure

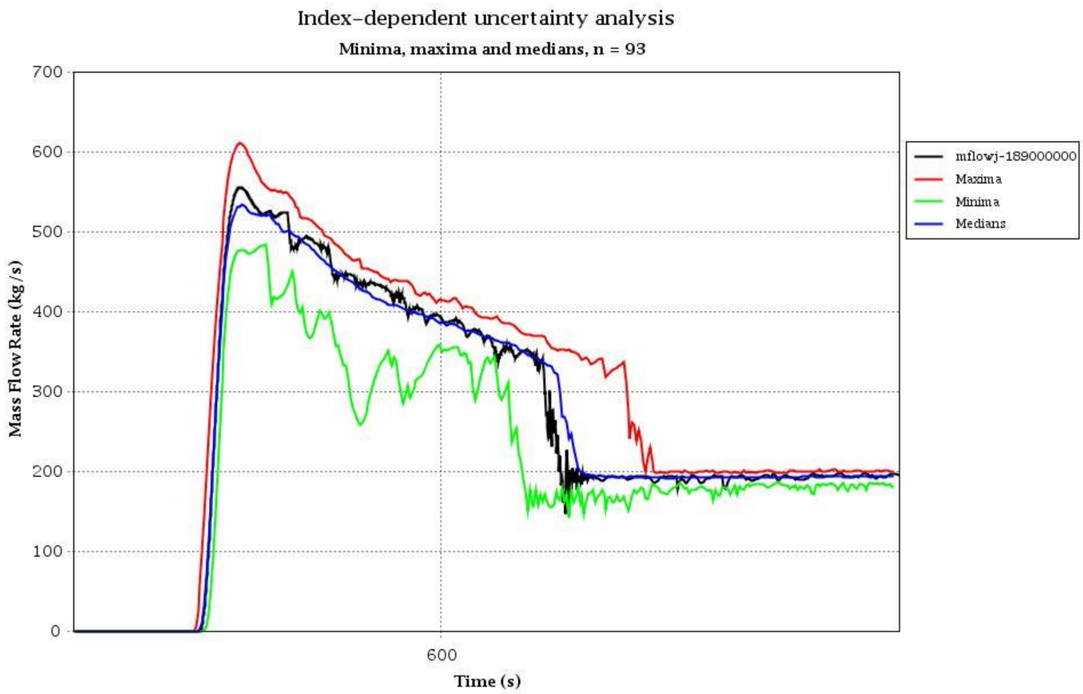

Figure 5.6: Uncertainty result - ECCS cold leg injection - loop 10

5.6. Uncertainty Results - First and Second Cladding Temperature Peaks

By using SUSA, we obtained the results for the hot rod cladding temperature picks, which are show on Table 5.3.

Table 5.3: First and second cladding temperature peaks

Case	First Temperature Peak (K)	Second Temperature Peak (K)
Reference Case	1166	1174
Lower Value	1067	1066
Upper Value	1251	1321

With the Pearson Ordinary Correlation in SUSA, we get scalar sensitivity results presented in Fig. 5.7 and Fig. 5.8.

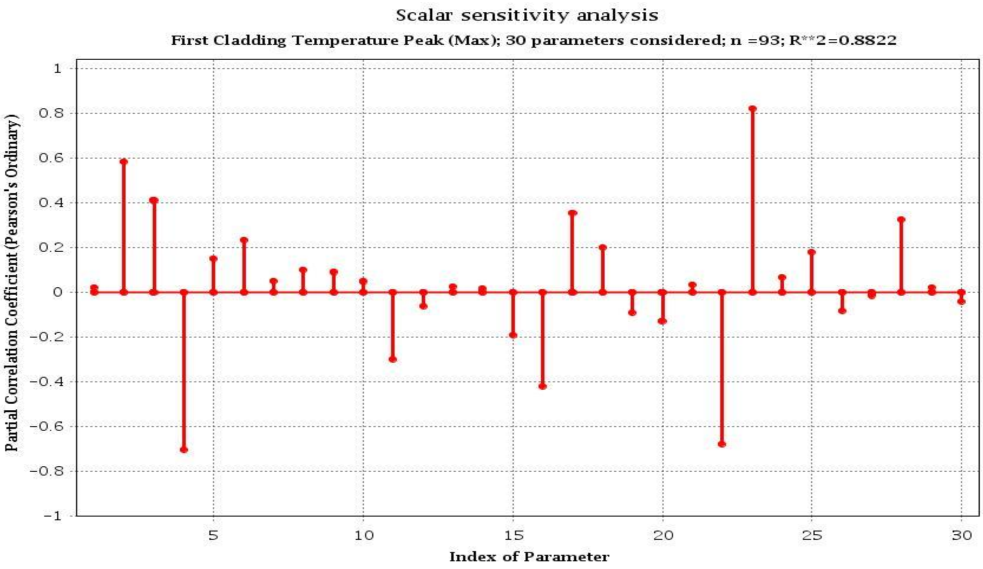

Figure 5.7: Partial CC (Pearson's) – first cladding temperature peak

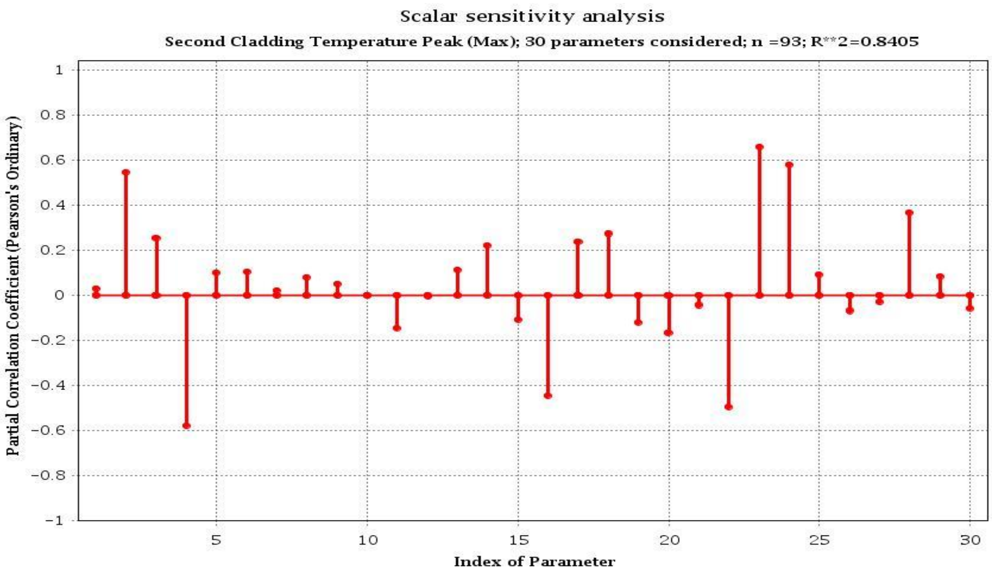

Figure 5.8: Partial CC (Pearson's) – second cladding temperature peak

Table 5.4 presents the importance ranking of the parameters on the first temperature peak (blowdown phase) and on the second temperature peak (reflood phase).

Table 5.4 – Parameter ranking for first and second cladding temperature peaks

Parameter ID	Parameter Name	First Temperature Peak Ranking*	Second Temperature Peak Ranking*
1	Containment pressure (multiplier)	17	16
2	Initial core power (multiplier)	4	5
3	Peaking factor hot rod (multiplier)	11	23
4	UO2 conductivity until 2000 K (multiplier)	3	4
5	UO2 conductivity above 2000 K (multiplier)	19	10
6	UO2 Specific heat below 2000 K (multiplier)	22	19
7	UO2 Specific heat above 2000 K (multiplier)	21	21
8	Initial accumulator pressure	12	12
9	Friction form loss in the accumulator line (multiplier)	26	25
10	Accumulators initial liquid temperature	9	17
11	Flow characteristic of LPIS (multiplier)	25	22
12	Pressurizer initial pressure	10	20
13	Pressurizer initial level	14	9
14	Friction form loss in the surge line (multiplier)	29	15
15	Pump Speed (factor)	15	14
16	Secondary pressure (factor)	16	13
17	Decay Heat Factor	28	27
18	Variation of gap length - all rods except hot rod	13	8
19	Variation of gap length - hot rod	18	18
20	Local drop pressure in path core - upper head	23	26
21	Heated Length as a CHF Factor	7	11
22	Foul factor	2	2
23	Discharge Coefficient	1	3
24	CCFL Correlation	5	1
25	CCFL Factor 01 (c)	30	24
26	CCFL Factor 02 (m)	6	6
27	Initial Accumulators Level (multiplier)	27	28
28	Interfacial Drag Correlation	8	7
29	Reflood Option	24	30
30	Entrainment Option – RPV In and Out	20	29

* - The parameters are presented according to their importance for relevant time trends (i. e., number 1 is the most influential, while number 30 is the less influential)

5.7. Discussion of Results

For this final report version, two additional uncertainty parameters were considered and some distribution limits of some parameters were modified, according to GRS technician's recommendation. More stable results were obtained for the uncertainty calculation and only a few of the 100 runs were aborted.

Sensitivity analysis coefficients were calculated for all six time trends and the ranking of parameters were obtained from the coefficients for the first three. The results apparently indicate the following finding:

- For the time trend "maximum cladding temperature", the parameters that seem to have the greatest influence were parameter 2 (initial power) and parameter 22 (foul factor);
- For the time trend "upper plenum pressure" the parameters that seem to have the greatest influence were parameter 12 (pressurizer initial pressure) and parameter 13 (pressurizer initial level); and
- For the time trend "primary mass inventory", the parameters that seem to have the greatest influence were parameter 9 (friction form in the accumulator line) and parameter 15 (pump speed).

For scalar sensitivity analysis, first and second cladding temperature peaks, there was a variation of -99 K and +85 K in relation to the reference values for the first peak temperature, and a variation of -108 K and +147 K for the second peak temperature.

For these two scalar variables, parameter 2 (initial power) was respectively the fourth and fifth most influential, and parameter 22 (foul factor) was the second most influential. For the first temperature peak, parameter 23 (discharge coefficient) was the most influential, and for the second temperature peak, parameter 24 (CCFL correlation) was the most influential.

The obtained results seem consistent with our understanding of the underlying phenomena on a LBLOCA.

6. CONCLUSIONS

Task 2.1 of project BR3.01/12 has proved to be of a fundamental importance for the licensing work developed at CNEN. This regulatory body did not have the skills on using an uncertainty methodology associated with the application of a best estimate thermal hydraulic code for NPP design, especially concerning Large Break LOCA, as required on the Brazilian adopted rules and guides. A lot has been learned about the use of such a methodology, SUSA, from the GRS in Germany. A workshop has been held at the end of January 2018 with our counterparts, at CNEN, when our preliminary work status was presented. The experts presented their recommendations for improvement of the work being done until now. The repetition of the uncertainty and sensitivity analysis of LBLOCA with SUSA was performed, and these final results are here being presented.

The simulation of the same LBLOCA presented at Angra 2 FSAR, despite the on-transient qualification restrictions, gave us more capabilities to license Angra 3 accident analysis, since the technicians who had worked on this activities for Angra 1 and 2 have retired some years ago. In our licensing activities, due to licensing requirements, the applicants have to present a rigorous set of documentation to prove their methodology to perform accident analysis is qualified. We consider that this work, although mainly related to get skills in the use of an uncertainty methodology, also contributed a lot to develop the associated licensing activities foreseen in the coming years, concerning the desirable independent accident analysis.

ACKNOWLEDGMENTS

We are grateful for the financial and technical support provided by the European Union and RiskAudit, what allowed us to obtain SUSA software [1] and associated training at GRS.

REFERENCES

1. GRS, "Software for Uncertainty and Sensitivity Analyses (SUSA) Version 4.0 – User's Guide and Tutorial", Garching, Germany (2015).
2. USNRC; "Relap5/Mod3.3 Code Manual – Volume I: Code Structure, System Models, and Solution Methods", Information Systems Laboratories, Inc., Idaho, USA (2010).
3. ELETRONUCLEAR, "Final Safety Analysis Report - Central Nuclear Almirante Álvaro Alberto – Unit 2", Rev. 14 (2016).
4. Madeira, A., Sabundjian, G. Pereira, LC, "An Angra 2 LBLOCA Simulation Model for Relap5mod3.3 Code with Uncertainty Analysis, Revision 02", Task 2.1, Project BRA3.01/12, Technical Report, CNEN, Rio de Janeiro, Brasil (2018).
5. Working Group, "III JONATER- Work Report", 3rd National Journey in Reactor Thermal Hydraulic, Reactor Coordination, CNEN, Rio de Janeiro, Brasil (1997).
6. Bonuccelli M., D'Auria F., Debrecin N., Galassi G.M., "A Methodology for the qualification of Thermalhydraulic Codes Nodalizations", *6th International Topical Meeting On Nuclear Reactor Thermalhydraulics*, Grenoble, France, October 5-8 (1993).
7. Madeira, A., Pereira, LC, "Memória de Cálculo Relativa aos Dados Geométricos do Vaso de Pressão do Reator de Angra 2 para o Relap5/Mod3.2", NT-CODRE-01/00, CODRE, CNEN, Rio de Janeiro, Brasil (2000).
8. Palmieri, E.T., Azevedo, C.V., "Dados de Entrada dos Geradores de Vapor de Angra II para Simulação com Relap5/Mod3", NI - CT4, CDTN, CNEN, Belo Horizonte, Minas Gerais, Brasil (2001).
9. Palmieri, E.T., Azevedo, C. V. G., Lapa, N. S., "Borges, R. C., Simulação do Gerador de Vapor de Angra II com o Código Relap5/mod3.2", *XII Encontro Nacional de Física de Reatores e Termohidráulica*, Rio de Janeiro, Brasil (2000).
10. CNEN, "An Angra 2 LBLOCA Simulation Model for RELAP5 3.3 Code with Uncertainty Analysis Task 2.1 of Project BRA3.01/12", CNEN Technical Report, Rio de Janeiro, Brasil (2017).
11. Galleti, M.R., "Angra 2 NPP Licensing – Regulatory Independent Calculation Description of Process to Achieve the LBLOCA Steady State Reference Nodalization with Relap5/Mod3.2.2gamma Code", NT-CODRE-03/01, CNEN, Rio de Janeiro, Brasil (2001).
12. Madeira A., Giannotti W., D'Auria F., "Sample use of CIAU for a Nuclear power plant transient simulation", *9th International Topical Meeting on Nuclear Reactor Thermalhydraulics*, San Francisco, California, USA October 3-8 (1999).
13. Madeira, A., Sabundjian, G. Pereira, LC, "An Angra 2 LOCA Simulation Model for Relap5mod3.3, Code Steady State Qualification (Preliminary Activities Concerning Task 2.1 of Project BRA3.01/12)", Review 01, Technical Report, CNEN, Rio de Janeiro, Brasil (2016).
14. Skorek, T., "Uncertainty Analysis of SUSA – Preparation of RELAP Input for Uncertainty Analysis", GRS Garching, Germany (2015).
15. BEMUSE Programme, "BEMUSE Phase V Report Uncertainty and Sensitivity Analysis of a LB-LOCA in ZION Nuclear Power Plant", NEA/CSNI/R (2009)13 (2009).