A MORE REALISTIC UNCERTAINTY ANALYSIS APPROACH FOR THE LOCA SAFETY CRITERION

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One of the safety criteria to be proved within a Best-Estimate Plus Uncertainty (BEPU) analysis for a postulated loss of coolant accident (LOCA) requires that the peak cladding temperature (PCT) of a fuel rod in the reactor core must not exceed 1200 °C with a probability of at least 95 % at a statistical confidence level of at least 95 %. In Germany, this safety criterion is assumed to be fulfilled, if the PCT of a penalized hot fuel rod does not exceed 1200 °C with the required high probability and statistical confidence level. Since it has been controversially discussed recently whether the focus on the penalized hot fuel rod actually provides the maximum PCT of all fuel rods, a more realistic uncertainty analysis approach has been proposed. This approach statistically considers all high-power fuel rods in the core. The paper describes the probabilistic modelling of the approach and discusses the computational costs depending on the safety criterion supposed to be fulfilled. Furthermore, the concept for the implementation of the more realistic analysis approach is outlined.

I. INTRODUCTION

In recent years, the calculations for demonstration that nuclear power plants (NPP) can safely control a LOCA have been more and more performed by using a best-estimate thermal-hydraulic (TH) code implementing validated models supposed to be as realistic as possible. Since there are many uncertainty sources which may affect the result provided by a best-estimate code, national and international safety guidelines require a quantification of the uncertainty of the result. In many countries (e.g. France, Germany, Lithuania, the Netherlands, Korea, USA), the corresponding BEPU analysis is performed by Monte Carlo (MC) simulation and the application of statistical methods.

A statistical BEPU analysis for a postulated LOCA must show (among others) that the PCTs of the fuel rods in the reactor core do not exceed 1200 °C with a probability of at least 95 % at a statistical confidence level of at least 95 %. In Germany, this safety criterion is assumed to be fulfilled, if the PCT of the so-called penalized hot fuel rod does not exceed 1200 °C with the required high probability and statistical confidence level. That means the MC simulation applied in this context has to provide values for the PCT of the penalized fuel rod which subsequently have to be statistically evaluated in order to prove the criterion.

The penalized hot fuel rod is screwed up with an axial power distribution considering the conservative bounding power distribution. Its axial power profile reaches the LOCA limit value which is about 40 W/cm above the set point of the power density limitation system. In Germany, it has been controversially discussed recently whether the focus on the penalized hot fuel rod actually provides the maximum PCT of all fuel rods in the core. Therefore, the reactor safety commission (RSK) which performs advisory work for the German federal ministry responsible for the safety of nuclear installations stated that a more realistic uncertainty analysis with additional statistical consideration of the high-power fuel rods would allow for answering that question.

A particular challenge for a more realistic uncertainty analysis is the consideration of the huge amount of high-power fuel rods in the core (about 5 % of all fuel rods). It requires the application of adequate probabilistic methods which help to estimate the computational effort and to find a practicable approach avoiding exorbitant costs. Another challenge is the treatment of the numerous uncertainties which may relate to the models implemented in the best-estimate code, to plant-specific initial and boundary conditions and, additionally, to rod specific data.

Section II first outlines the method currently applied in a LOCA uncertainty analysis and, then, describes the approach to a more realistic uncertainty analysis. Emphasis is on the probabilistic modelling of the approach and on the computational costs associated with the safety criterion. Section III is dedicated to the concept for the implementation of the more realistic uncertainty analysis approach. It includes a description of the LOCA model to be applied and explains how the necessary fuel parameters are obtained. Furthermore, Section III gives an overview on the input uncertainties to be considered and shortly outlines the tool and practical steps of the uncertainty analysis. The conclusions are presented in Section IV.

II. UNCERTAINTY ANALYSIS APPROACHES

In paragraph II.A of this section, the BEPU analysis method currently applied to prove the LOCA safety criterion is outlined with emphasis on the internationally renowned method proposed by GRS (GRS-method). In paragraph II.B, the new method proposed for a more realistic uncertainty analysis is described.

II.A. GRS-Method

The GRS-method for proving the LOCA safety criterion is based on MC simulation and the application of statistical methods (Fig. 1).

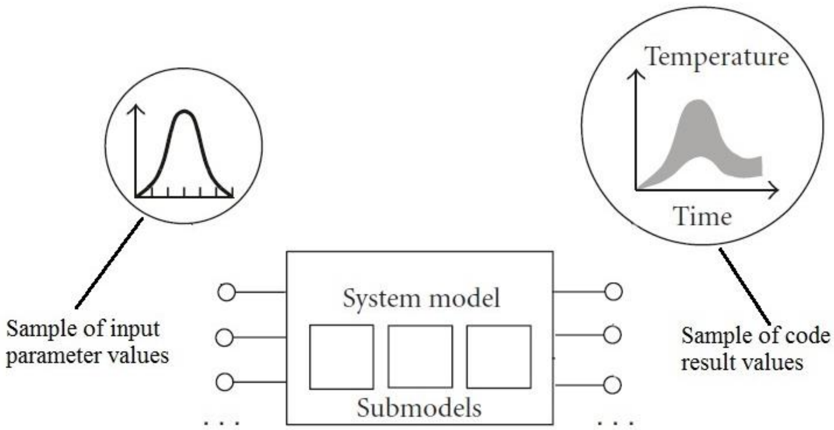

Fig. 1. BEPU analysis according to Monte Carlo method.

In the first analysis step, the uncertainty sources which may essentially contribute to the uncertainty of the result (e.g., PCT) of the applied TH code are identified. Important uncertainty sources are the models implemented in the code. Models are based on a scattering of measurements or are simplified to some degree so that the level of predictive accuracy of a model – even of a validated model – is not precisely known. Additionally, there are uncertainties on plant-specific initial and boundary conditions as well as on input data related to fuel rods.

Once the relevant uncertainty sources of the computational result have been identified, the state of knowledge on the corresponding uncertain input parameters is quantified. This is done by indicating, per uncertain input parameter, a range of possible values, an appropriate probability distribution and, if necessary, a dependence relationship to one or more other uncertain parameters. After this step is finished, different values for the uncertain input parameters are sampled. According to the method proposed by GRS, the simple random sampling procedure is applied in this context. It provides sets of parameter values randomly selected from a multivariate probability distribution satisfying the individual probability distributions and dependencies quantified as state of knowledge. That means a simultaneous variation of the uncertain input parameters is performed based on the quantified state of knowledge. Each sampled set of parameter values is then supplied as input to a corresponding simulation run of the TH-code. After all simulation runs are finished, the different PCT values obtained for the penalized fuel rod are statistically evaluated with regard to the LOCA safety criterion. The criterion requests that the PCT of the so-called penalized hot fuel rod does not exceed 1200 °C with a probability of at least 95 % at a statistical confidence level of at least 95 %.

According to the GRS-method, the upper limit $PCT_{95/95}$ of a left-open (95 %, 95 %) tolerance interval according to Wilks' [1, 2] is calculated from the PCT values of the penalized fuel rod. $PCT_{95/95}$ covers a proportion (probability) of at least β = 95 % of the possible PCT values at a confidence level of at least γ = 95 % (Eq. (1)). Therefore, the LOCA safety criterion is fulfilled, if the upper (95 %, 95 %) tolerance limit $PCT_{95/95}$ does not exceed the limiting value of 1200 °C.

$$P(P(PCT \leq PCT_{95/95}) \geq \beta) \geq \gamma \tag{1}$$

The calculation of Wilks' tolerance limits requires that the values obtained for the computational result can be considered as a random sample. Therefore, according to the GRS method, the simple random sampling procedure is applied to select the values of the uncertain input parameters (see above). Simulation runs performed on the basis of a random sample of input parameters provide a random sample of values for the corresponding computational result. The probability distribution of the computational result does not matter. Wilks tolerance limits can be applied to any distribution.

An important requirement of Wilks tolerance limits is a minimum number of values from which they can be calculated. That means, a minimum number of sets of values must be sampled for the uncertain input parameters and transferred to corresponding simulation runs. The required minimum number n depends on the requested probability (e.g. $\beta = 95$ %) as well as on the statistical confidence level (e.g. $\gamma = 95$ %) and is given by Wilks' formula [1, 2]. For the upper ($\beta \times 100$ %; $\gamma \times 100$ %) tolerance limit, the formula is given by Eq. (2):

$$1 - \beta^n \geq \gamma \tag{2}$$

where $\beta \times 100$ is the probability (%) and $\gamma \times 100$ is the confidence level (%). The confidence level $\gamma \times 100$ accounts for the effect of considering just a limited sample of results and gives the minimum percentage of all possible samples for which the respective tolerance limit covers the proportion (probability) of at least $\beta \times 100$ %.

The minimum number of runs which must be performed to be able to calculate the upper (95 %, 95 %) tolerance limit of a computational result is 59. In this case, the largest value of the 59 results corresponds to the (95 %, 95 %) tolerance limit. If more simulation runs can be afforded, not the largest but a computational result of lower order is the tolerance limit. For instance, if 100 simulation runs are performed, the second largest computational result corresponds to the (95 %, 95 %) tolerance limit.

In summary, it can be stated, that the number of simulation runs needed to be performed to prove the LOCA safety criterion according to the GRS-method is completely determined by the requested probability and statistical confidence level. It is independent of the number of uncertain input parameters. This characteristic is also considered for the more realistic approach in paragraph II.

II.B. More Realistic Approach

Whereas the method currently applied in a LOCA uncertainty analysis focuses on the penalized hot fuel rod (see paragraph II.A), the new more realistic method has to statistically consider all high-power fuel rods in the core. Each of these fuel rods is supposed to behave individually and independent of the behavior of the other high-power fuel rods. Therefore, the PCTs of all high-power fuel rods must be calculated to determine whether the LOCA safety criterion is fulfilled. Additionally, the relevant input uncertainties have to be considered. Like with the currently applied GRS-method (see paragraph 1), they refer to models implemented in the TH code, numerical solution algorithms as well as to plant-specific initial and boundary conditions. Furthermore, there are rod-specific input data which are not precisely known and, therefore, must be considered as uncertain.

In the following, the probabilistic modelling for statistically handling the high-power fuel rods is considered. Two safety criteria and the corresponding computational costs to prove the respective criterion are discussed.

II.B.1. Probabilistic Modelling

Let X_i be an indicator variable indicating whether the PCT of the high-power fuel rod No. i exceeds 1200°C ($X_i = 1$) or not ($X_i = 0$), i=1, …, N. Then, the probability distribution of X_i is a Bernoulli distribution (Eq. (3)):

$$P(X_i = 1) = p_i\,, \quad P(X_i = 0) = 1 - p_i \tag{3}$$

where p_i is the probability for $X_i = 1$ ($P(X = 1)$).

If X represents the number of high-power fuel rods with the PCT exceeding 1200°C, X can be represented as the sum of the N independent (not necessarily identically distributed) Bernoulli variables $X_1, \ldots, X_N$ with N = total number of high-power fuel rods in the core (Eq. (4)). The probabilistic model of variable X can be described by the Poisson Binomial distribution (Generalized Binomial distribution) in Eq. (5).

$$X = \sum_{i=1}^{N} X_i \tag{4}$$

$$P(X = m) = \sum_{\{(X_1,\ldots,X_N) | \sum X_i = m\}} \prod_{i=1}^{N} p_i^{X_i} (1 - p_i)^{1 - X_i} \tag{5}$$

Eq. (6) gives the probability that none of the high-power fuel rods shows a PCT exceeding 1200°C.

$$P(X = 0) = \prod_{i=1}^{N} (1 - p_i) \tag{6}$$

Expectation *E(X)* and variance *Var(X)* of *X* are given in Eq. (7) and Eq. (8), respectively.

$$E(X) = \sum_{i=1}^{N} p_i \tag{7}$$

$$Var(X) = \sum_{i=1}^{N} p_i (1 - p_i) \tag{8}$$

Based on the current LOCA safety criterion, the strongest criterion which can be requested to be fulfilled, if all high-power fuel rods are considered, says that none ($X = 0$) of the high-power fuel rods must show a PCT exceeding 1200°C with a probability of at least $\beta = 0.95$ at a statistical confidence level of at least $\gamma = 0.95$. The probabilistic formulation of this criterion is given in Eq. (9):

$$P(P(X = 0) \geq \beta) \geq \gamma \tag{9}$$

The minimum number of MC runs which must be performed to prove the criterion in Eq. (9) (compare to Eq. (1)) can be derived from Eq. (2) ($\beta = 0.95$, $\gamma = 0.95$) or Eq. (10) (with m=n) and is $n = 59$. Thereby, each MC run is supposed to calculate the PCTs of all high-power fuel rods from a selected set of values of the uncertain input parameters. The criterion is fulfilled, if all PCTs remain below 1200 °C ($X = 0$) in each of the $n = 59$ MC runs. If one or more MC runs provide at least one fuel rod with the PCT exceeding 1200 °C ($X > 0$), the number of MC runs required to prove the criterion must be increased and can be derived, for instance, from Eq. (10) which is based on Clopper – Pearson confidence intervals [3].

$$\frac{m}{m + (n - m + 1) q_{F_\gamma}} \geq \beta \tag{10}$$

with n = total number of MC runs, m = number of MC runs with $X = 0$, and $q_{F_\gamma} = \gamma \times 100$ %-quantile of the *F*-distribution with $v_1 = 2(n-m+1)$ and $v_2 = 2m$ degrees of freedom.

Since the computational effort would be exorbitant and, therefore, prevent a more realistic LOCA uncertainty analysis, if the fulfillment of the safety criterion in Eq. (9) is requested, the RSK formulated another criterion. This safety criterion is a bit weaker than that in Eq. (9) and requires, that the PCTs of all high-power fuel rods except at most one must not exceed 1200 °C ($X \leq 1$) with a probability of at least $\beta = 0.95$ at a statistical confidence level of at least $\gamma = 0.95$ (Eq. (11)).

$$P(P(X \leq 1) \geq \beta) \geq \gamma \tag{11}$$

At the first glance, it can be assumed that the minimum number of runs which must be performed to prove the criterion in Eq. (11) is $n = 59$ (compare to Eq. (9)). However, the number of necessary runs can be reduced, if the criterion in Eq. (12)

with an appropriately chosen probability $0 < \beta' \leq \beta$ is considered. Fulfillment of the criterion in Eq. (12) implies fulfillment of the criterion in Eq. (11).

$$P(P(X = 0) \geq \beta') \geq \gamma \tag{12}$$

To determine the probability β' in Eq. (12), the Binomial distribution *Bin(p, N)* with parameters $p = E(X)/N$ (Eq. (7)) and N is used as conservative estimate of the Poisson Binomial distribution for values of $X \leq 1$. If $X' \sim Bin(p, N)$, the expectation $E(X')$ of X' equals to the expectation $E(X)$ of X and the variance $Var(X')$ of X' is given by the formula in Eq. (13).

$$\begin{aligned} Var(X') &= Np(1-p) \\ &= \sum_{i=1}^{N} p_i(1-p_i) + \sum_{i=1}^{N}(p_i - p)^2 \\ &= Var(X) + \sum_{i=1}^{N}(p_i - p)^2 \end{aligned} \tag{13}$$

If β' is sufficiently high (i.e. $\beta' > (1-{}^{1}/_{N})^{N} \rightarrow E(X) < 1$), the probability $P(X \leq 1)$ of the Poisson Binomial distribution does not fall below the corresponding probability $P(X' \leq 1)$ of the Binomial distribution *Bin(p, N)*. This can be derived from the formula of the variance $Var(X')$ in Eq. (13) and the well-known Cantelli inequality. So, $P(X' \leq 1) \geq \beta$ implies $P(X \leq 1) \geq \beta$ (Eq. (14)).

$$P(X \leq 1) \geq P(X' \leq 1) \overset{!}{\geq} \beta \tag{14}$$

$P(X' \leq 1) \geq \beta$, if parameter p of the Binomial distribution *Bin(p, N)* fulfills the relationship in Eq. (15).

$$p = \frac{1}{N}\sum p_i \leq q_{Beta_{1-\beta}} \tag{15}$$

where $q_{Beta_{1-\beta}} = (1 - \beta)\times 100$ %-quantile of the standard Beta distribution *Beta(a, b)* with parameters $a = 2$ and $b = N$-1.

Eq. (15) follows from the well-known relationship between the Binomial and the Beta distribution indicated in Eq. (16).

$$P(X' \leq M) = \sum_{i=0}^{M}\binom{N}{i}p^i(1-p)^{N-i} = \frac{1}{Beta(M+1; N-M)}\int_p^1 u^M(1-u)^{N-M-1}du \geq \beta \tag{16}$$

The relationship in Eq. (15) is true, if the relationship in Eq. (17) can be shown to be fulfilled. Here, the well-known relationship $A_N \geq G_N$ between the arithmetical mean A_N and the geometrical mean G_N is used. Eq. (17) means that the probability that the PCTs of all high-power fuel rods do not exceed 1200 °C (X=0) must be at least $(1- q_{Beta1-\beta})^N$.

$$P(X = 0) = \prod_{i=1}^{N}(1-p_i) \geq (1-q_{Beta_{1-\beta}})^N \tag{17}$$

From Eqs (13)-(17), it can be concluded that the criterion in Eq. (11) is fulfilled, if the criterion in Eq. (12) is fulfilled with $\beta' = (1- q_{Beta_{1-\beta}})^N$. The minimum number n of MC runs which must be performed to prove the criterion in Eq. (12) depends on the probability β' and the required confidence level $\gamma = 0.95$ where β' itself depends on the required probability $\beta = 0.95$ and on the number N of high-power fuel rods. N is considered to be about 5 % of the total number of fuel rods in the core. These are about 2000 – 3000 fuel rods. It can easily be calculated, that $\beta' \geq 0.70$ for $N \geq 2000$ (already for $N \geq 500$). With $\beta' \geq 0.70$, the minimum number of MC runs which must be performed is $n = 9$ (see Eq. (2) or Eq. (10)). In each of these runs, the PCTs of all high-power fuel rods must remain below 1200 °C. If one or more MC runs provide at least one fuel rod with the PCT > 1200 °C, the number of MC runs must be increased to prove the criterion (see Eq. (9) where q_{F_β} has to be replaced by $q_{F_{\beta'}}$).

II.B.2. Practical Aspects

To prove the LOCA safety criterion discussed in paragraph II.B.1, it has to be determined for each MC run whether the PCTs of all high-power fuel rods remain below 1200 °C. In other words, the maximum PCT (PCT_{max}) over all high-power fuel rods is the result of interest per MC run performed in the more realistic LOCA uncertainty analysis. So, if it can be shown that PCT_{max} does not exceed 1200 °C with a probability of at least $\beta \times 100$ % at a statistical confidence level of at least 95 % where β= 0.95 for the criterion in Eq. (9) and β = 0.70 for the criterion in Eq. (11), the safety criterion is fulfilled. To this purpose, the upper ($\beta \times 100$ %, 95 %) tolerance limit of PCT_{max} can be determined similarly to what is done according to the GRS method described in paragraph II.A. If the upper ($\beta \times 100$ %, 95 %) tolerance limit of PCT_{max} does not exceed 1200 °C, the safety criterion is fulfilled.

To determine the upper (95 %, 95 %) tolerance limit, a minimum of n = 59 MC runs must be performed. For the upper (70 %, 95 %) tolerance limit, a minimum of n = 9 MC runs is necessary. From all PCT_{max} values provided by the minimum number of MC runs, the largest one corresponds to the tolerance limit.

The number of high-power fuel rods to be considered is at least 5 % of the total number of fuel rods in the core. Since the PCTs of all high-power fuel rods have to be calculated, the proof of the safety criterion in Eq. (9) requiring a minimum of n = 59 MC runs is not practicable. The bit weaker safety criterion in Eq. (11) requiring at least n = 9 MC runs is supposed to be the only criterion which can currently be proven with feasible computational effort.

III. IMPLEMENTATION CONCEPT

The practicability of the more realistic LOCA uncertainty analysis approach will be demonstrated by a specific application. In this Section, the concept of the implementation of this approach is explained with reference to the application case.

The LOCA scenario to be investigated is assumed to occur in a German pressurized water reactor (PWR) with 3850 MW thermal power and to be initiated by a double ended cold leg offset shear break (design basis accident). The scenario is characterized by the loss of off-site power at turbine trip. The accumulator system is supposed to initiate coolant injection into the primary system below a pressure of 2.6 MPa. High- and low-pressure ECC injection is available. A single failure is assumed in the broken loop check valve for ECC injection from accumulator, high- and low- pressure system, and one hot leg accumulator is unavailable due to preventive maintenance. These assumptions are considered to be the worst unavailability agreed between applicants and assessors.

In Paragraph III.A., the TH model of the LOCA scenario is outlined. Paragraph III.B gives an overview on the uncertain input parameters identified as potentially important and describes the steps to be performed for the uncertainty analysis.

III.A. TH Model and Fuel Parameters

In paragraph III.A.1, the TH model to be applied in the more realistic LOCA uncertainty analysis is described. Paragraph III.A.2 explains how the fuel parameters needed for the analysis are obtained and considered in the TH model.

III.A.1 TH Model

The TH code to be applied for the LOCA analysis is the code ATHLET (Analysis of THermal-hydraulics of LEaks and Transients) which has been developed for the analysis of the whole spectrum of leaks and transients in PWRs and BWRs [4].

A detailed four loop model of the reference PWR is used for the analysis. Each loop consists of the main coolant line, the steam generator with the main steam lines and a simplified feed water line, and the emergency core cooling (ECC) system. The pressurization system comprises the pressurizer, the safety and relief valves and the blow-off tank. Special attention is given to the quasi 3D-model of the reactor pressure vessel (RPV) illustrated in Fig. 2. The RPV is composed of 8 thermal hydraulic channels in the down comer and core bypass, 17 thermal hydraulic channels inside the core barrel, which range from the lower plenum to the top of the upper plenum including the control rod guide tubes. Each thermal hydraulic channel is linked by cross connection pipes to the neighboring thermal hydraulic channels. The 17 core channels are arranged by a central channel and two rings with 8 azimuthal channels each. The central channel contains 9 fuel elements, each channel of the inner ring 5 fuel elements and each channel of the outer ring 18 fuel elements. The high number of fuel elements in the outer ring is based on UPTF experiments. These experiments showed that, for the hot leg ECC injection, the break through area to the core is up to 20 fuel elements. Another reason for the distribution of fuel bundles is to allocate the number of the highest powered fuel rods (5 % of the total number of fuel rods in the core) as equally as possible to the 17 thermal hydraulic channels. Each thermal hydraulic core channel contains a thermal hydraulic channel for a hot fuel element and a hot channel. Each hot channel includes a hot fuel rod and 6 to 8 surrounding fuel rods depending on the amount of control rod guide tubes. The fuel rods of the hot fuel element are represented by an average fuel rod to which the average parameter values of the rods in the hot fuel element are assigned. The fuel rods of the residual fuel elements in each of the 17 thermal hydraulic channels are represented by two average fuel rods, one for the low powered fuel rods and one for the higher powered fuel rods.

A simplified one node containment model is used for the determination of back pressure at the break. A detailed model for I&C (Control, limitation and safety functions) ensures that all actions from the reactor protection system are correctly activated.

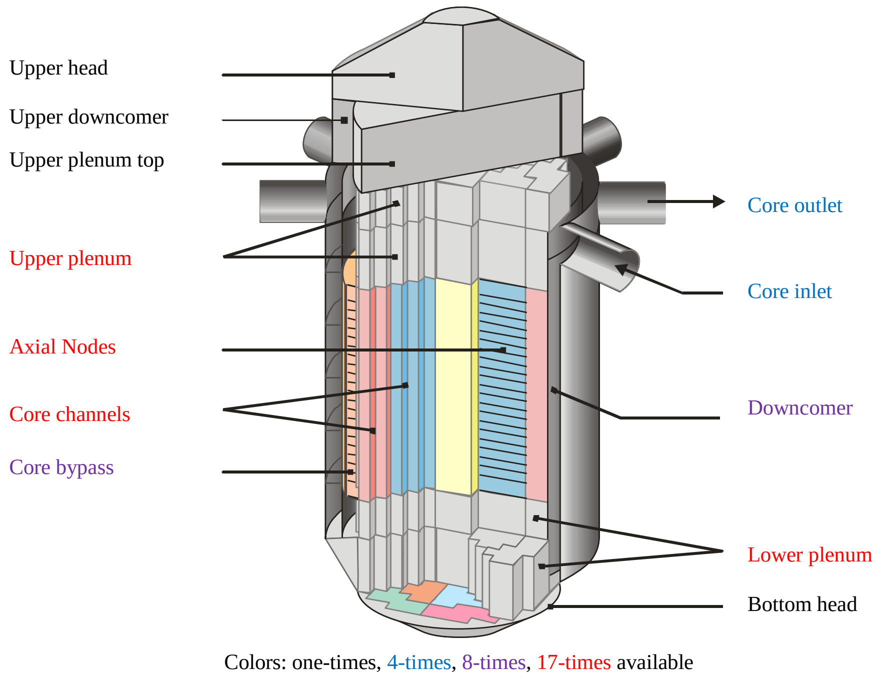

Fig. 2. Quasi 3D-model of the reactor pressure vessel.

III.A.2 Fuel Parameters

According to the RPV model described in paragraph III.A.1, a total of 17 core channels each including exactly one high-power fuel rod can be considered per run of the code ATHLET applied for the LOCA simulation. Since at least 2250-2900 high-power fuel rods (5 % of the total number of fuel rods in the core with either (16 × 16) or (18 × 18) fuel assemblies) have to be considered for a more realistic uncertainty analysis, at least 133-171 different ATHLET runs must be performed to determine the PCTs of all high-power fuel rods.

The fuel assemblies of the reference PWR considered in the application case are of size 18 × 18. So, at least 2900 high-power fuel rods have to be calculated. This implies that at least 171 ATHLET runs have to be performed.

The steady-state power and burn-up data needed to be considered for the high-power fuel rods as well as for the corresponding fuel assemblies and neighbor fuel rods are selected from a pin file including output data of a neutronic code applied to an actual core loading of the reference PWR. Based on an appropriate preparation and subsequent evaluation of the data, groups of 17 high-power fuel rods each are built and assigned to the corresponding input file of an ATHLET run. That means the power and burn-up data referring to each fuel rod of a group is assigned as input to one of the 17 available core channels of the core model considered per ATHLET run.

The length of a fuel rod is obtained from the pin file as well and appropriately considered in the ATHLET input file. Fabrication parameters like the cladding and the pellet material are derived from another data file.

III.B. Uncertain Parameters and Analysis Tool

Paragraph III.B.1 gives an overview on the input uncertainties to be considered in the more realistic LOCA uncertainty analysis. Paragraph III.B.2 shortly outlines the tool selected to be applied for the uncertainty analysis and explains the analysis steps to be performed.

III.B.1 Uncertain Parameters

The uncertain input parameters identified as potentially important in the LOCA analysis are classified in so-called global (overall) uncertain parameters and rod-specific uncertain parameters.

The global uncertain parameters comprise:

- model parameters referring to critical flow, heat transfer, evaporation, condensation, wall and interfacial shear, form loss, main coolant pump head, and torque
- parameters indicating different model correlations for heat transfer and friction
- parameters for bypass flow cross sections in the reactor vessel
- a parameter for temperature of flooding tank and accumulator water
- parameters for activation of function of safety systems
- a parameter for containment pressure
- a parameter for core power
- a parameter for decay heat
- parameters for convergence criteria

The rod-specific uncertain parameters refer to each high-power fuel rod considered in the analysis. They comprise:

- parameter for the radial power factor for hot rods and surrounding rods (hot channel factor)
- parameters for gap width (6 burn-up classes)
- parameters for fuel thermal conductivity, fuel heat capacity and fuel density
- pellet diameter (6 burn-up classes)
- operational fission gas release (6 burn-up classes)

III.B.2 Analysis Tool

The tool selected to be applied for the uncertainty analysis is SUSA 4 [5]. It combines the statistical methods needed for the analysis with a comfortable graphical user interface (GUI, Fig. 3).

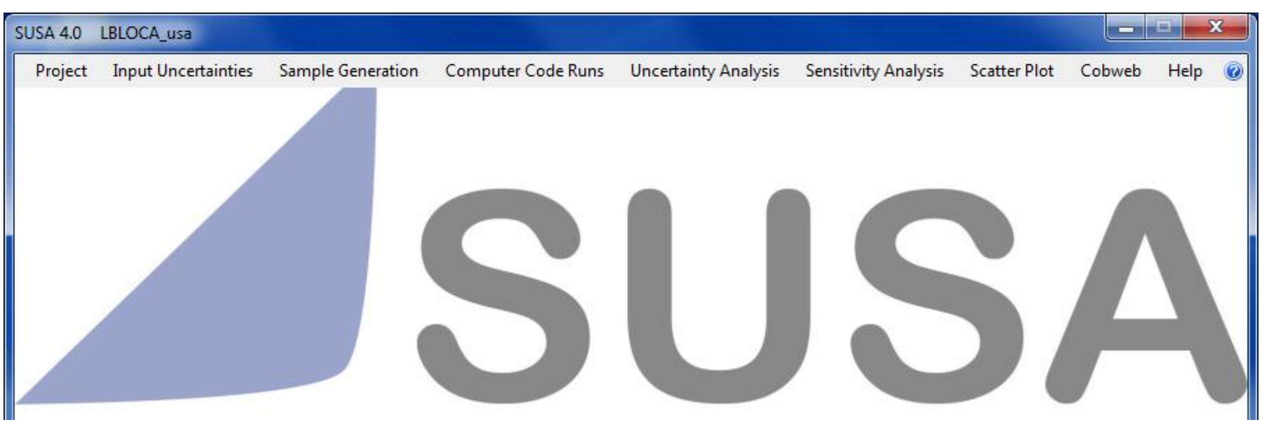

Fig. 3. Main SUSA 4 window.

The first important step which must be performed within SUSA 4 comprises the manual input of each uncertain parameter and the specification of the corresponding probabilistic information (range, distribution, dependence relationship) to be used as uncertainty quantification (menu ‘Input Uncertainties’). With regard to the more realistic uncertainty analysis approach, this analysis step would be rather extensive, especially since the rod-specific uncertain parameters of at least 2900 fuel rods (5 % of the total number of fuel rods in the core with (18 × 18) fuel assemblies) would have to be specified. Therefore, it was decided to specify - besides the global uncertain parameters (paragraph III.B.1) - only the rod-specific uncertain parameters with respect to a single fuel rod. Since the probabilistic information on each rod-specific uncertain parameter applies to all fuel rods, the abbreviated input specification does not mean loss of information and just has to be appropriately considered in the subsequent analysis steps.

The next important analysis step is the sampling of different sets of values for the specified uncertain parameters (menu 'Sample Generation'). To prove the LOCA safety criterion, a minimum of $n = 9$ sets of parameter values is necessary (paragraph II.B.2). But to account for the abbreviated input specification, $n_1 = 26163$ sets of parameter values have to be sampled. n_1 is the product of $n \times n_C \times n_A$ with $n = 9$, $n_C = 17$ (number of core channels per ATHLET run) and $n_A = 171$ (number of ATHLET runs necessary to consider at least 2900 high-power fuel rods). The sets of parameter values can easily be prepared and reformatted in the form (Table I) needed for the automatic launching of 1539 (= $n \times n_A$) ATHLET runs. The interface to ATHLET implemented in SUSA 4 (menu 'Computer Code Runs') is able to automatically generate the ATHLET input files with respect to the different sets of parameter values and to start the corresponding runs. The results provided by the ATHLET runs can be imported into SUSA 4 for the final statistical evaluation.

From the temporal evolution of the cladding temperature of a fuel rod, SUSA 4 can automatically calculate the corresponding PCT as the maximum cladding temperature over time. Based on the PCT values for all fuel rods in all ATHLET runs, the maximum PCT can be calculated. It corresponds to the upper (70 %, 95 %) tolerance limit of the maximum PCT over all high-power fuel rods and, therefore, must be compared with the limiting value of 1200 °C to prove the LOCA safety criterion (paragraph II.B.2).

TABLE I. Structure of the Sample of Uncertain Parameters

Index i of MC runs	Index j of ATHLET runs	Global uncertain parameters $P^g(i,1), \ldots, P^g(i,n_g)$	Rod-specific uncertain parameters		
			Channel 1 $P^{(j-1)*17+1}(i, 1) \ldots, P^{(j-1)*17+1}(i,n_r)$		Channel 17 $P^{(j-1)*17+17}(i, 1) \ldots, P^{(j-1)*17+17}(i,n_r)$
1	1	$P^g(1,1), \ldots, P^g(1,n_g)$	$P^1(1,1), \ldots, P^1(1,n_r)$	…	$P^{17}(1,1), \ldots, P^{17}(1,n_r)$
	⋮	⋮	⋮		⋮
1	171	$P^g(1,1), \ldots, P^g(1,n_g)$	$P^{2891}(1,1), \ldots, P^{2891}(1,n_r)$	…	$P^{2907}(1,1), \ldots, P^{2907}(1,n_r)$
2	1	$P^g(2,1), \ldots, P^g(2,n_g)$	$P^1(2,1), \ldots, P^1(2,n_r)$	…	$P^{17}(2,1), \ldots, P^{17}(2,n_r)$
	⋮	⋮	⋮		⋮
2	171	$P^g(2,1), \ldots, P^g(2,n_g)$	$P^{2891}(2,1), \ldots, P^{2891}(2,n_r)$	…	$P^{2907}(2,1), \ldots, P^{2907}(2,n_r)$
			⋮		
9	1	$P^g(9,1), \ldots, P^g(9,n_g)$	$P^1(9,1), \ldots, P^1(9,n_r)$	…	$P^{17}(9,1), \ldots, P^{17}(9,n_r)$
	⋮	⋮	⋮		⋮
9	171	$P^g(9,1), \ldots, P^g(9,n_g)$	$P^{2891}(9,1), \ldots, P^{2891}(9,n_r)$	…	$P^{2907}(9,1), \ldots, P^{2907}(9,n_r)$

II. CONCLUSIONS

The paper presented an approach for a more realistic LOCA uncertainty analysis. The approach allows for statistically considering all high-power fuel rods in the core. These are about 5 % of the fuel rods of a core loading. The safety criterion supposed to be demonstrated with practicable computational costs requires that the PCTs of all high-power fuel rods except at most one must not exceed 1200 °C with a probability of at least 95 % at a statistical confidence of at least 95 %. However, the computational costs are large. The PCTs of all high-power fuel rods have to be calculated in order to determine whether the safety criterion is fulfilled. Additionally, the influence of input uncertainties on the PCTs has to be considered in corresponding MC simulation runs. The number of input uncertainties is huge. The uncertainties refer to models implemented in the TH code, initial and boundary conditions as well as to rod-specific input parameters.

The paper additionally presented the concept for the implementation of the more realistic uncertainty analysis approach. Important components of this concept are on the one side, the TH code and the RPV model implemented in the code and, on the other side, the tool used for the extensive uncertainty analysis. A practical application based on the presented implementation concept will be performed in the near future.

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