PROBABILISTIC ASSESSMENT FOR NUCLEAR FUEL RODS BEHAVIOR

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ABSTRACT

BACO is a code for the simulation of the thermo-mechanical and fission gas behavior of a cylindrical fuel rod under operation conditions. Input parameters and, therefore, output ones may include statistical dispersion. In this paper, experimental CANDU fuel rods irradiated at the NRX reactor together with experimental MOX fuel rods and the IAEA'CRP FUMEX cases are used in order to determine the sensitivity of BACO code predictions. We analyze the CARA and CAREM fuel rods relation between predicted performance and statistical dispersion in order of enhanced their original designs. These exercises show the sensitivity of the predictions concerning such parameters and the extended features of the BACO code for a probability study.

1. INTRODUCTION

To get nuclear power generation within safety and economic criteria requires a deep knowledge on fuel behavior under many different situations. The energy production economic might be greatly improved by means of relatively minor corrections on the design, fuel processing and operating conditions any of these requires checking carefully the fuel design. This fact must consider parts performance as well as their in service thermo-mechanical coupling. The classical tool, which has been used to study these coupling, is numerical simulation on computer codes to obtain results quantitatively and even qualitatively valid. Numerical predictions are strongly influence by realistic modeling.

BACO is a code for the simulation of the thermo-mechanical and fission gas behavior phenomena in a cylindrical fuel rod under operation conditions. The 2.40 is the present version of the code. Our modeling approach is based on using simple models, which are however sustained on phenomenological ideas and critical evaluation of their consistency. Input parameters and, therefore, output ones may include statistical dispersion.

To better understanding the uncertainties and their consequences, the mechanistic approach must be augmented by probabilistic analysis. BACO includes a probability analysis within their structure including uncertainties in fuel rod parameters, code parameters and fuel models. These characteristics are emphasized in this paper. They do not only related to fuel rod knowledge and modeling, but can also be applied in safety and economics assessments to define the operation conditions and to asses further developments. BACO has been used for simulating PWR, CANDU, BWR, MOX, and experimental fuel rods. In the same way, it is used for the design of advanced fuels (CARA and CAREM). The code performance was tested against other ones of similar features. BACO has participated in several co-ordinated round robin benchmarks of fuel code predictions against experimental results (D-COM and FUMEX).

Argentina has two nuclear power stations under operation: Atucha-I (a Pressure Vessel PHWR) and Embalse (CANDU 600 type), and one under construction (Atucha II). Basic fuel design is different in both cases. Predicting the thermal and mechanical performance of the CANDU fuel is challenging for computer codes not designed “ad hoc”. One must remember the fuel performance characteristics (collapsible cladding, filling gas pressure, cladding creep down during irradiation, etc.). The CARA Fuel Project [1] and the CAREM Reactor Project [2], where BACO is embedded, require a code with extended burnup and probabilistic capabilities.

2. BACO CODE

The BACO code structure and models in its present versions have already been described by Marino et al. [3], including steady state and transient thermal analysis. Nowadays, the number of instructions is about eleven thousand FORTRAN 90 sentences. Data post-processing improves the code’s performance and analysis of results.

On modeling the UO_2 pellet, elastic deformation, thermal expansion, creep, swelling, densification, restructuring, cracks and fission gas release are included. While for the Zry cladding, the code models elastic deformation, thermal expansion, anisotropic plastic deformation, and creep and growth under irradiation. The modular structure of the code easily allows added of different material properties. It can be used for any geometrical dimensions of cylindrical fuel rods with UO_2 pellets (either compact or hollow, with or without dishing) and Zry cladding.

Fuel rod power history and either cladding or coolant outside temperatures must be given to the program. Rod performance is numerically simulated using finite time steps (finite differential scheme). The code automatically selects time steps according to physical criteria. Temperature profile within pellet and cladding, main stresses at pellet and cladding, radial and axial crack pattern in the pellet, main strains and hot geometry of pellet and cladding, change in porosity, grain size and restructuring of the pellet, fission gas release to the free volume in the rod, trapped gas distribution in the fuel and in the UO_2 grain boundary, internal gas pressure and current composition of the internal gas, dishing shape evolution, are calculated. The output contains the distribution along the rod axis of these variables.

We assume cylindrical symmetry for the fuel rod; our model is bidimensional and angular coordinates are not considered. However, angular dependent phenomenon, as well as radial cracking, is simulated via some angular averaging method. For the numerical modeling the hypotheses of axial symmetry and modified plane strains (constant axial strain) are adopted. The fuel rod is divided in axial sections in order to simulate its axial power profile dependence. The mechanical and thermal treatment and the pellet, cladding and constitutive equations are available from Reference [3].

3. BACO CODE SENSITIVITY ANALISYS

The uncertainties on results of a validated fuel computer code with an experimented user come from many different sources:

1) Input data of the codes:
   a) Neutronic and reactor data,

b) Power history of the irradiation,
c) Fuel data:
   i) Dimensional data
   ii) Material properties
2) Internal data of the code (and code structure):
   a) Code parameters,
   b) Modeling,
      i) Physical constants,
      ii) Parameters of the model,
      iii) Field of application of the model.

Also, we can join these data around the point of view of its influence on the uncertainties:
1) Modeling and its empirical or theoretical parameters,
2) Data provided by direct measures due to in reactor irradiation and fuel test, and
3) Fuel manufacturing data and fuel design data.

We can require best models for our codes and then we solve the first point. We can require best measurements during irradiation, material testing and reactor parameters. That means it is possible an improvement of code results from modeling, reactor and material data.

The same does not happen with the parameters of the fuel due to manufacturing process. The tolerances of fuel dimensions are a consequence of their process and they are sustained by the basic design. Then we must include the treatment of this source of uncertainties.

The first and easy way to analyze these topics is the definition of a set of worst cases. Those cases are the coupling of the variations of fuel parameters taking account the tolerances in order to produce the worst situations (as maximum stress, maximum strains, extreme temperatures, etc.).

Some fuel performance codes include a probability analysis within their structure covering uncertainties in input, fabrication, parameters and models [4, 5, and 6]. The BACO code (version 2.40) includes probabilistic analysis with statistical dispersion of the fuel rod parameters.

A BACO´s probabilistic analysis of power fuel reshuffling have been performed to the Atucha I NPP [7], where we analyze the susceptibility of hoop stress during fuel reshuffling at different powers and burnups. Here we reproduce the recommendation of the designer for fuel reshuffling with simplified rules. The fuel for the Atucha I NPP are analyzed in the Reference [8] and, the fuel for the EMBALSE NPP (CANDU type, Argentina), are analyzed in Reference [9].

We use three different techniques for sensitivity analysis:
1) Extreme cases analysis.
2) Parametric analysis.
3) Probabilistic (or statistical) analysis.

The “extreme cases analysis” consists in the finding which combination of fuel rod parameters their possible extreme values (code input data) produce the worst situation about fuel rod behavior. With this analysis we could define the tolerance of the fuel rod parameters.

The “parametric analysis” is the study of the individual influence of each fuel rod parameter in the fuel rod behavior (temperatures, stresses, deformations, pressures, etc.). With this analysis we find the correct weight of each fuel rod parameter.

The “probabilistic analysis” is a Monte-Carlo technique, which combine several random of fuel parameter (input data) with its statistical distribution. Each probable input data could be a real fuel rod, and the series of M-C calculation have a significant impact on the calculated results.

4. BACO CODE VALIDITY TEST AND PROBABILISTIC APLICATIONS

4.1. CO-ORDINATED RESEARCH PROJECT ON FUEL MODELING AT EXTENDED BURNUP

The IAEA's CRP FUMEX (Co-Ordinated Research Project on Fuel Modeling at Extended Burnup) is a blind-test developed on a set of experiments in order to compare fuel performance with code predictions. The OECD-HALDEN reactor (Norway) provided data. Sets of fuels are

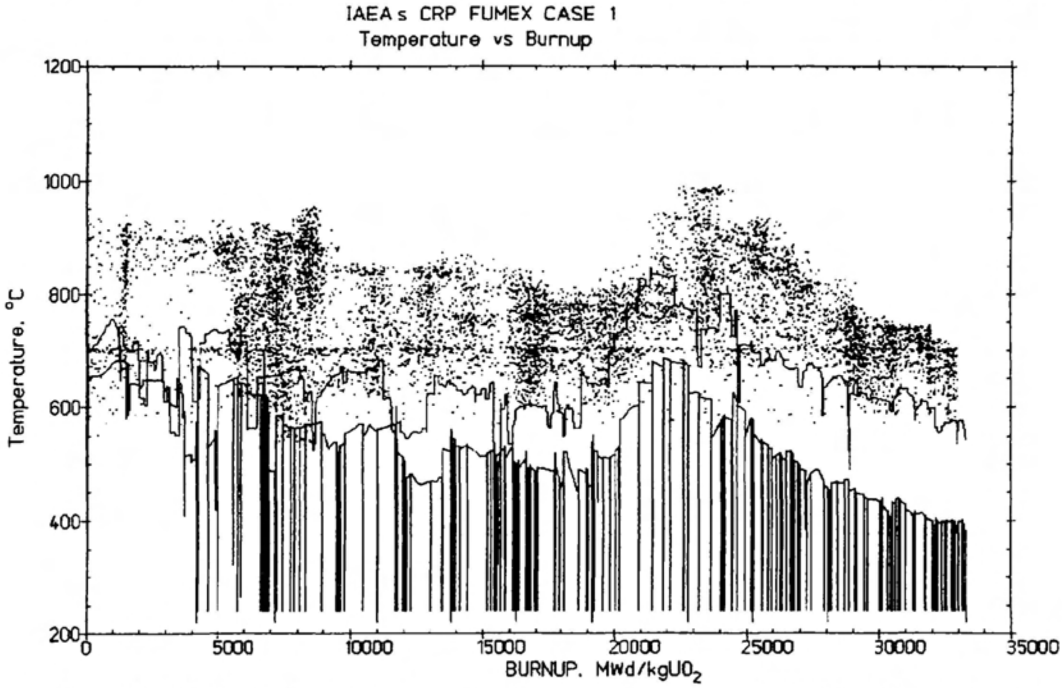

Figure 1: Probabilistic analysis of the pellet center temperature (FUMEX Case 1) including the measurements and the BACO code v2.20 result.

instrumented following the evolution of some parameters (pellet center temperature, inner pressure of the rod, cladding elongation, fission gas release, cladding diameter). The experiments include PIE analysis. The burnup reached for the rods were rods intermediate (25 MWd/kgU) and high (50 MWd/kgU) [10].

As an example of the BACO Code performance during the CRP FUMEX we include some of our results for the first exercises (FUMEX Case 1). The calculated fraction of fission gases released at EOL (End of Life) is 2.2 % (and the predicted value during the "blind test" stage was 2.5 %). The experimental value was 1.8 % (see figure 2). Figure 1 shows the measurement during irradiation of the temperature at the pellet center (filled line) and the BACO calculation before FUMEX revision (filled line with shutdowns). The

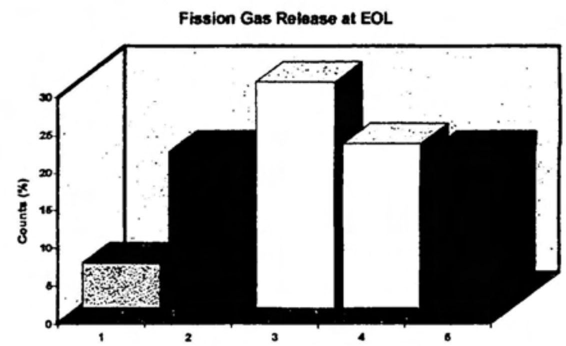

Figure 2: Histogram with the Fission Gas Release at End of Life (EOL) calculated with BACO code 2.40

temperature monitoring was made each fifteen minutes along the irradiation. The measurement uncertainty was ± 50 °C. The probabilistic analysis was done using the present version of the code for the fission gas release and the temperature of the pellet at the thermocouple position (dot lines in Figure 1). The M-C evaluation for the pellet center temperature shows an overpredicted average with a great dispersion not easy to follows due to the big numbers of shutdowns and start-ups.

The Figure 2 shows the histogram with the fission gas release using the dispersion assumed during the CRP FUMEX. The present value of calculation is 2.52 % and a $\sigma = 0.17$ % of fission gas release.

4.2. EXPERIMENTAL IRRADIATION AT THE NRX REACTOR (Notley, 99)

The work reported by Notley [11] was used for testing the BACO code and results reported References [3, 12]. In Notley's work six Zircaloy-sheathed UO_2 fuel elements were irradiated at power outputs between 760 and 600 W/cm to a burnup of about 5500 MWd/tonU. Then both of them and another pair of new rods were irradiated at lower powers for a further 1250-1700 MWd/tonU. The experiment was irradiated in the X-2 loop of NRX reactor. All elements were destructively examined and some of them were measured during the irradiation. The predicted and measured rod radius change $\Delta R/R$, fission gases released, columnar and equiaxed grains and central hole are provided by Notley [11] and calculated with BACO [3, 12].

From the point of view of the codes the couples of rod namely HZB-HZC and HZF-HZZ are identical, but, of course, the fission gas release reported was different. Nevertheless, the probabilistic analysis shows small dispersion for these values (see Table 1).

The discrepancy between measurements and calculation is not explained with probabilistic analysis. We must enhance the fission release model because the Notley's irradiations are close to the limit of validation.

Table 1: Volume of fission gases released. (Units: cm^3 STP)

	HZB	HZC	HZF	HZZ
Vol(gas) [Measure.]	10.6	11.5	17.4	13.7
Vol(gas) [BACO]	7.94		11.12	
σ [BACO]	0.04		0.05	

4.3. MOX de PETTEN

Within our interest on studying MOX fuel performance, the irradiation of the first Argentine prototypes of PHWR MOX fuels began in 1986 with six rods fabricated at the α Facility (CNEA, Argentina). These experiences were made in the HFR-Petten reactor, Holland. The goal of this experience was to study the fuel behavior with respect to PMCI-SCC. An experiment for extended burnup was performed with the last two MOX rods. During the experiment the final test ramp was interrupted due to a failure in the rod. The posirradiation examinations were indicated that PCI-SCC was a mechanism likely to produce the failure [13]. That analysis was predicted with the calculated stresses [14]. The parameters of the MOX irradiation, the preparation of the experiments and post-irradiation analysis were sustained by the BACO code predictions.

4.3.1. "EXTREME CASES" ANALYSIS OF THE MOX FUEL ROD

The purpose of this exercise is considering how the combination of assumed extreme rod dimensions conditions, but within reasonable tolerance for its fabrication, can affect performance. We define two extreme situations:

1) A rod with the largest gap between pellet and cladding compatible with the as-fabricated tolerances, and
2) A rod with the smallest gap.

The first situation should have to rise up the maximum temperature in the fuel, and the second to maximum stress between pellet and cladding.

4.3.2. PROBABILISTIC ANALYSIS OF THE BU15 EXPERIMENT

As said in the Introduction the flexibility of the BACO code and its speed in computer time allows performing systematic statistical analysis. Using allowed fabrication dimensional limits and a statistical distribution of values within those; several runs (a minimum of 1000) are performed with different set of initial values for the rod dimensions [15]. We study the predicted variations in:

1) Pellet center temperature,
2) Cladding hoop stress, and
3) Gas pressure predictions.

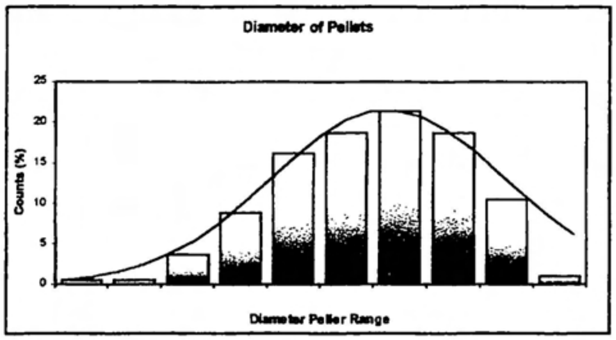

Figure 3: Histogram of the pellet diameters. The columns are between the maximum and minimum specified values [$Ø_p = (1.040 \pm 0.001)$ mm]. The curve is the associated Gauss distribution.

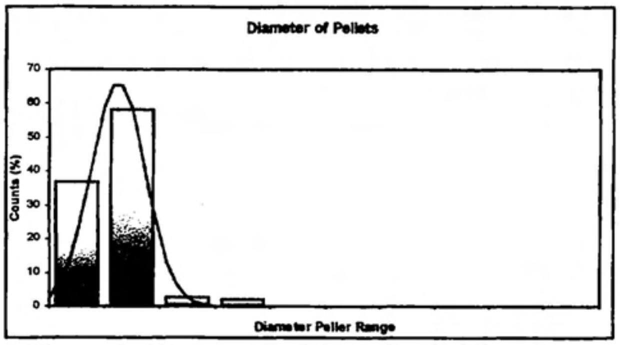

Figure 4: Histogram of the pellet heights. The ten columns are between the maximum and minimum specified values [$h_p = (11. \pm 1.)$ mm]. The curve is an approximated Gauss distribution.

Table 2: MOX fuels irradiated at Petten reactor.
Some statistical parameters of the fuel rods.

Pellets	Main Value (or specification)	Standard Deviation	Minimum Value	Maximum Value
Pellet diameter (cm)	1.0402	0.0005	1.0390	1.0414
Pellet height (cm)	1.1217	0.0204	1.1000	1.3000
Density (gr/cm^3)	10.522	0.048	10.350	10.650
...	...	...	...	...
Cladding				
Cladding inner diameter	1.170 cm	...	1.166	1.174
...	...	...	...	...

The rod input data were randomly selected within assumed deviations for pellet diameter and height, inner and outer diameter of the cladding and pellet density. The random selection of input values was done assuming a Gauss distribution of values between limits. See Table 2 and figures 3 and 4.

The Figures 5 represent the BACO code probabilistic analysis of some performance parameters in the MOX fuel rod A.1.3. We plot in the curves:

1) Standard parameters of input data of the rod, (standard calculation)
2) The parameters of the maximum gap situation, ("extreme case" analysis)
3) The parameters of the minimum gap situation, ("extreme case" analysis) and
4) The points of the Monte-Carlo selection, (probabilistic analysis)

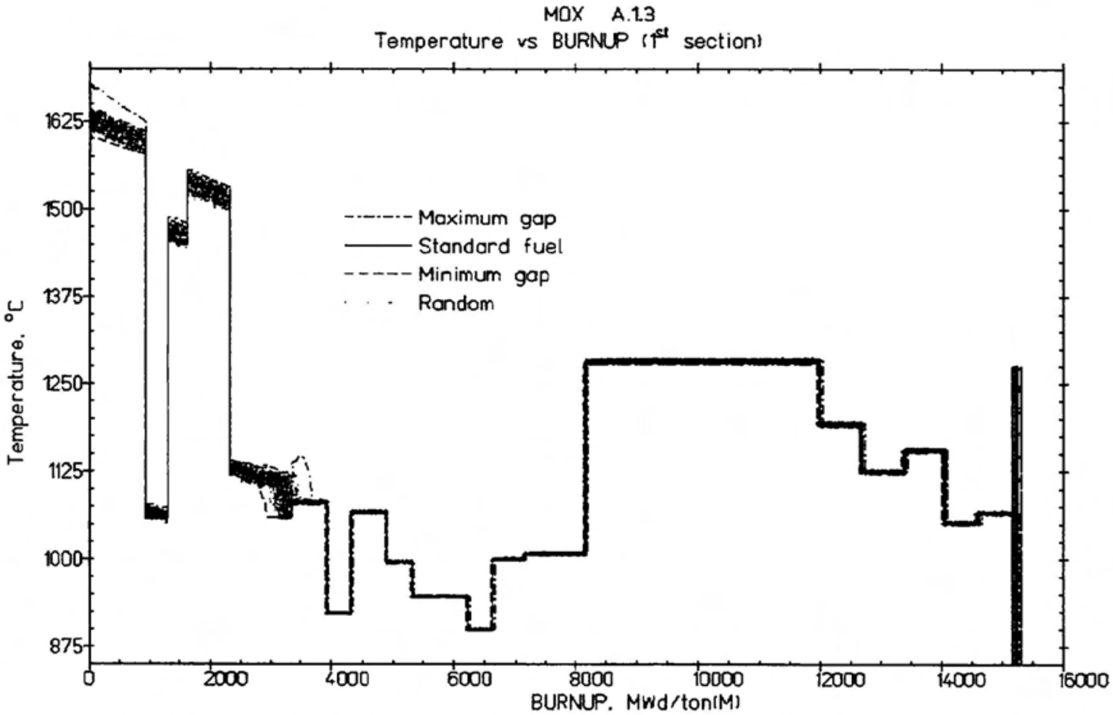

Figure 5: Pellet center temperature in the first segment of the fuel for the BU15 experiment (A.1.3 rod)

Figure 5 includes the pellet center temperature to the maximum gap situation at the bottom of the fuel rod. The largest temperature attained in this case is 1675 °C (while it is of 1600 °C the minimum gap situation). The curves calculated have shown a narrow band due to the strict QA under lab conditions. We obtain a stable solution with all the parameters studied (temperature, stresses, pressures and deformations) [15]. All the random points calculated are between the extreme values in as-fabricated tolerances, taken with approximate realistic values. There is convergence of dots at EOL (End of Life) due to pellet-clad contact. Figure 6 shows a histogram of the pellet center temperature at EOL, after the final ramp.

The cladding hoop stress dispersion with the same inputs as the previous plot show a great dispersion at the middle of life due to the pellet-cladding contact situation. There are points out of the extreme limits of the previous analysis. The calculation shows that the hoop stresses converge during the irradiation that is clearly demonstrated by the small dispersion at EOL previous at the final ramp.

The gas pressure calculation takes account of the thermal calculation, dimensional calculation (stresses), fission gas release, etc. That is the coupling of all fuel rod parameters (input data and behavior modeling). We find a small dispersion at BOL. The calculated values of pressure diverge during irradiation. Finally, after 4000 MWd/ton(M), there are values both smaller and larger than those predicted at the extreme conditions of the "gap" size situation.

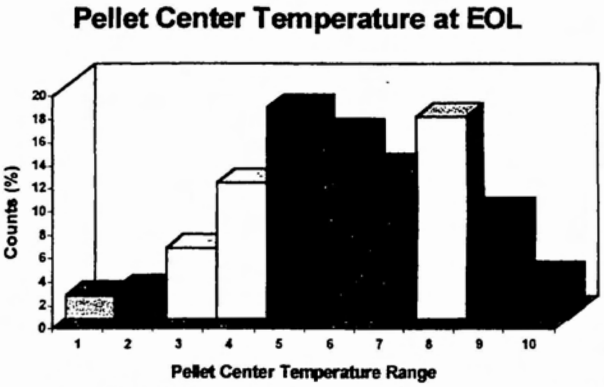

Figure 6: Histogram of the pellet center temperature at End of Life (EOL). The columns are between the maximum and minimum values (1275-1278°C).

5. FUEL ROD DESIGN USING PROBABILISTIC CALCULATION WITH BACO

5.1. CARA FUEL ROD: A PARAMETRIC ANALYSIS APPROACH

An approach to the parametric analysis of a CARA fuel rod is sketched in Figures 7 to 10. We are finding the weight of the different rod parameters in order to identified its right influence on fuel behavior. Figures just include the most significant parameters at the present calculation: pellet radius, UO_2 density, clad inner radius, pellet height and dishing depth. Figure 7 includes the susceptibility with the hoop stress at the inner surface of the cladding during a powerful (and possible) reshuffling during irradiation. The X-axe is between 0 and 1 (minor and mayor values of the parameter). With these results we tune up the parameters and we obtain a new set of parameters with a new response sketched in the Figure 8.

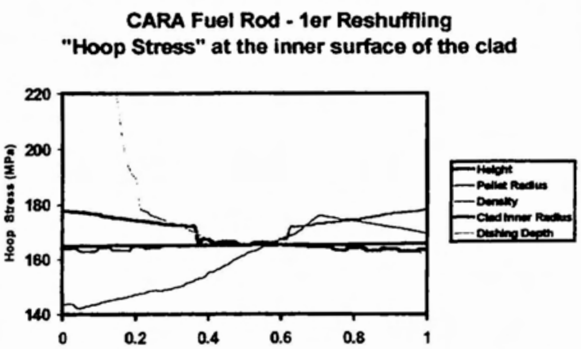

Figure 7: Parametric analysis of the susceptibility on the "hoop stress" at the inner surface of the cladding of a CARA fuel rod.

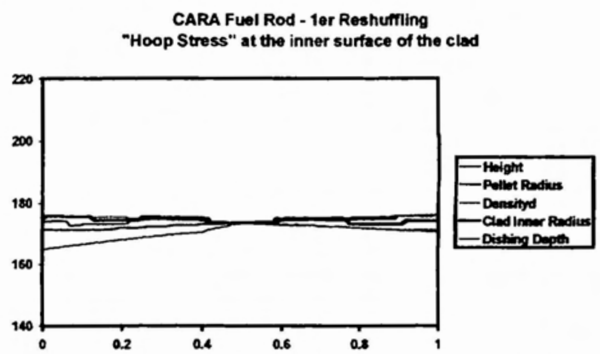

Figure 8: Parametric analysis of the susceptibility on the "hoop stress" after tuning parameters of the CARA fuel.

In Figure 9 we analyze the response around the pellet center temperature of the same parameters during a powerful ramp at beginning of life (BOL). The lowest UO_2 density produces the highest temperatures due to densification. (Densification increases the gap pellet-cladding, so reduce the conductance increasing the temperature.)

The pellet reaches its minimum temperature when the pellet or the inner clad diameters have the smallest gap. Nevertheless, we lost the handicap of these particular diameters when we execute the corresponding analysis of the "hoop stress". Those diameters reach the highest stresses on the cladding. That stresses are incompatible with safety margins for the cladding.

We repeat the calculation of susceptibility with many different stresses, pressures, deformations, temperatures, etc. under different irradiation conditions. This procedure allows obtain a deep knowledge of the influence of each individual parameter into the fuel behavior. The Figures 8 and 10 show the new calculation after tuning the parameter of the CARA fuel.

At present, due to this analysis some of the main parameters of the CARA fuel rod are pellet radius, dishing depth and clad inner radius. Dishing radius and density of UO_2 were significant. Volume plenum and pellet heights were not negligible. Finally, the rest of parameters were negligible or they are out of the scope of the BACO code.

These calculations enable us to determine the first appreciation of values of parameters and its extreme values (or as-fabricated tolerances).

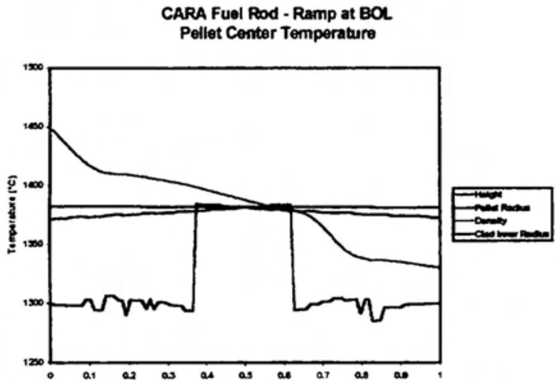

Figure 9: Parametric analysis of the susceptibility on the pellet center temperature of a CARA fuel rod.

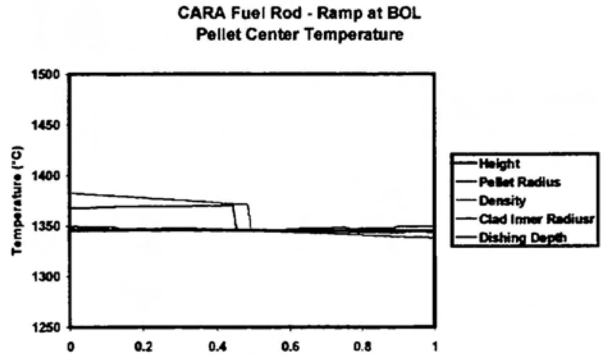

Figure 10: Parametric analysis of the susceptibility on the pellet center temperature after tuning parameters of the CARA fuel.

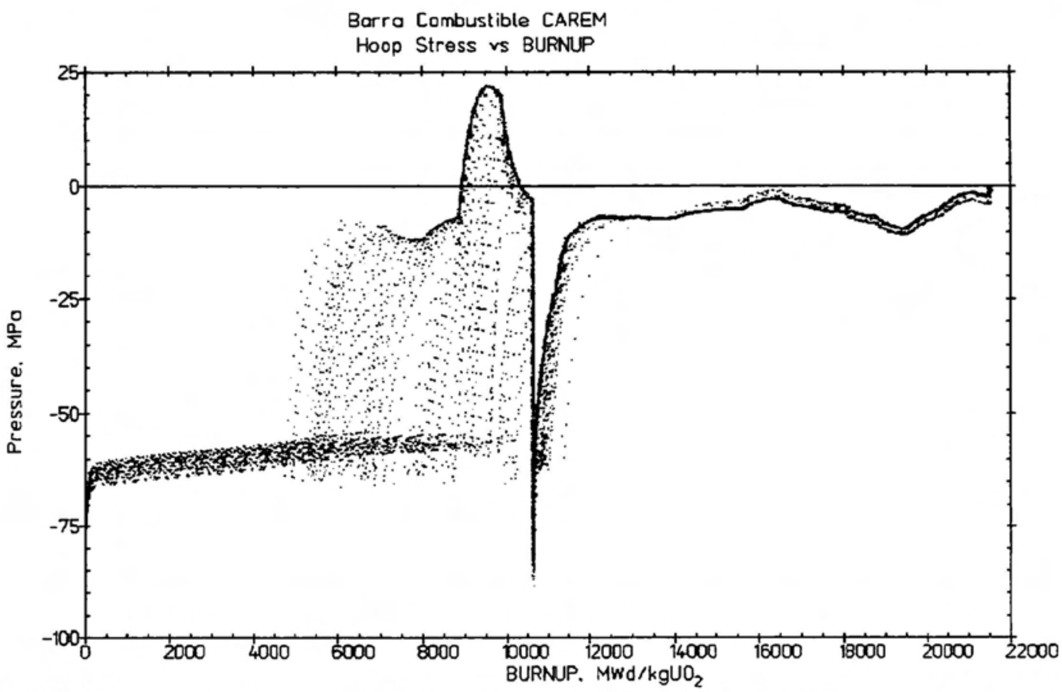

Figure 11: Probabilistic analysis for the "hoop stress" of a CAREM fuel rod.

5.2. CAREM FUEL ROD: A PROBABILISTIC ANALYSIS APPROACH

A probabilistic analysis could be performed without the above calculations with the BACO code. Nevertheless the computational cost of the Monte-Carlo calculation can be reduced when the influence of the parameters had been tested. We present the first probabilistic results with the fuel rod for the CAREM reactor after a wide set of "parametric analysis".

The Figure 20 shows the "hoop stress" for that fuel at the most demanding position into the core. We find conservative curves in all the calculations. Further study could analyze the influence in the behavior of the stress reversal at the maximum power during irradiation or the increment of the dispersion with burnup of the gas pressure. More calculations and feedback with the CAREM Reactor design group will converge in a set of conservative parameters for this new fuel.

6. CONCLUSIONS

The schedule sketched in this paper begins with a validated code for the simulation of the fuel rod behavior under irradiation, almost for the internal use in the institution. The helpful due to international project as the CRP FUMEX are relevant at this point. An example of institutional benchmarking of the BACO code was presented with the NRX irradiation. Here we show that the sensitivity analysis could not be enough to understand the discrepancies between experiments and modeling. A MOX fuel rod failure due to PCI-SCC was presented. The BACO code was a computing tool during all the stages of the experiments. The original scope of the MOX irradiation was the correct research, developing and manufacturing of MOX fuels in the α Facility (CNEA).

We are showing that is not enough a simple running code in order to simulate the behavior of a fuel rod. "Parametric analysis" and "extreme cases" calculations must be done. But the analysis sketched shows that is not enough the study of that cases. The smallest dispersion found in the selected parameter (temperature, hoop stress and gas pressure) is due to the QA procedures into the laboratories. Nevertheless, it is easy to see that the probability distributions of the fuel rod parameters must be known and statistical analysis must be included in order to follows the correct influence of the manufacturing QA procedure of fuel elements. A complete fuel element design must consider the dispersion in rod dimensions due to fabrication. Changes in the design of rod in 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 probabilistic study. The modular structure of the BACO code and its detailed coupling of thermo-mechanical and irradiation-induced phenomena become it in a powerful tool for the prediction of the influence of material properties on the fuel rod performance and integrity.

7. ACKNOWLEDGEMENTS

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