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A Multi-scale and Multi-Physics Simulation Methodology with the state-of-the-art tools for safety analysis in Light Water Reactors applied to a Turbine Trip Scenario (PART II)

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ABSTRACT

The development of the computer technology, as well as the research in the different science fields governing the core behavior of a Light Water Reactor, allows implementing all the known physics and consider detailed scales of analysis. Conversely to conservative approaches, the Best Estimate approach applies the available science by means of models and correlations that are applied in different scales using simulation tools. With this approach, the critical elements of the core can be evaluated with realistic predictions that can adjust the operation conditions and core design to more cost-efficient values without compromising the safety of the Nuclear Power Plant.

The authors of this paper present the second part of a multi-scale and multi-physics methodology for the evaluation of fast transients in Light Water Reactors. In this part, the results obtained from the coupled Neutron Kinetics and Thermal-Hydraulics channel-by-channel core model are used for a detailed thermal-hydraulic pin-by-pin analysis and thermomechanics pin model. The aim of this work is to evaluate the safety analysis of the critical fuel rod in Turbine Trip scenario. For that purpose, the critical fuel rod is located using the minimum Critical Power Ratio. This safety variable is predicted in a thermal-hydraulic pin-by-pin model using CTF-UPVIS code. Afterwards, the conditions of the critical rod are loaded in a pin model for a simulation with FRAPCON/FRAPTRAN.

Moreover, this paper proves the Best Estimate capability of the presented methodology by means of comparing the results with equivalent simulations that are more conservative, or consist of more limited simulation scales. On the one hand, the Best Estimate prediction is compared against the envelope of the minimum Critical Power Ratio along the axial nodal distribution of the simulated fuel rod. In addition, another comparison is made against assuming constant fuel-cladding gas conductance, showing the enhancement added by considering the axial distribution of this parameter, provided by FRAPCON/FRAPTRAN. On the other hand, the results of this methodology are compared against the limitation of accounting only the bundle radial average value of the minimum Critical Power Ratio. Furthermore, the Best Estimate results are complemented with an Uncertainty and Sensitivity analysis that will define the statistical boundaries of the prediction according to the 95/95 criterion.

1. INTRODUCTION

Nuclear Safety Assessment is moving towards Best Estimate (BE) calculations (Perin et al., 2017). BE simulations allow predicting realistic results that avoid assuming conservative boundaries for defining the operation of Nuclear Power Plants. For performing BE analysis, simulation tools must account in a high level of detail the physics governing the phenomena of the behavior of the core elements and also a detailed scale of the elements. Moreover, modeling in detail the core elements will show a more accurate evaluation of the critical safety parameters during a given transient. Nevertheless, such reduction of the conservatism in the Nuclear Safety Assessment requires complementing the calculations with the corresponding Uncertainty and Sensitivity Analysis (Hernández-Solís et al., 2011) to define the confidence interval of the tracked safety quantities.

This paper presents a methodology for a pin level safety evaluation accounting the thermal-hydraulics and the thermomechanics using the state-of-the-art tools. In addition, the boundaries of the prediction of the target out variable are defined, applying a methodology for the uncertainty quantification based on the Wilks formula. The methodology is applied to a Turbine Trip scenario where one of the figures of merit is the Minimum Critical Power Ratio (MCPR) (Adamsson et al. 2011). This methodology shows the capabilities of the state-of-the-art tools and complements the results with an uncertainty and sensitivity analysis. This paper completes the application case of a multi-scale and multi-physics methodology for the analysis of fast transient scenarios (USNRC, 2007). Figure 1 shows a diagram of data flow of the different scales and physics used in this methodology.

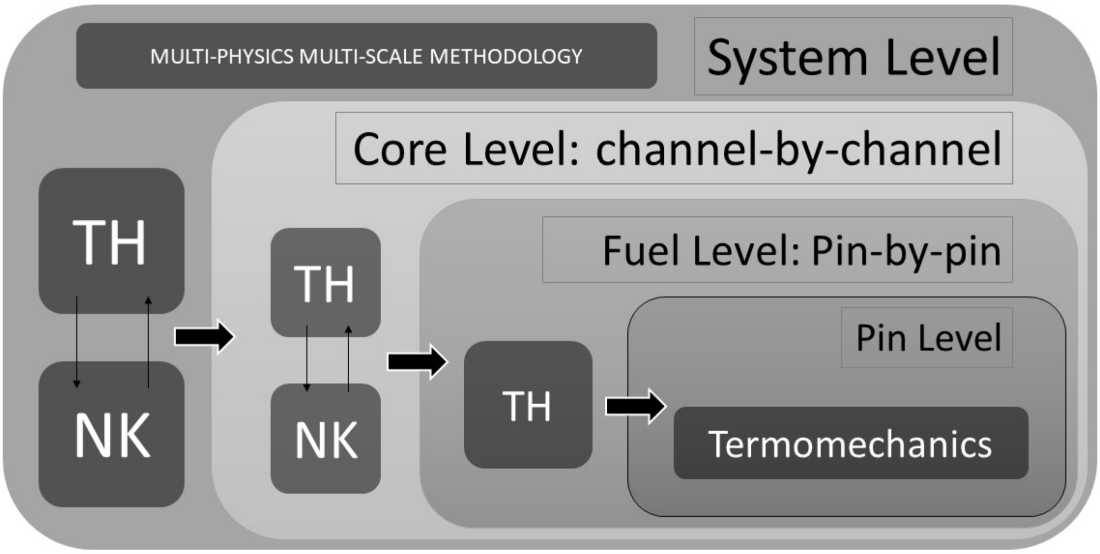

Figure 1.- Diagram of the steps and codes used in the proposed methodology.

The current section is an introduction of the work, including the description of the simulation scenario and the state-of-the-art tools that the methodology uses. Section II describes the steps of the simulation methodology. The following section shows the discussion of the results and the section IV is used for the conclusions and the ongoing work.

1.1 Description of the scenario

The authors apply the methodology to a Turbine Trip (TT) scenario. This transient type is categorized as postulated accident by Chapter 15 of the NUREG-0800 (USNRC, 2007). A TT causes the sudden closure of the turbine control valves (TCVs) and hence a pressure shock wave travels along the steam lines to the vessel dome. The result is a pressure peak that generates a collapsing of the void in part of the reactor. The feedback between the thermal-hydraulics (TH) and the neutron kinetics (NK) provokes a consequent power peak. This power peak is mitigated by means of Selected Rod Insertion (SRI) maneuver. Afterwards, the operator drives the reactor core to safety conditions, i.e. reduction of core power and mass flow, by means of opening the Turbine Bypass Valves (TBVs). Moreover, the valves controlling the recirculation loop of the core are operated to assure a safe core flow level.

This kind of transient is characterized by a fast evolution of the variables governing the core behavior, such as pressure, power or mass flow. Due to this, the feedback between TH and NK is significantly relevant, and coupled models are of major interest. Table 1 shows the evolution of the core operation during the transient.

Table 1.- Turbine Trip Fuel Cycle 18 sequence of events.

Time (ms)	Event	Time (ms)	Event
0	Core flow at 3370.85 kg/s	490	Bypass Valves at ~ 50 %
0	Dome pressure at 71.9 bar	780	Peak Vessel Dome Pressure 7.31 MPa
0	Turbine Trip	1020	Bypass Valves reached maximum opening ~ 82 %
218	Control Valves begin to close	1410	SRI Rod Full-In
260	Bypass Valves begin to open	2030	Peak Steam Flow 2170.7 kg/s
300	Control Valves at ~ 9.125 %	4880	Recirculation FCV at 18 %
300	SRI Channels initiation	9100	Core flow after transient at ~ 1892 kg/s
305	Recirculation FCV closed at 66%	9980	Power Peak at ~ 58 %
440	Bypass Valves at ~ 25 %	29980	Vessel Dome Pressure 6.80 MPa

1.2 State-of-the-art tools

The authors of this paper propose the continuation of a methodology developed for the analysis of fast transients in Light Water Reactors (LWRs). The authors presented in previous paper to be published (Hidalga et al., 2019) a methodology capable to track the critical fuel channel in a TT scenario, using coupled models of TRACE/PARCS and CTF-UPVIS/PARCS. The critical fuel channel was afterwards simulated using the detailed boundary conditions of that channel in a pin-by-pin fuel assembly model of CTF-UPVIS.

For the continuation of the development of this methodology, the critical fuel pin is tracked from the fuel assembly pin-by-pin model. A further step will analyze the thermomechanics using the detailed pin boundary conditions. For that purpose, the methodology extends the results from the pin CTF-UPVIS (Avramova et al., 2008) model with a FRAPCON/FRAPTRAN (Geelhood, et al., 2015), (Geelhood et al., 2016) pin model. The latter will account the burnup effect accounted in the heat conductance of the fuel-cladding gas gap. Notice that CTF-UPVIS only assigns a unique gap conductance for the full rod and the FRAPCON/FRAPTRAN model takes into account the axial variation of the pellet-clad gap properties. The results are a BE prediction of the MCPR by means of accounting the known physics available to be implemented in simulation codes.

In addition, following the guidelines of the USNRC (USNRC, 2003) the BE results are complemented with an Uncertainty and Sensitivity (U&S) Analysis. The methodology uses the DAKOTA toolkit (Adams et al., 2016) for the statistical analysis that will define the margins on the prediction of the MCPR performed by FRAPTRAN/FRAPCON. Table 2 shows the versions and codes referred in this subsection.

Table 2.- Information of versions of the state-of-the-art codes applied in the methodology.

Code	Code version	Developer	Property
PARCS	parcs_m16_UPVIS_v1801_ifr	U. MICHIGAN	USNRC
TRACE	Trace-v50p3	ISL	USNRC
CTF-UPVIS	CTF_UPVIS_v1701_r0_x64_r	Senubio (ISIRYM/UPV)/CTF Users Group	UPV/CTF Users Group
FRAPCON	Frapcon-4.0	PNL	PNL
FRAPTRAN	Fraptran-2.0	PNL	PNL
DAKOTA	Dakota-6.4	Sandia National Laboratories	Sandia National Laboratories

2. DESCRIPTION OF THE SIMULATION METHOD

The presented methodology uses as input data the boundary conditions of the critical fuel channel from the simulation of the TT scenario, undertaken in previous steps of the presented methodology (Hidalga et al., 2019). The critical fuel channel is selected using the criterion of the MCPR. The boundary conditions are loaded automatically using a MATLAB© application that avoid the user interference. The simulation of the first step is carried out by CTF-UPVIS in a pin-by-pin model. The results reveal the location of the critical fuel pin according to the MCPR criterion that a MATLAB© application applies. Then, the boundary conditions of the critical fuel pin are loaded automatically in the FRAPCON/FRAPTRAN model that performs two substeps. The first one generates the restart file with FRAPCON that accounts the burnup effect until the step of the fuel cycle when the TT takes place. The second substep performs the transient scenario of the TT with FRAPTRAN using the historical effect of FRAPCON.

The simulation of the previous steps reveals the axial location of the MCPR starting from the coarse system model of TRACE/PARCS until the final step of the whole methodology that simulates the fuel pin with FRAPCON/FRAPTRAN. The use of BE codes and BE boundary conditions requires from a U&S analysis.

The available scientific literature reveals which are the most relevant variables that can introduce uncertainty in the prediction of the MCPR. Each variable will be defined in terms of mean value and standard deviation. The method for the uncertainty and sensitivity analysis is based on Wilks method (Wilks, 1941). Therefore, in order to obtain coherent statistical results, a sample of size n is run. Each of the n cases corresponds to the transient simulation which each of the selected input variables perturbed randomly according to their Probability Density Function (PDF), defined by the aforementioned statistical parameters. The result is a distribution of the output target variable obtained with the simulation of the n cases. DAKOTA toolkit generates the perturbation matrix, pre- and post-processing the information to obtain the uncertainty of the target output variable, in this cases the MCPR. Moreover, DAKOTA will define the correlation between the uncertainty of the selected input variables and the uncertainty of the output target variable. The details and results of this part of the proposed methodology are discussed in subsection Uncertainty and Sensitivity Analysis of section III.

The application of every step of the presented methodology will define the MCPR for the critical node and its statistical boundaries according to the 95/95 criterion.

2.1 Discussion of results

This section shows the results of the analysis at pin level. The first subsection shows the evaluation capabilities of the MCPR with CTF-UPVIS, i.e. average, critical and envelope value of this safety variable. The next subsection adds the results of the fuel pin analysis with FRAPCON/FRAPTRAN which means considering the thermomechanics and the fuel gap conductance. The results are compared against the prediction of CTF-UPVIS. In the last subsection the results of FRAPCON/FRAPTRAN are complemented with the U&S analysis.

2.2 Fuel level analysis with CTF-UPVIS pin-by-pin model

This step moves in the scale detail level from the channel-by-channel model used in previous work of the authors to the pin-by-pin level of the target fuel assembly. The boundary conditions of the critical fuel channel are loaded in the detailed pin-by-pin model. The available results reveals which fuel assembly type corresponds to the critical fuel channel. The corresponding fuel model of CTF-UPVIS is selected by the methodology from the database of pin-by-pin fuel assembly types.

The boundary conditions are retrieved from the output files of the previous step and loaded in the input deck automatically. This is done by means of a MATLAB© based interface, avoiding user-effect interference. The simulation of the pin-by-pin model accounts several details including an advanced design of the water rods and Partial Length Rods (PLR). In addition, CTF-UPVIS allows introducing an average heat conductance of the fuel-cladding gap that is applied uniformly to the axial length of the rod.

The results of the simulation with CTF-UPVIS and the corresponding post-processing tool allow tracking the critical fuel pin according to the minimum CPR criterion. Afterwards, the critical fuel pin is modeled in a single fuel pin input deck for CTF-UPVIS. Figure 2 shows the radial location of the critical fuel pin in the layout of the simulated fuel model. Figure 3 shows the axial nodal distribution with the height and the definition of Water Rods and Partial Length Rods.

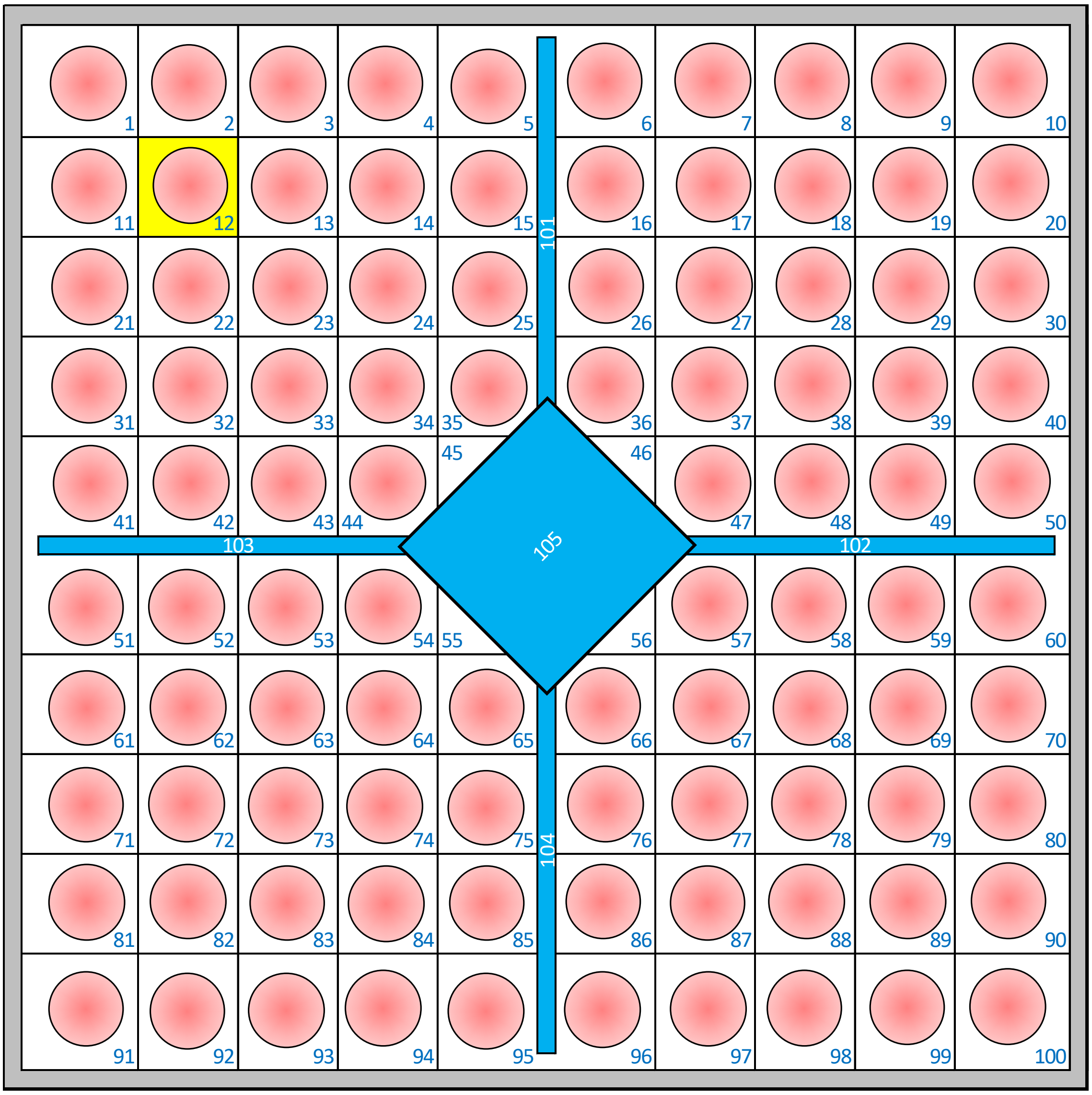

Figure 2.- Layout of the fuel model simulated with CTF-UPVIS numbering the fuel subchannels. The critical fuel pin detected in the simulation is highlighted.

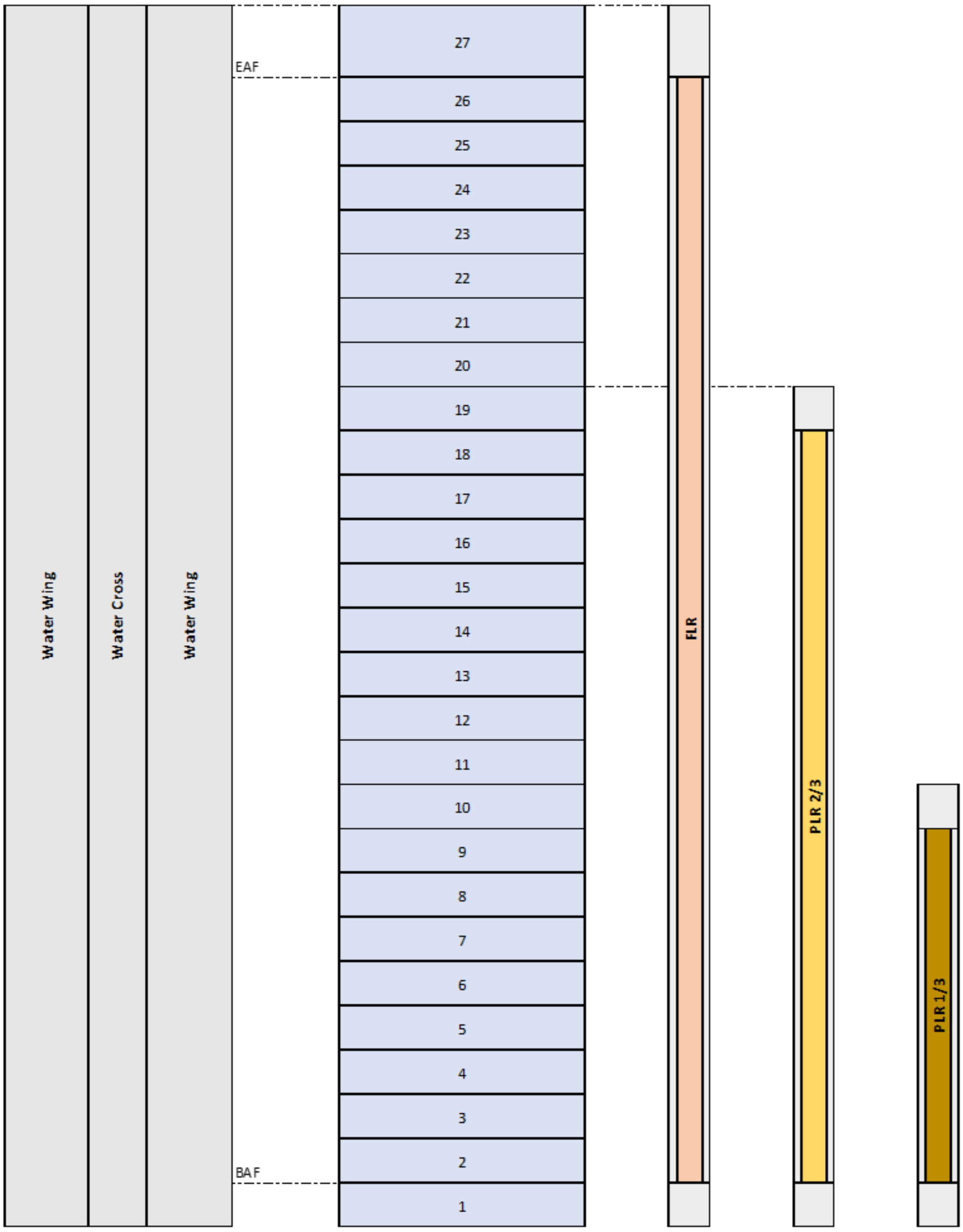

Figure 3.- Axial nodal distribution of the fuel model simulated with CTF-UPVIS with the design of the Partial Length Rods and Water Rods.

The fuel pin-by-pin model of CTF-UPVIS allows retrieving the critical fuel pin according to the MCPR criterion. Moreover, the result is compared to the average fuel value and the envelope of the MCPR. Figure 4 shows the prediction of the MCPR with different approaches. The MCPR prediction of the whole transient takes place at the initiation of the simulation and corresponds to rod number 12 axial node 19. Therefore, the critical MCPR is the evolution of that location along the transient. This result is compared to the envelope of the MCPR, that corresponds to the lowest MCPR that can be found in different rods and axial nodes along the transient. This envelope is a more conservative approach since it presents the worst case scenario for each time step of the simulation. In figure 4, the critical MCPR is the evolution of the MCPR of rod 12. The envelope is the evolution of the MCPR of the critical value along the fuel assembly model, i.e. the location is moved from one step to another, to the rod and axial node that has the MCPR at each time step.

Moreover, the radial average value of the MCPR is added to the comparison, in order to show the enhancement of accounting a pin level simulation tool instead of a bundle average model. The average MCPR correspond to the average value at each axial level of the fuel model. In the former curve, the value is located at node 17 during the full duration of the transient. Furthermore, figure 4 adds the axial node of the MCPR for each approach for every time step.

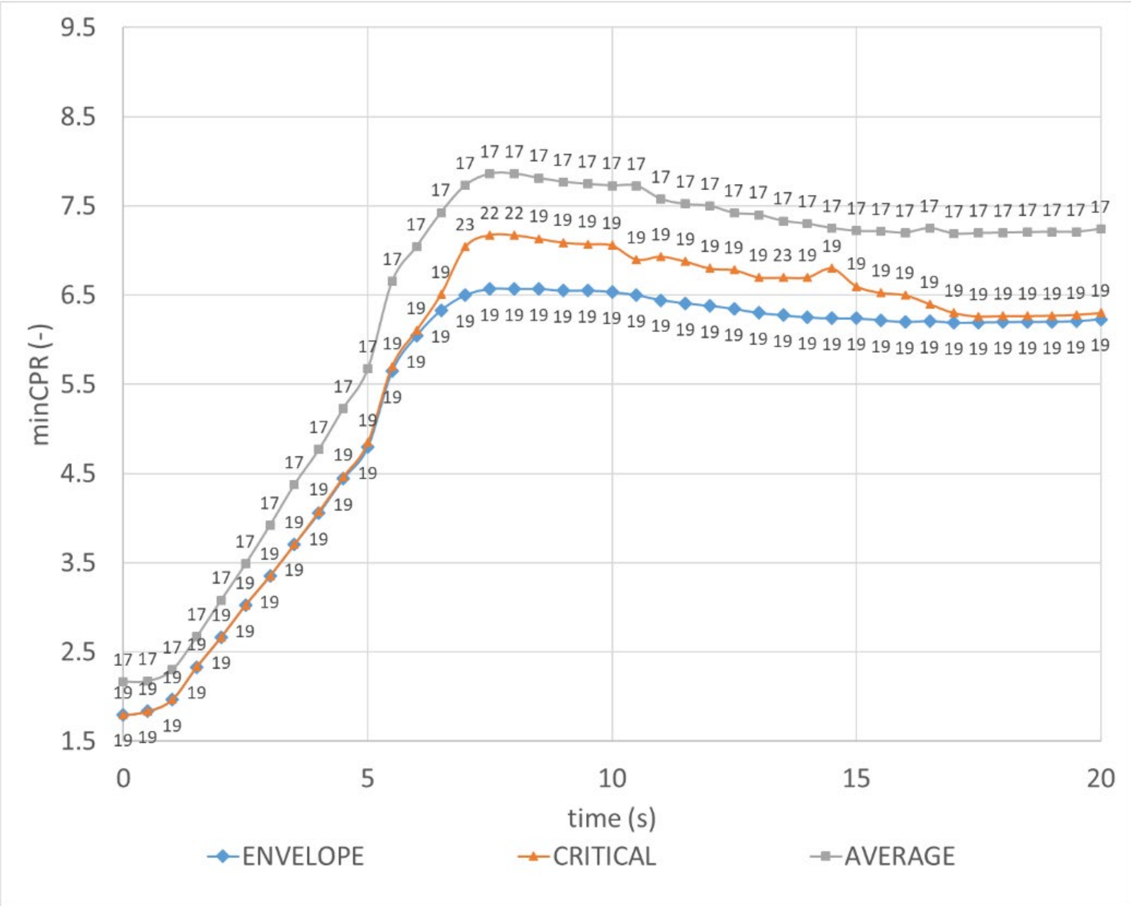

Figure 4.- Comparison of the averaged MCPR of the pin-by-pin model, the envelope of the MCPR and the critical fuel pin predicted by CTF-UPVIS.

As commented, the average value is located at axial node 17. The envelope value locates the MCPR at node 19 during the transient, being this node of fuel rod 12 until the transient time of 5 seconds. After 5 seconds, the envelope moves to rod 2 until 16 seconds of the transient, to finally end in fuel rod 11. As figure 2 depicts, both rods 11 and 2 are adjacent to the critical rod.

In view of the results, an averaged prediction of the MCPR overpredicts the envelope and the BE value of the critical fuel pin. Therefore, a prediction based in an averaged fuel channel has to be combined with a safety coefficient in order to assure a safe design or operation conditions. The more conservative approach is the envelope, which considers the MCPR among every fuel pin and every axial node. The prediction of the critical fuel pin is the closest to realistic results since it shows the conditions of the fuel pin that endures the worse conditions. In addition, each figure shows the axial node where the MCPR is located. Notice that the averaged prediction detects the MCPR in lower positions than the critical and envelope results, i.e. average MCPR is located at node 17 and the critical and envelope lowest location is at node 19. The averaging of the MCPR presents a more conservative evaluation of the safety conditions of the fuel bundle locating the value of the MCPR in a lower node that for the real case, however, averaging the MCPR would need a correction of the value, since it is overestimated regarding the real one detected in the critical fuel rod.

2.3 Pin analysis with FRAPCON/FRAPTRAN

This subsection presents the results of the thermo-mechanical analysis at pin level. The aim of this step of the presented methodology is to achieve a deeper scale level accounting the burnup effect and the evaluation of the fuel rod integrity. The results of this subsection focus on the target variable of the transient case, being the MCPR. Nevertheless, this step of the methodology can include the analysis of further safety variables, if applies, such as the oxide layer evolution, cladding deformation and hydride deposition.

The BE approach is fulfilled with FRAPCON/FRAPTRAN. The data base available for this methodology designed for KKL allows tracking the history of the operation of the fuel rod selected as critical by the previous step. Following with the procedure, the MCPR will be evaluated, loading the boundary conditions for the FRAPCON/FRAPTRAN model for the fuel pin of subchannel 12.

The boundary conditions of the fuel pin are loaded in FRAPCON model. This means defining the operation conditions of the fuel cycle of the target fuel pin until the burnup step when the transient scenario of the TT took place. These operation conditions are the fuel pin power, the inlet coolant enthalpy and mass flow, the outlet pressure and the axial power profile. The information is retrieved from the corresponding database available for the application of this methodology.

The results of the simulation with FRAPCON is a restart file that will be used with the corresponding input deck of FRAPTRAN. These two inputs are used to simulate the transient case of the TT. FRAPCON adds the effect of the burnup until the step of the fuel cycle where the transient case takes place. This procedure accounts the effect of the burnup in the axial distribution of the fuel-cladding gap conductance.

The capabilities of FRAPTRAN include the prediction of the pellet-clad gap behavior. This feature allows a more realistic prediction of the heat transfer distribution along the rod axial length. As a result, one can expect a more realistic prediction in the analysis of the cladding surface heat transfer, and hence in the prediction of the MCPR. The previous step, CTF-UPVIS analysis has the limitation of applying one single heat transfer coefficient of the pellet-clad gap along the whole length of the rod. For this reason, it is necessary to perform this last step of the methodology, in order to achieve a BE analysis.

The results of the simulation with FRAPCON/FRAPTRAN are compared to the results of a fuel pin model with CTF-UPVIS where a conservative approach has been accounted. Regarding the fuel-cladding gas gap, FRAPCON/FRAPTRAN takes a BE approach by defining the axial distribution of this variable along the pin. Conversely, CTF-UPVIS uses the lowest value of the axial distribution of the fuel-cladding gap conductance used by FRAPCON/FRAPTRAN. Figure 5 shows the comparison of the prediction of the MCPR in the different cases.

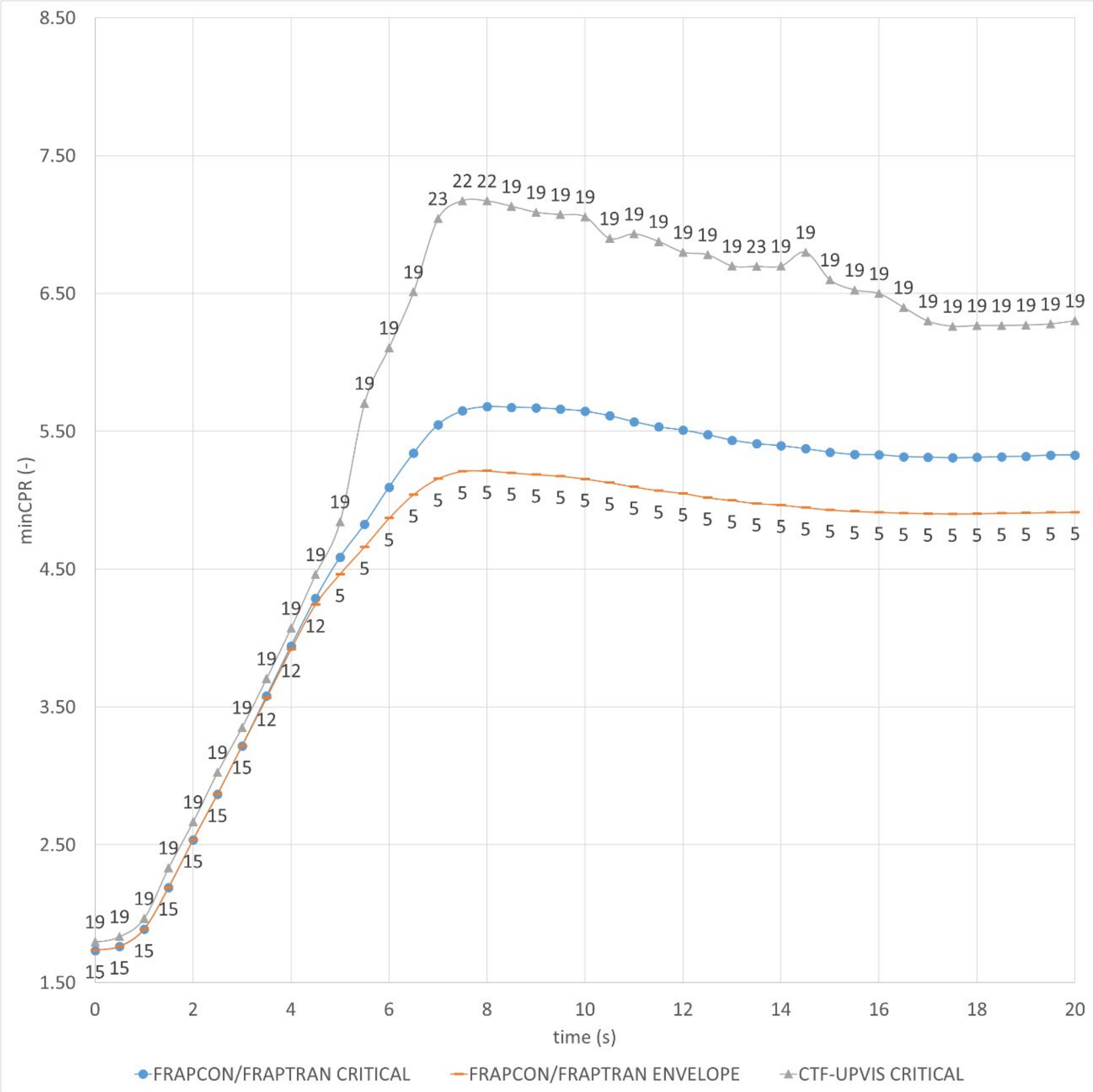

Figure 5.- Prediction of the MCPR by FRAPCON/FRAPTRAN pin model compared with the prediction of the CTF-UPVIS pin model.

The results show that the most conservative approach, i.e. CTF-UPVIS with the maximum gap conductance, predicts worse conditions for the fuel during the transient. On the other hand, the use of the BE model of FRAPCON/FRAPTRAN allows defining the envelope of MCPR of the simulated pin rod and also locating the axial node with endures the worse conditions. The results of the critical node are above the conservative approach of assuming the envelope of the worst case every time step. Therefore, the methodology provides a BE approach and the option of a conservative approach by defining the envelope of the worst cases. In addition, the MCPR is located at node 15 according to the prediction of FRAPCON/FRAPTRAN. This result reveals that accounting the BE approach gives a location of MCPR in a lower node than the previous step, i.e. CTF-UPVIS fuel bundle level.

2.4 Uncertainty and sensitivity analysis

This subsection describes the methodology for the Uncertainty and Sensitivity Analysis. For that purpose, the authors use a conventional methodology (Ánchel et al., 2012). With the Uncertainty Quantification (UQ) the authors define the variability of the output variable caused by the variability of the selected input variables. The UQ uses a random sample of the output variable obtained from the simulation of the sample size where the input variables are varied randomly.

The results are complemented by a Sensitivity Analysis (SA). This analysis evaluates the influence of the input variables on the output variables. The SA yields measures that assign a numerical value to this influence. In further work, this measures can be used to rank the effect of each input variable in the output variable.

The approach reported in this paper will use the scientific literature to account the uncertainty of the most relevant variables affecting the uncertainty of the prediction of the MCPR. The final result of the methodology is to evaluate the upper and lower boundaries of the prediction of the minimum CPR and which is the probability of the simulation results to obtain a result in such Confidence Interval.

The features of this step include the DAKOTA toolkit, the scientific literature (Ikonen et al., 2014) in order to realize an appropriate UQ, and the Wilks theory. The Wilks theory is used to set the sample size of the needed simulations. The method is based on introducing perturbations in the selected input variables, according to their PDFs. This set of perturbations generate a certain number of simulations to be run, i.e. the size of the sample. For the case presented in this report, the sample size is of 146, according to Wilks Formula. This sample size is derived from the selected Statistic Criterion, namely 95/95. This criterion defines that the 95% of the cases of the sample will fall into a Confidence Interval of 95%. This criterion is sufficient to accomplish the acceptance criteria of the Nuclear Authority. According to the scientific literature, table 3 shows the selected input variables that are assumed to introduce uncertainty in the prediction of the MCPR.

Table 3.- Sources of uncertainty considered.

parameter	units	mean	Std. Dev./boundary	PDF
Cladding outer diameter	(m)	0.009500	0.000019	Normal
Cladding inner diameter	(m)	0.008357	0.000019	Normal
Pellet dish radius	(m)	0.002475	0.000063	Normal
Fuel density	(%)	95.50000	0.750000	Normal
Pellet diameter	(m)	0.008192	0.000006	Normal
Cladding roughness	(μm)	0.635500	0.317250	Normal
Fuel roughness	(μm)	1.600500	0.799750	Normal
Plenum length	(m)	0.029531	0.000884	Normal
Outlet pressure	(bar)	73.64400	0.010000	Normal
Inlet mass flow	(kg/s)	0.113807	0.010000	Normal
Inlet temperature	(K)	550.6200	±0.01000	Uniform

The results are obtained using a MATLAB-based interface that pre-processes the statistical distribution of the target input variables in order to generate the input for DAKOTA. Afterwards, DAKOTA generates the 146 cases for FRAPTRAN. Once the simulation of the 146 cases is done, DAKOTA realizes the post-processing retrieving the statistics of the Uncertainty and Sensitivity analysis. Figure 6 shows the definition of the Confidence Interval (CI), the mean value of the Uncertainty Quantification, and the result of the nominal value with the pin model of FRAPTRAN.

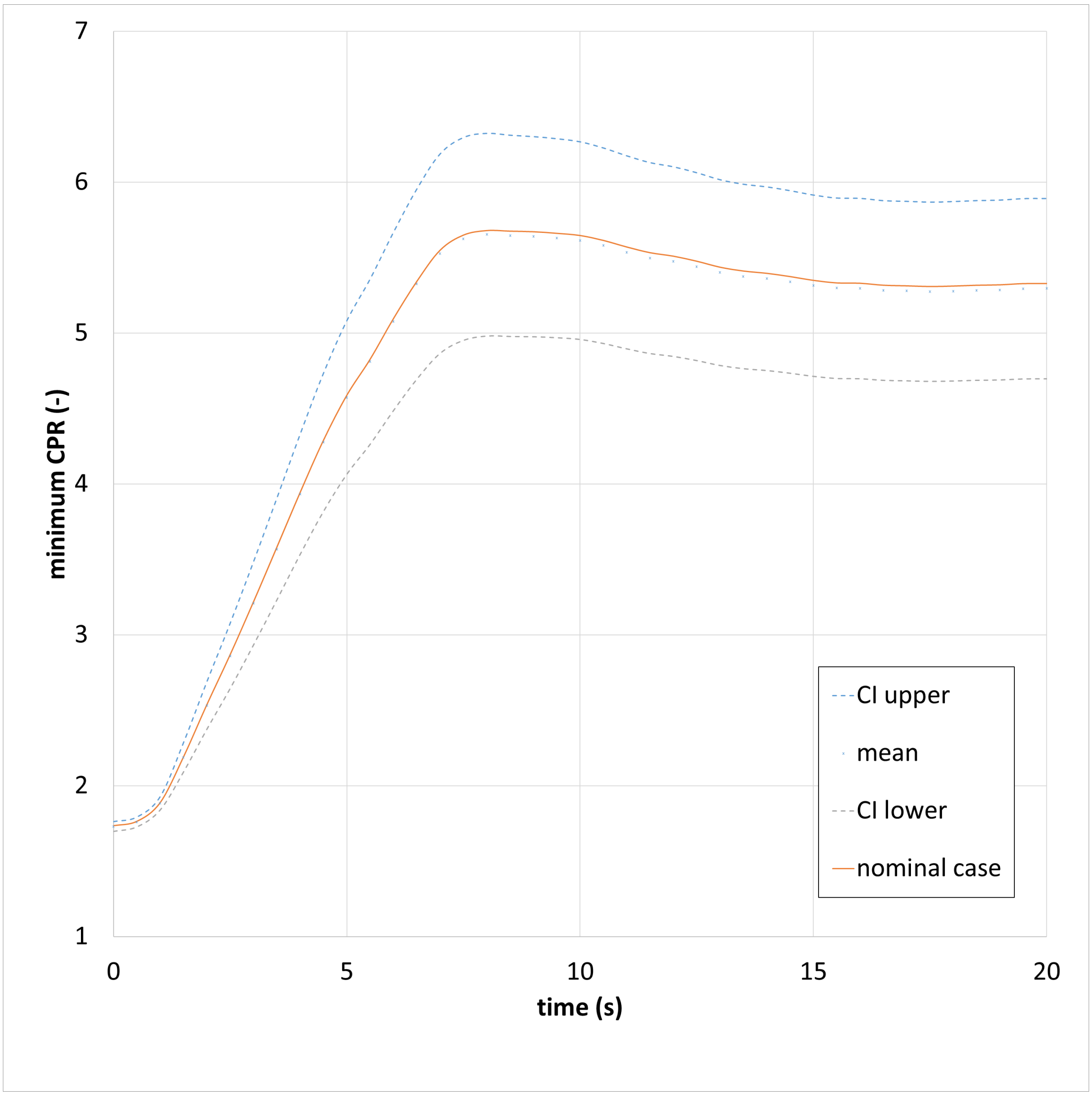

Figure 6.- Statistics results of the minimum CPR prediction with FRAPTRAN pin model.

As it can be expected, the nominal value of the simulation matches with the mean value of the sample. This step of the methodology defines the statistical boundaries with the 95/95 criterion. The results of the UQ revealed that for each time step the results of the 146 cases fell into the CI with a probability between 99.32 and 95.89 per cent. Therefore, the 95/95 criterion is met.

In addition, the DAKOTA toolkit has the feature of defining the SA. This analysis reveals how the uncertainty of the MCPR (as target output variable) is sensitive to the variations of the selected input variables. The procedure is made by analyzing the correlation between the input variables and the output variable. For this purpose, this simulation methodology uses the Partial Rank Correlation Coefficients (PRCC). It is assumed that values of PRCC above 0.16 in absolute value reveal significant effect of the uncertainty of the input in the uncertainty of the output. Figure 7 shows the result of the SA for table 3 variables.

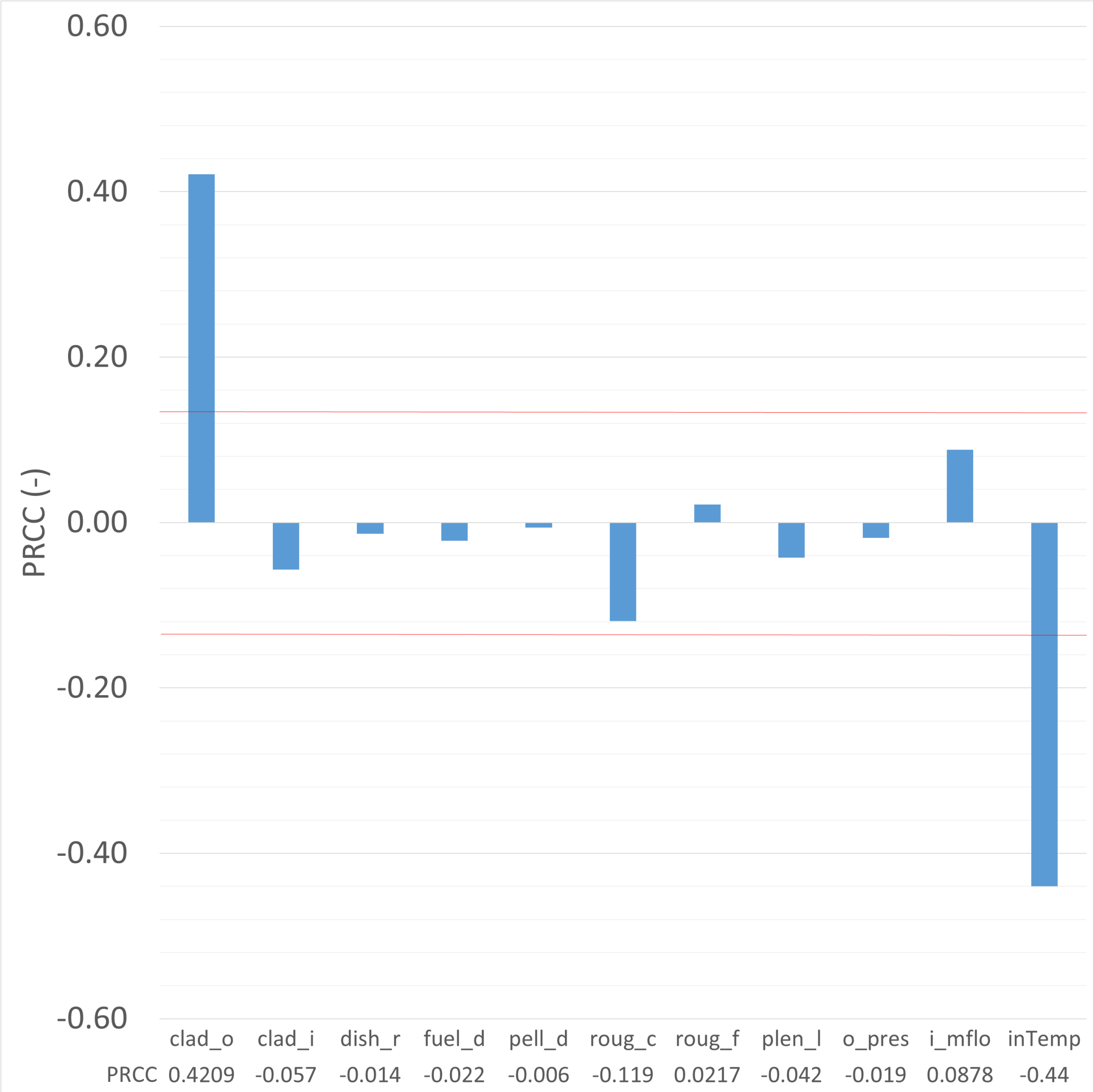

Figure 7.- Sensitivity Analysis of the transient case.

The results of figure 7 are supported by table 2.

Table 4.- Sensitivity Analysis of the transient case.

Variable	units	variable name	PRCC
Cladding Outer diameter	m	clad_o	0.4209
Cladding Inner Diameter	m	clad_i	-0.0567
Pellet Dish Radius	m	dish_r	-0.0137
Fuel Density	%	fuel_d	-0.0223
Pellet Diameter	m	pell_d	-0.0060
Cladding Roughness	µm	roug_c	-0.1194
Pellet Roughness	µm	roug_f	0.0217
Plenum Length	m	plen_l	-0.0424
Outlet Pressure	bar	o_pres	-0.0186
Inlet Mass Flow	kg/s	i_mflo	0.8780
Inlet Temperature	K	inTemp	-0.4400

In view of the results in figure 7 and table 4, it can be concluded that the input parameters affecting significantly the uncertainty of the MCPR correspond to the operation conditions of mass flow and inlet temperature of the coolant. The MCPR parameter is directly dependent on the Critical Heat Flux (CHF) correlation, and this parameter is determined by coolant conditions such as the flow quality, therefore it is expectable to highlight the uncertainty in the coolant inlet conditions as main source of uncertainty in the MCPR. Furthermore, the MCPR, as well as the CHF, depend in the heat transfer capacity of the fuel rod. For this variable, parameters such as the cladding diameter and the roughness play a relevant role, and therefore, the uncertainty of these parameters affect to the uncertainty of the prediction of the MCPR in the methodology.

3. CONCLUSIONS AND FURTHER WORK

The results presented in this paper and in its first part-paper show the capabilities of a multi-scale and multi-physics methodology to evaluate at different scales the Safety Variables suggested by the USNRC. Within the different steps of the methodology it has been possible to evaluate the MCPR from a coarser scale to a finer one, applying a Best Estimate approach by means of Best Estimate codes such as TRACE and CTF-UPVIS and the coupled TH and NK. On the other hand, the fuel pin analysis was undertaken using FRAPCON/FRAPTRAN codes.

The proposed methodology has been applied to a TT scenario of KKL in its fuel cycle 18. The step of the system and core simulations revealed good agreement against real plant data for the power and pressure behavior during the transient. The different steps allowed to evaluate the transient scenario locating the critical fuel channel, the critical fuel pin and the critical axial node according to the MCPR. Moreover, the proposed methodology included the calculation of the envelope evolution of the MCPR which allows a comparison of a conservative approach versus a Best Estimate approach.

The use of the fuel behavior code FRAPCON/FRAPTRAN allowed introducing axial dynamic variations in the fuel-cladding gap conductivity. This feature is used to achieve a Best Estimate calculation. The results of the fuel pin analysis where complemented by an Uncertainty and Sensitivity analysis. These results revealed that the analyzed safety variable meets the 95/95 criterion and hence, meets the requirements of the USNRC. Therefore, the presented methodology can be defined as an appropriate tool for the safety assessment.

Future work can be headed to design a channel-by-channel system model, that would lead to skipping the core simulation with CTF-UPVIS/PARCS by tracking directly the critical fuel channel. On the other hand, once the critical fuel channel is located, the core channel-by-channel model can be modified replacing the critical fuel channel by a pin-by-pin model that would be surrounded by the adjacent fuel channels providing the corresponding boundary conditions. This modification would skip the step of the pin-by-pin fuel model simulation and would provide directly the critical fuel pin.

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