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Sensitivity analysis applied to nuclear fuel performance related to fabrication parameters and experiments

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ABSTRACT

The BACO code for the simulation of the behaviour of a nuclear fuel rod under irradiation could be used as a tool for sensitivity analyses of rod performance according to the different material models being adopted. The behaviour of the Atucha I fuel (a KWU PHWR reactor) is considered as an example of the BACO code capabilities. The results of extreme conditions of operation according with the as-fabricated fuel tolerances and a sensitivity analysis of that situation are included.

INTRODUCTION

Fuel behaviour at the reactor is the result of several materials performing at extreme conditions of temperature, mechanical and chemical solicitation. Fuel design and numerical predictions depend heavily on a realistic modelling that includes the coupling between the different set of phenomena taking place in the fuel, the cladding, the interfaces, and gap spaces. The code BACO version 2.30 models synergistically the thermal and mechanical behaviour of a cylindrical nuclear fuel rod. Our approach is based on using simple models but also based on physically sound ideas and, within the same concept, results are critically examined for consistency. The BACO code is essentially a tool for sensitivity analyses of rod performance according to the different material models being adopted.

The CRP- FUMEX (Co-ordinated Research Project on Fuel Modelling at Extended Burnup) of the IAEA (International Atomic Energy Agency), where Argentina was a participant with BACO, included a second set of calculation referred to sensitivity analysis of calculated parameters around temperature, fission gas release and gas pressure.

The behaviour of the Atucha I fuel (a KWU PHWR reactor) is considered in this paper as an example of the BACO code capabilities. We perform a set of calculations including the results of extreme conditions of operation according with the as-fabricated tolerances of the fuel in order to produce the worst situation under irradiation.

BACO includes a probability analysis within their structure covering uncertainties in input, manufacturing, parameters and models. The influence of some typical fabrication parameters and fuel cycles is analysed. The sensitivity of cladding hoop stress predictions to fabrication tolerance in fuel geometry is studied. To this purpose, 100000 runs were performed with different input data for ours fuels. These were randomly selected within assumed fabrication tolerance for example: pellet diameter and height, inner and outer cladding diameter and pellet density.

ATUCHA I FUEL ROD BEHAVIOUR

The Atucha-I (a Pressure Vessel PHWR) fuel assembly consists of a supporting rod and 36 pre-pressurized, self-standing 600 cm long fuel rods, similar to the PWR rod except for its unusual length and non-enriched UO_2 pellets are used.

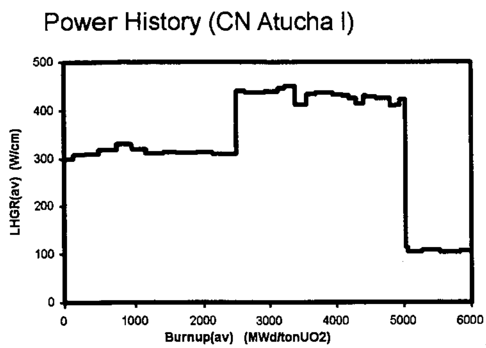

Figure 1: Typical strong power history for the CN Atucha I.

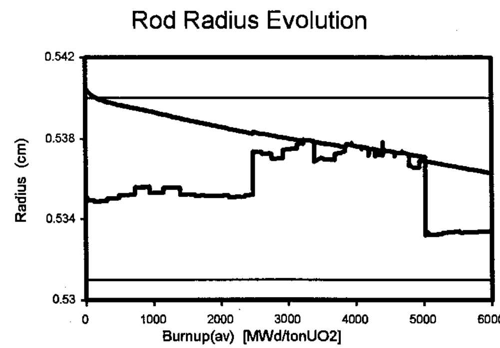

Figure 2: Pellet and cladding radius evolution due to the power history of the Figure 1.

The Figure 1 shows an example of a strong power history for the nuclear power plant of Atucha I where on line reshuffling power ramp could be easily defected. There are two on line reshuffling operations. The calculations made with the BACO code includes the standard parameters of the reactor and the original design of the fuel element. The power history was provided by the PUMA [1] code (neutronic calculation).

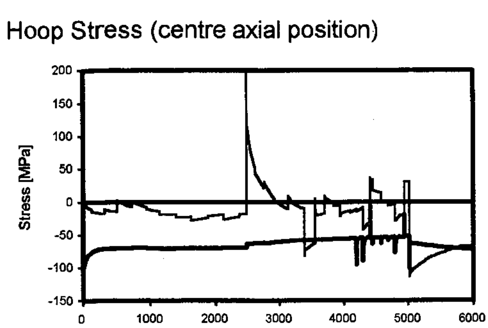

Figure 3: "Hoop stress" at the cladding in the middle of the rod. Standard (thick line) and maximum gap situation (thin line).

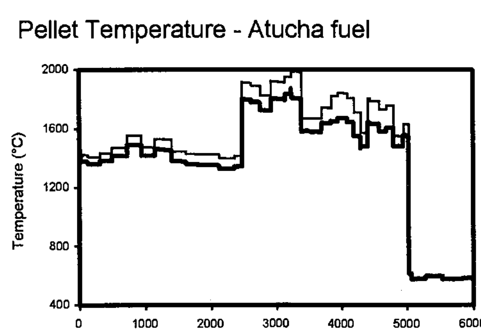

Figure 4: Pellet centre temperature during the irradiation in the middle of the rod. Standard (thick line) and maximum gap situation (thin line).

The Figure 2 includes the evolution of pellet and cladding inner radius at an axial section at the middle of the fuel rod. As a reference , two horizontal lines were included: the same radius at beginning of life (the upper line represents the initial inner radius of the cladding and the other one is the pellet radius). There is a situation of pellet-cladding contact during the irradiation of the second stage (between the two reshuffling operations). The cladding radius decrement is due to "creep down".

The Figure 3 shows the cladding tangential stress at its inner surface ("hoop stress"). Here, there are compression stresses during the irradiation. The same plot shows the curve assuming the hypothesis of minimum gap compatible with the as-fabricated tolerances. Here, there is stress reversal at the cladding during the irradiation and it reach a maximum stress of $\sigma = 180$ MPa during the first reshuffling. That value is slightly up to the threshold to induce failures due to SCC [2, 3].

The Figure 4 shows the temperature at the pellet centre as a function of burnup at the same fuel rod axial section the previous figures. The same plot shows the temperature at the pellet centre with the assumption of maximum gap compatible with the as-fabricated tolerances (thin line).

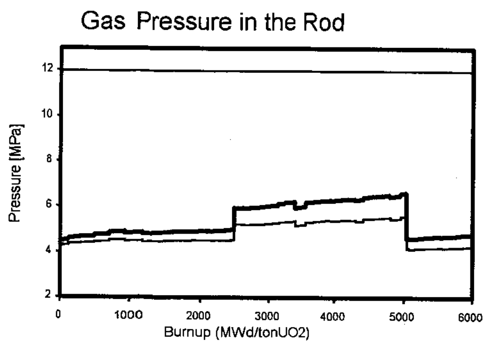

Figure 5: Pressure of the free gases in the inner volume of the fuel and coolant pressure. Standard (thick curve) and maximum gap (thin curve) situations.

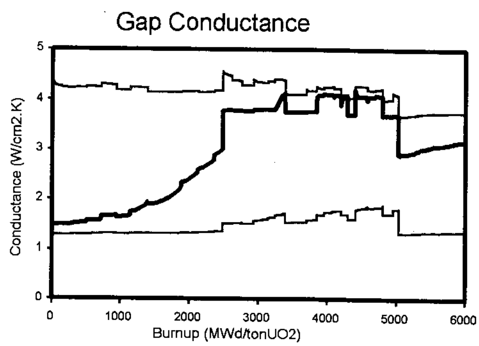

Figure 6: Conductance of the gap at the half position of the fuel rod. Standard (thick curve), minimum gap (upper thin curve) and maximum gap (lower curve) situations.

The Figure 5 represents the pressure gas in the rod due to fission gas release and initial filling gases. The plot includes the standard gap situation (thick curve) and the maximum gap situation (thin curve). As a reference the pressure of the coolant is included (horizontal upper line). The maximum gas pressure is even smaller than the coolant pressure.

The Figure 6 is a representation of the gap conductance in the middle of the fuel rod. There is a direct relation among the conductance, the fission gas release (thermal calculation) and the gap size (dimensional calculation). The minimum gap situation (thin upper curve) produce the best heat transfer between pellet and coolant due to the pellet-cladding contact during the irradiation. The worst heat transfer (thin lower curve) is produced for the continuous open gap due to the initial maximum gap situation. During the first and third stage of irradiation (before the first reshuffling and after the second one) is clearly seen the enhancement of the conductance due to the effect of gap size reduction.

The previous set of figures and calculations illustrates about the wide scope of situations that BACO can solve. The results of BACO are essentially a graphical output. The meaning of that situation is the information are into the Figures. Some examples of that situation is the correspondence between design parameters (UO_2 melting temperature, maximum pressure of free gases into the rod, maximum stresses, etc.) and the plots sketched.

BACO 2.30, like some fuel performance codes include a probability analysis within their structure covering uncertainties in input, fabrication, parameters and models [4]. The influence of some typical fabrication parameters and fuel cycles is analysed in this section. The sensitivity of cladding hoop stress predictions to fabrication tolerance in fuel geometry is studied. To this purpose, 100000 runs were performed with different input data for Atucha I fuel. These were randomly selected within assumed fabrication tolerance for pellet diameter and height, inner and outer diameter of the cladding and pellet density. Table 1 shows the maximum variation allowed for the calculation.

Table 1: Assumed percent of tolerance in as-fabricated fuel parameters

Fuel parameter	as-fabricated tolerance [%]
Pellet diameter	0.9
Pellet height	8.3
Cladding inner diameter	3,7
Cladding outer diameter	4.2
Density	1.4

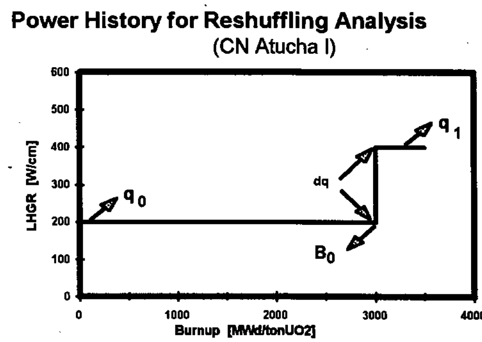

Figure 7: Standard power reshuffling for Atucha I fuel.

The power input sketched in Figure 7 is adopted with $B_0 = 4000$ MWd/tonUO_2, (B_0: Burnup at reshuffling), $q_0 = 400$ W/cm (q_0: preconditioning power) and a ramp of dq = 200 W/cm to reach $q_1 =$ 600 W/cm (the maximum power level for the fuel rod, $q_1 = q_0 + dq$). We calculate the probability that, by varying homogeneously the fuel dimensional parameters within the assumed fabrication tolerances of Table 1, the cladding tensile stress of $\sigma_{SCC} = 170$ MPa [2, 3] being reached during the power ramp.

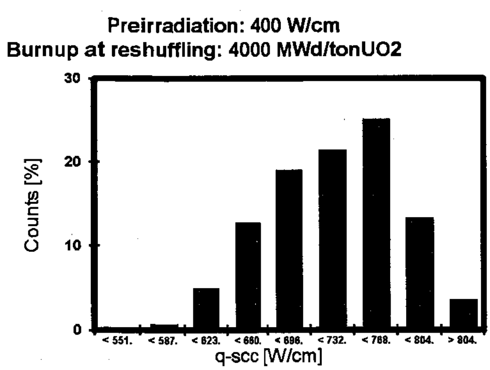

Figure 8: Probability of stress threshold $\sigma_{SCC} = 170$ MPa to be reached during a power ramp dq = 200 W/cm. The probability values are plotted against the range in power difference value q_{SCC} , for which the threshold is predicted to be reached.

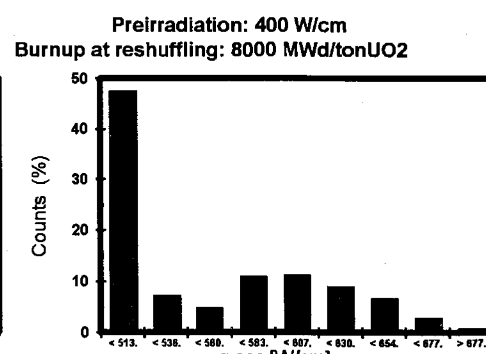

Figure 9: Idem Figure 8, but the burnup at reshuffling is equals to 8000 MWd/tonUO_2. We are using a uniform random distribution of fuel values for BACO input between the as-fabricated tolerance values.

The random selection of input values was done assuming a uniform distribution of values between limits. The random variation of input parameters leads to several thousand runs, where the code calculates the final power q_{SCC} within the ramp, which is needed for attaining the hoop stress value σ_{SCC}.

We obtain that in 5 % of the cases, the threshold value is effectively reached during the ramp. In Figure 8, we plot the relative contribution to that percentage at different values of q_{SCC} (q_{SCC}: final power to reach the SCC threshold, $q_{SCC} = q_0 + dq_{SCC}$) , within the ramp. The plot includes the mean value of the step of the histogram as the x-axe. It can be seen that, the lowest values for dq_{SCC} approach the probability of 5%. The values of the figures with $q_{SCC} \geq 600$ W/cm mean a success operation. For illustration purpose about the probability distribution behaviour we are including the range in power needed to reach σ_{SCC}.

We repeat the above calculation for the same variations in fuel parameters but assuming a higher burnup (8000 MWd/tonU) at the first position of the fuel. In this case (see Figure 9), the prefixed SCC threshold value is attained in 80% of the cases, during the 200 W/cm ramp. It can be seen in Figure 9, that in most cases (50%), this happens right at the start of the ramp (at $dq_{SCC} < 100$ W/cm).

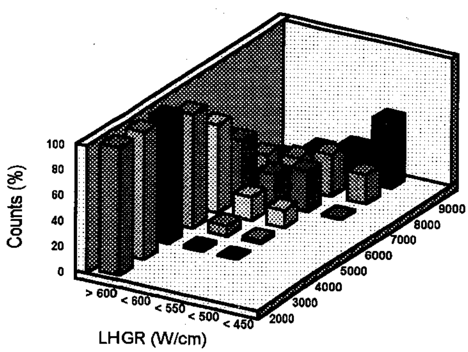

Figure 10: Probability of SCC threshold to be reached at intermediate values q_{SCC} (LHGR in the figure) in a power ramp of $dq = 200$ W/cm and $q_0 = 400$ W/cm.

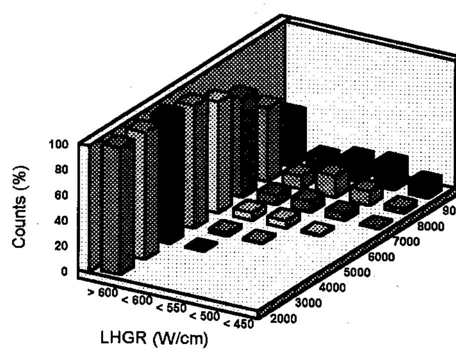

Figure 11: As Figure 10 but preconditioning power is $q_0 = 200$ W/cm.

The 3-D histogram of Figure 10 shows the same kind of probability data reported in the previous Figures 8 and 9, but adding the burnup at reshuffling as a third parameter axis. Here, also, we plot the relative number of cases where the SCC threshold value is attained at the ramp within a value q_{SCC} of power range. Different preconditioning burnups are tried and the corresponding probabilities of reaching the assumed σ_{SCC} (SCC hoop stress threshold) at each of them, also during a ramp of $dq = 200$ W/cm, are plotted. The preconditioning power before reshuffling is q_0=400 W/cm (see Figure 4) and the burnup at reshuffling varies between 2000 MWd/tonUO_2 and 9000 MWd/tonUO_2. The rows of columns corresponding to "> 600" are the successful reshufflings. This value decrease with the burnup B_0 (see plot). The ranges of q_{SCC} values plotted in the figures are: $q_{SCC} < 450$ W/cm ("< 450" in the figure), 450 W/cm $< q_{SCC} <$ 500 W/cm ("< 500" in the figure), ... , 550 W/cm $< q_{SCC} <$ 600 W/cm ("< 600" in the figure), and $q_{SCC} > 600$ W/cm ("> 600" in the figure).

Again, in Figure 11, we plot the probability of reaching the assumed σ_{SCC} at the cladding within a giving power change range, q_{SCC}; now, in a ramp of $dq = 400$ W/cm ($dq_{SCC} \leq 400$ W/cm) and at an initial preconditioning power $q_0 = 200$ W/cm. It can be seen that a larger q_0 value increases the probability of reaching SCC threshold more than a dq ramp larger value. This trend also occurs when the burnup B_0 at reshuffling is increased.

The extension of this analysis is the inclusion of different distribution of probabilities of the parameters included in the BACO code calculations. We analysed two distributions: 1) a Gauss distribution and 2) a Gauss distribution fenced by the tolerances. The standard deviation in both cases is assumed as the as-fabricated tolerances.

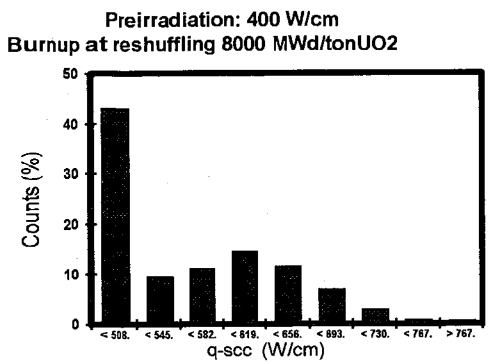

Figure 12: Idem Figure 9, but using a Gauss distribution for fuel data with the tolerance value as the standard deviation.

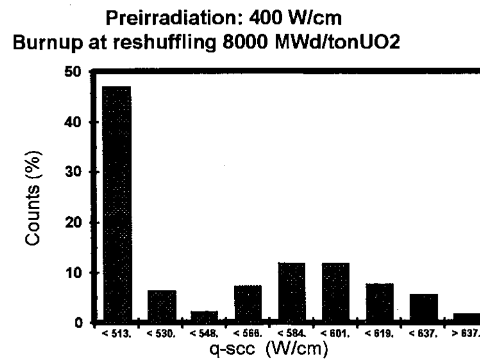

Figure 13: Idem Figure 9, but using a Gauss distribution for fuel data fenced by tolerance values.

The Figure 12 is the relative number of cases where the SCC threshold value is attained at the ramp within a value q_{SCC} of power range, similar to Figure 9 but with a Gauss distribution for the parameters of Table 1. The Figure 13 is a histogram similar to the previous figure by using a Gauss distribution fenced by values of the fuel tolerances. The Figures 14 and 15 are similar to Figure 10 using the previous distributions.

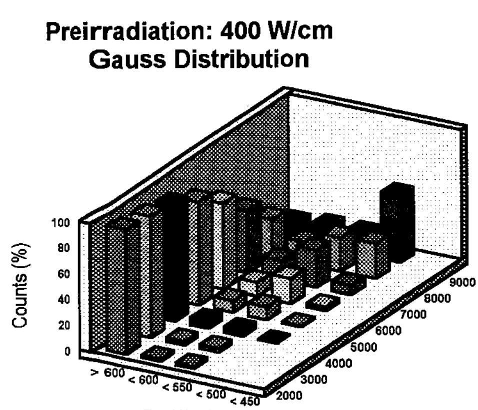

Figure 14: Idem Figure 10 but using a Gauss distribution for fuel data with the tolerance value as the standard deviation.

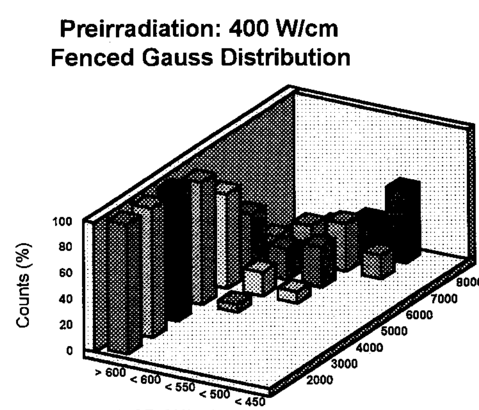

Figure 15: Idem Figure 10, but using a Gauss distribution fenced by tolerance values for fuel data.

The real probability distributions of the parameters included in the BACO code calculation depends of the manufacturing procedures, material behaviour and QA procedures. We are not including: 1) the uncertainty of the neutronic parameters or during irradiation, and 2) the sensibility of the models of material behaviour included in the BACO code. The first point may be treated in the same way that the intrinsic parameters of the rod. The sensibilities of the models must be treated with a carefully description, based on experiments, of the range of validation of each model.

A SECOND ROUND ABOUT ATUCHA I FUEL BEHAVIOUR

The extension of the last analysis is explained with the calculation performed with the Atucha I fuel example of the first section of this paper. The sensitivity analysis applied with the power history of Figure 1 using a uniform distribution produced a set of calculations where the Figure 16 (pellet centre temperature) is an example. We included the standard case and the worst cases (see Figure 4).

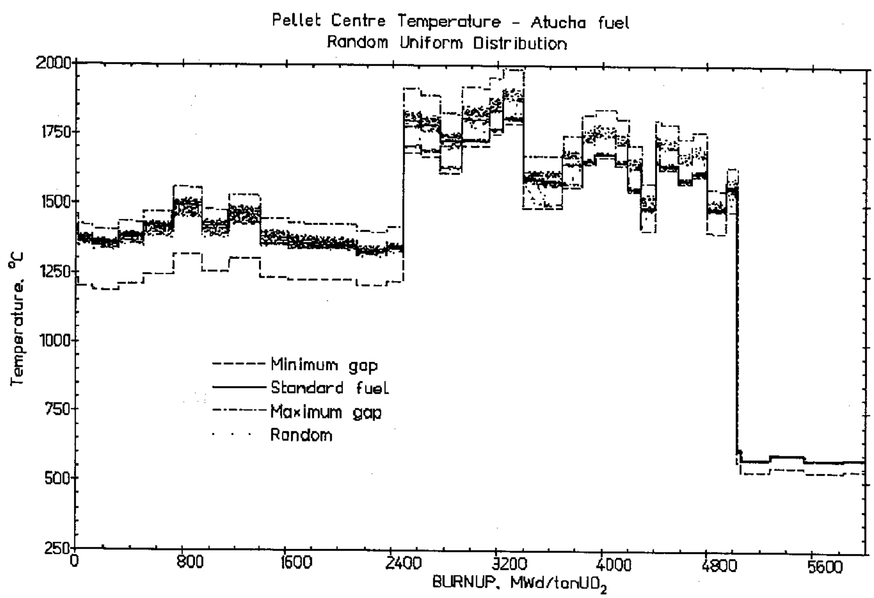

Figure 16: Pellet centre temperature at the half axial section of the fuel.

The two bands of points between the curves of the extreme cases after the first reshuffling are produced taken account if the gap closure was or not at beginning of life (BOL). It is clearly seen the relevance of the knowledge of the real distribution of probabilities of each parameter of the rod and the relation among themselves (i.e., cladding radius and cladding thickness).

CONCLUSIONS

The basic design of fuel elements is evaluated around this point, as we are showing with the Atucha I fuel example. The helpful due to international project as the CRP FUMEX are relevant at this point [5, 6]. We are showing that is not enough a simple running code in order

to simulate the behaviour of a fuel rod. The calculation performed using extreme parameters of the fuel element are relevant.
The SCC criteria for fuel failure used for this calculation is the basis for the developing of a complex model for fuel performance. But, that criterion was enough for the beginning of the understanding of the influence of the fuel tolerances. Further steps of this work include the evaluation of Iodine in the rod and cracks opening.
The sensibility analysis for the Atucha I fuel shows the importance of the distribution probability associated with the fuel rod and reactor parameters. A complete fuel element design must include these patterns of calculations. The sensibility analysis sketched in that point shows that is not enough the study of extreme cases.
We adopt a hoop stress value at the cladding of 170 MPa as a realistic limiting threshold stress that allows SCC to initiate (though, actually, it only results in a progressive deterioration once the proper atmosphere has been attained inside the rod). The reshuffling analysis included in the first section is a statistical complement to the power ramp analysis of the paper of [2].
Using that value of the hoop stress at the cladding proposed above as a limiting value and assuming fixed values for burnup and power increase at reshuffling, the sensitivity of the results to variations in rod geometry design and fabrication parameters can be tested. This exercise shows, on one hand, the sensitivity of the predictions concerning such parameters and, on the other, the potentiality of the BACO code for a probability study. The latter is due to the quick running of the code and to the modular character of the data input and of the numerical and graphical output. The results shown here, have only a qualitative purpose, and are not representative of the variations in the fuel rod fabrication, where the dimensional variations are kept to a narrow band within tolerance.
A probabilistic fuel performance is not independent of the fuel elements parameters distribution. A detailed modelling of fuel failure probability needs a detailed modelling of probability fuel behaviour. A set of specific experiment is relevant during the development of the modelling using sensitivity analysis. An example of BACO code assistance of experimental procedures is include in Reference [7].

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