Probabilistic Safety Criteria On High Burnup HWR Fuels

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Abstract

BACO is a code for the simulation of the thermo-mechanical and fission gas behaviour of a cylindrical fuel rod under operation conditions. Their 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. The techniques for sensitivity analysis defined in BACO are: the "extreme case analysis", the "parametric analysis" and the "probabilistic (or statistics) analysis". We analyse the CARA and CAREM fuel rods relation between predicted performance and statistical dispersion in order of enhanced their original designs taking account probabilistic safety criteria and using the BACO's sensitivity analysis.

1. INTRODUCTION

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

BACO is a code for the simulation of the thermo-mechanical and fission gas behaviour phenomena in a cylindrical fuel rod under operation conditions. The 2.40 is the present version of the code. Our modelling 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 probabilistic analysis within their structure including uncertainties in fuel rod parameters, code parameters and fuel models. These characteristics are emphasised in this paper. They do not only related to fuel rod knowledge and modelling, 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 another 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", from 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 HWR 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 modelling the UO_2 pellet phenomena, such as 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 azimutal symmetry in cylindrical coordinates 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 modelling 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) Modelling,

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) Modelling 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 modelling, 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 analyse 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 (such as maximum stress, maximum strains, extreme temperatures, etc.).

Several 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 analyse 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 analysed in the Reference [8] and, the fuel for the EMBALSE NPP (CANDU type, Argentina), are analysed 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 finding which combination of fuel rod parameters their possible extreme values (code input data) produce the worst situation about fuel rod behaviour. With this analysis we could define the tolerance of the fuel rod parameters. This technique is the first step in order to define the as-fabricated tolerances of the fuel element.

The "parametric analysis" is the study of the individual influence of each fuel rod parameter in the fuel rod behaviour (temperatures, stresses, deformations, pressures, etc.). With this analysis we find the correct weight of each fuel rod parameter in order to understand the fuel behaviour with a far and wide scope. This technique is the second step in order to tune the as-fabricated tolerances with an engineering overview specially when we are designing fuel elements.

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 Modelling 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. A set of fuels are instrumented following the evolution of some parameters (pellet centre temperature, inner pressure of the rod, cladding elongation, fission gas release, cladding diameter). The experiments include PIE (post-irradiation) analysis. The final burnup reached for the rods were intermediate (25 MWd/kgU) and high (50 MWd/kgU) [10, 11].

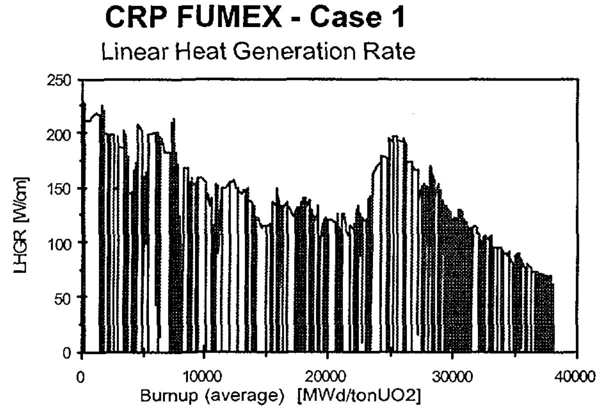

Figure 1: Linear Heat Generation Rate (power history) as a function of the averaged burnup of the fuel rod.

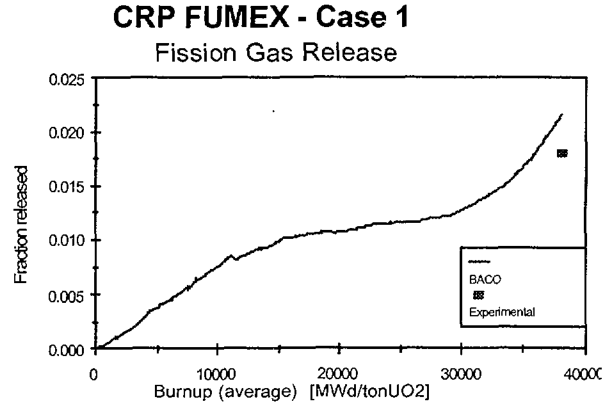

Figure 2: Fraction of fission gas released as a function of averaged burnup of the fuel rod. BACO code version 2.20 (before FUMEX version).

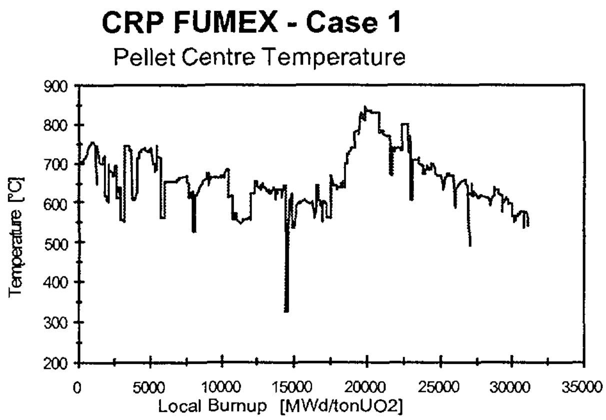

Figure 3: Pellet centre temperature. CRP FUMEX Case 1. "On line" temperature measured at the OECD Halden Reactor.

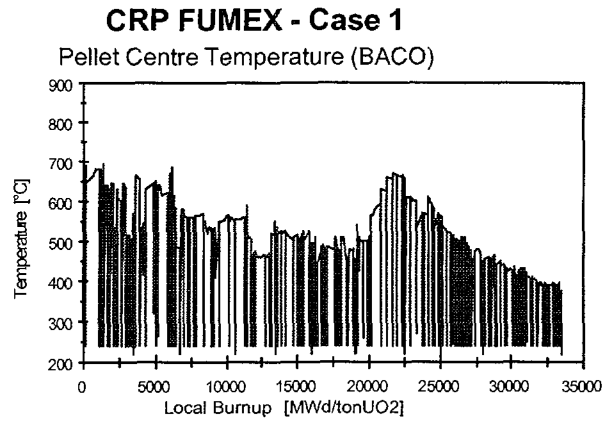

Figure 4: BACO output for the pellet centre temperature. CRP FUMEX Case 1. BACO code version 2.20 (before FUMEX version).

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 figure 1 shows the power history (input data) for that case. 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 3 shows the measurement during irradiation of the temperature at the pellet centre (top of the nuclear fuel rod). The temperature monitoring was made each fifteen minutes along the irradiation. The measurement uncertainty was ± 50 °C. Figure 4 includes the BACO code calculation [12]. The CRP FUMEX case 1 looks equivalent as the fuel for the CAREM Reactor [2].

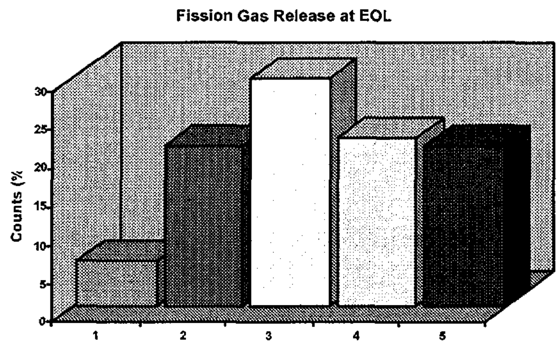

Figure 5: Histogram with the Fission Gas Release at End of Life (EOL) calculated with BACO code 2.40

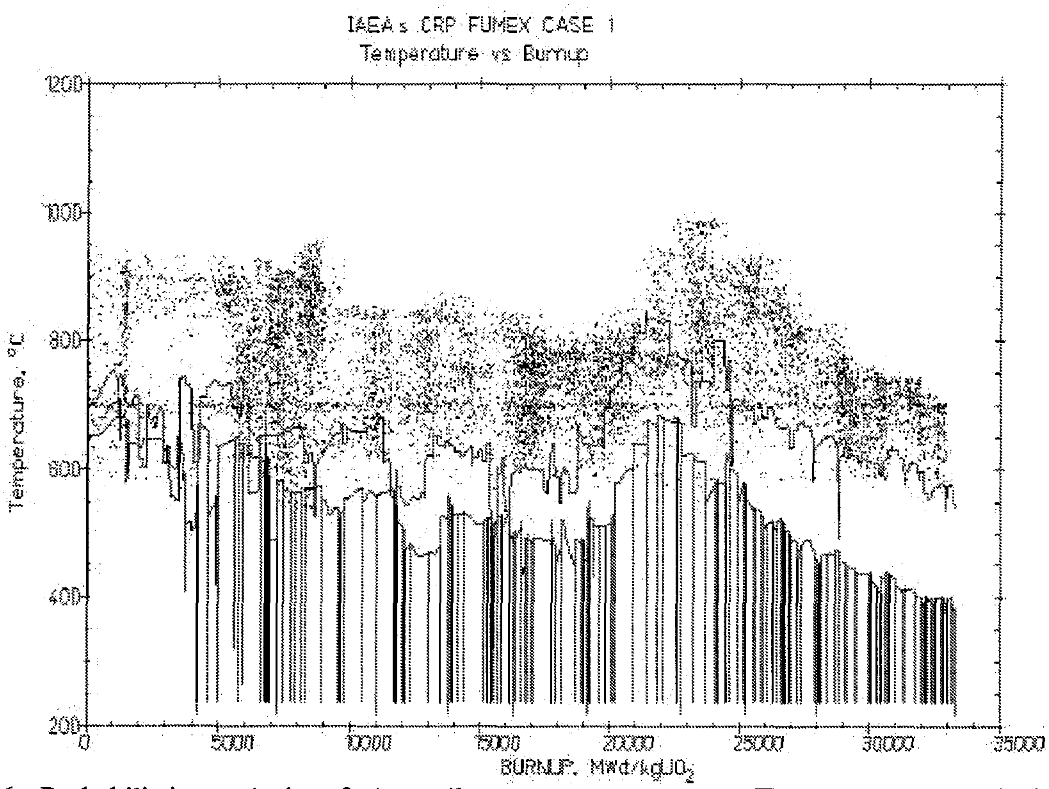

Figure 6: Probabilistic analysis of the pellet centre temperature (FUMEX Case 1) including the measurements and the BACO code v2.20 result.

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. The Figure 5 shows the histogram with the fission gas release. The Figure 6 shows the M-C evaluation for the pellet centre temperature. The curves calculated (dot lines) shows an overpredicted average with a great dispersion not easy to follows due to the big numbers of shutdowns and start-ups. We are using the uncertainties assumed during the CRP FUMEX (± 5 % uncertainty in power, ±5 μm in initial gap and ± 5 % in UO_2 thermal conductivity) [11]. Here we are introducing the coupling of uncertainties due to irradiation data, as-fabricated tolerance and modelling. The same calculation produces a very small dispersion if we take accounts just the as-fabricated tolerance in the gap.

4.2. EXPERIMENTAL IRRADIATION AT THE NRX REACTOR (Notley, 1980)

The work reported by Notley [13] was used for testing the BACO code and results reported References [3, 14]. 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 ΔR/R, fission gases released, columnar and equiaxed grains and central hole are provided by Notley [13] and calculated with BACO [3, 14].

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) [Experimental.]	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 behaviour 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 [15]. That analysis was predicted with the calculated stresses [16]. 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. In this case 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.

For the same power history of figure 7, figure 10 includes the pellet centre temperature to the maximum gap situation at the bottom of the fuel rod. The largest temperature attained in this case is 1675 °C (against 1600 °C for the minimum gap situation). Figure 12 includes the BACO calculation of hoop stress with a minimum gap situation. Here we have not seen a big change; the wide range between both situation at the middle of life is due to the hard contact happens. The curves calculated have shown a narrow band due to the strict QA under lab conditions. We obtain a stable solution, with the three parameters mentioned, which probes that the BACO code is a good tool to be used for fuel rod design.

4.3.2. PROBABILISTIC ANALYSIS OF THE BU15 EXPERIMENT

As it was noted in the Introduction, the flexibility and computer time saving capabilities of the BACO code 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.

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 limited with maximum and minimum values. See Table 2 and figures 8 and 9.

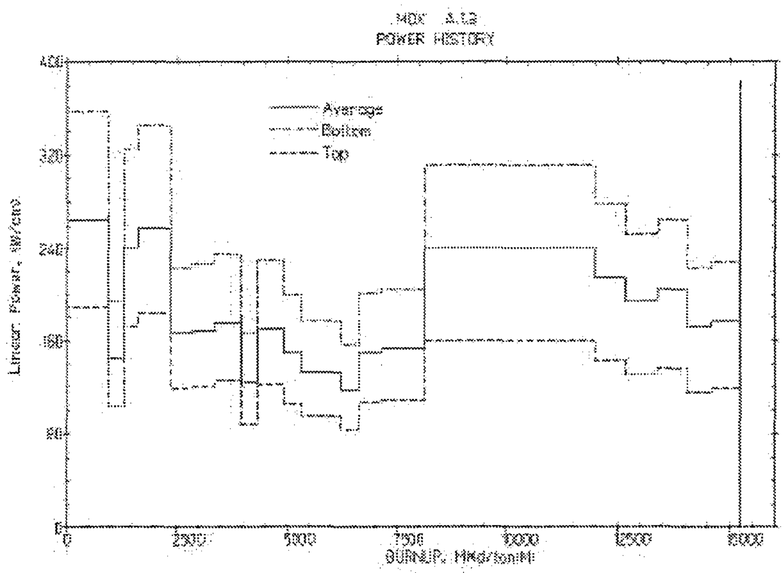

Figure 7: Linear heat generation rate in function of burnup for the A.1.3 fuel rod. The curve upper curve correspond with the top of the fuel, the lower curve correspond with the defective zone of the rod. The maximum during the last power ramp corresponds with the "bottom" of the rod.

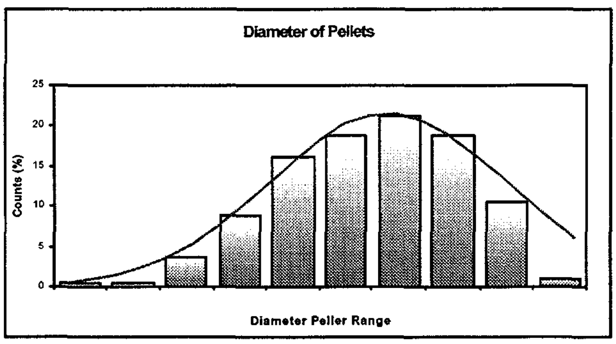

Figure 8: Histogram of the pellet diameters. The columns are between the maximum and minimum specified values [$\varnothing_p = (1.040 \pm 0.001)$ mm]. The curve is the associated Gauss distribution.

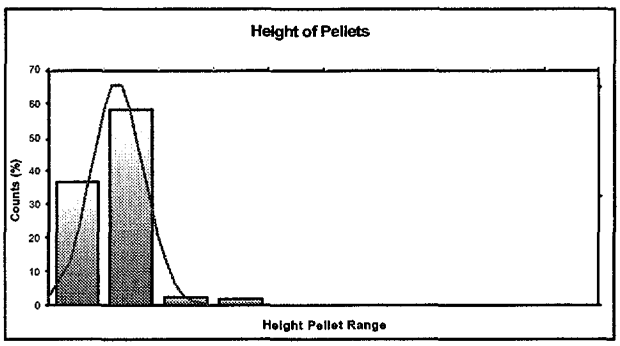

Figure 9: Histogram of the pellet heights. The ten columns are between the maximum and minimum specified values [$h_p = (11. \pm 1.)$ mm]. The curve is an approximated Gauss distribution.

The Figures 10, 12 and 14 represent the BACO code sensitivity 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,
2) The parameters of the maximum gap situation,

3) The parameters of the minimum gap situation, and
4) The points of the Monte-Carlo selection (probabilistic analysis).

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
...	...	...	...	...

Figure 10 is the BACO code calculation for the pellet centre temperature to the same previous history of Figure 1. 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 11 shows a histogram of the pellet centre temperature at EOL, after the final ramp.

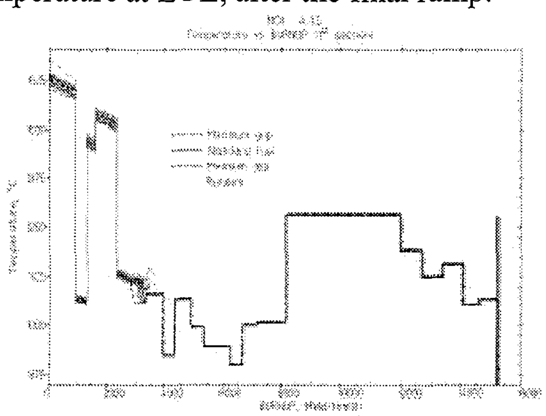

Figure 10: Pellet centre temperature in the first segment of the fuel for the BU15 experiment (A.1.3 rod)

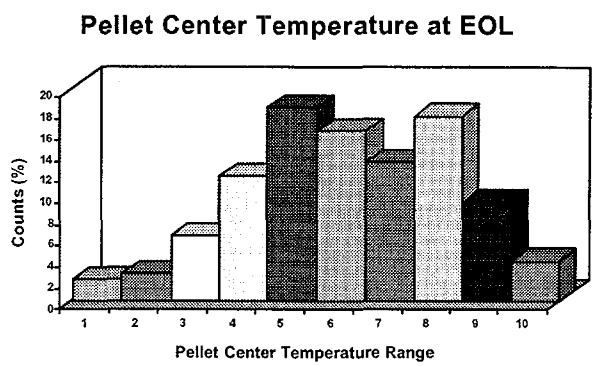

Figure 11: Histogram of the pellet centre temperature at End of Life (EOL). The columns are between the maximum and minimum calculated values (1275-1278°C).

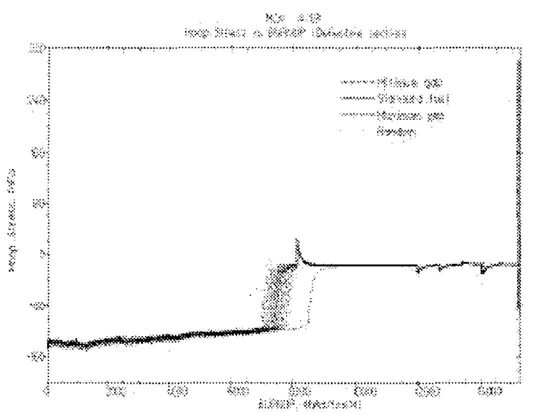

Figure 12: Hoop stress at the defective segment of the fuel rod for the BU15 experiment (A.1.3 rod)

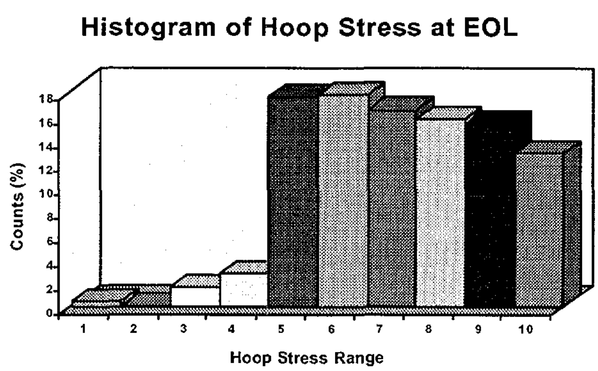

Figure 13: Histogram of the hoop stress at End of Life (EOL). The columns are between the maximum and minimum calculated values (292-302 MPa).

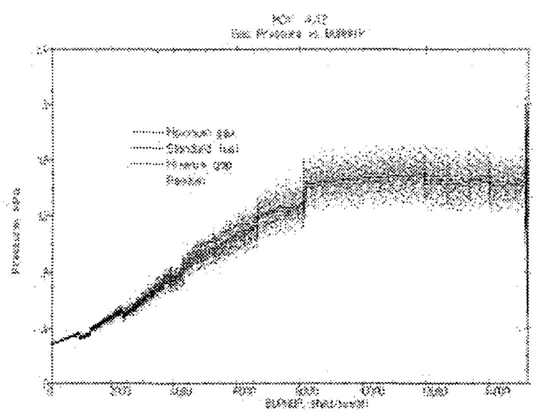

Figure 14: Gas pressure of the free gases in the fuel rod for the BU15 experiment (A.1.3 rod)

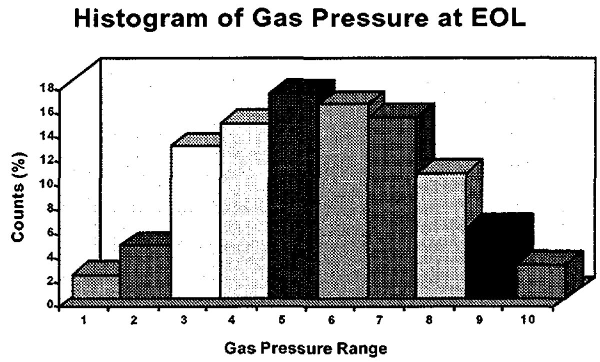

Figure 15: Histogram of the gas pressure of the free gases in the rod at End of Life (EOL). The columns are between the maximum and minimum calculated values (1.60-2.07 MPa).

Figure 12 shows the cladding hoop stress dispersion with the same inputs as the previous plot. The points 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 (see figure 13).

Figure 14 is the free gas pressure at the fuel rod. 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 behaviour modelling). There is 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 15 is a histogram of the rod gas pressure of the free gases at EOL. The main value agrees with the one calculated for the standard fuel parameters.

The laboratory condition produces a narrow dispersion due to the adjustment, tuning and QA of the fuel rod parameters, as well as, the irradiation conditions. Nevertheless, the standard calculation and the "extreme case analysis" do not reproduce exactly the fuel behaviour.

5. FUEL ROD DESIGN USING PROBABILISTIC SAFETY CRITERIA. CALCULATION WITH BACO CODE.

5.1. CANDU and ATUCHA I FUEL ROD SENSITIVITY ANALYSIS

A sensitivity analysis of a CANDU fuel is detailed in Reference [9]. And, for the Atucha I fuel, in the Reference [8]. The main finding of sensitivity analysis calculation, when we are focussed in the pellet centre temperature, cladding hoop stress and gas pressure (due to illustrative purposes), are:

1) Random temperature curves are between "extreme limits" curves.
2) There are some curves of cladding hoop stress either smaller or greater than the "extreme limits".
3) Great dispersion at the starting of the irradiation for cladding hoop stress.
4) The cladding hoop stress curves converge with the burnup.
5) There are gas pressure curves either smaller or greater than the "extreme limits".
6) The dispersion of the pressure of free gases increases with the burnup.

"Extreme case analysis" was the aim of their original designs. The sensitivity analysis applied on a very well known fuel conduct us to conservative curves. Nevertheless, we find several suggestions about the fuel operation when SEU is done in Atucha I [8, 18, and 19].

5.2. CARA FUEL ROD: A PARAMETRIC ANALYSIS APPROACH

An approach to the parametric analysis of a CARA fuel rod is sketched in Figures 16 to 19. We are finding the weight of the different rod parameters in order to identified its proper influence on fuel behaviour. Figures just include the most significant parameters at the present calculation: pellet radius, UO_2 density, clad inner radius, pellet height and dishing depth.

In Figure 16 we analyse the response about the pellet centre temperature during a powerful ramp at beginning of life (BOL). The X-axe is between 0 and 1 (minor and mayor values of the parameter). 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.)

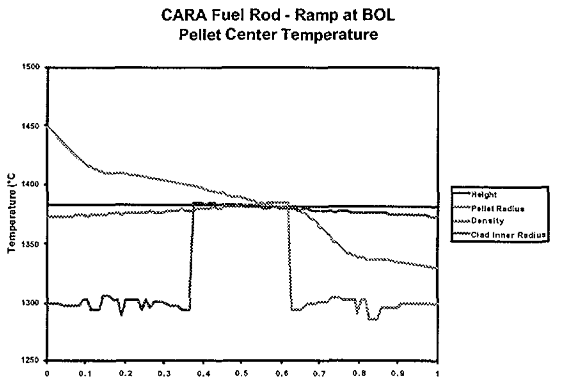

Figure 16: Parametric analysis of the susceptibility on the pellet centre temperature of a CARA fuel rod.

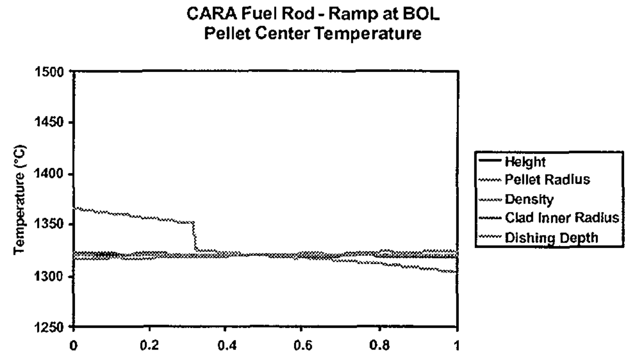

Figure 17: Parametric analysis of the susceptibility on the pellet centre temperature after tuning parameters of the CARA fuel and "feedback" with the manufacturer.

Figure 18 includes the susceptibility with the hoop stress at the inner surface of the cladding during a powerful (and possible) reshuffling during irradiation. Figures 16 and 18 are the "parametric analysis" after "extreme case analysis".

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 integrity.

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 behaviour.

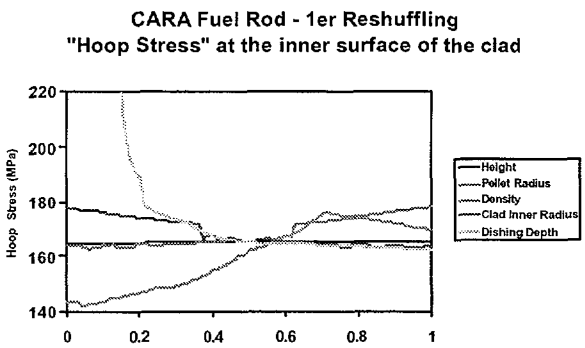

Figure 18: Parametric analysis of the susceptibility on the "hoop stress" at the inner surface of the cladding of a CARA fuel rod.

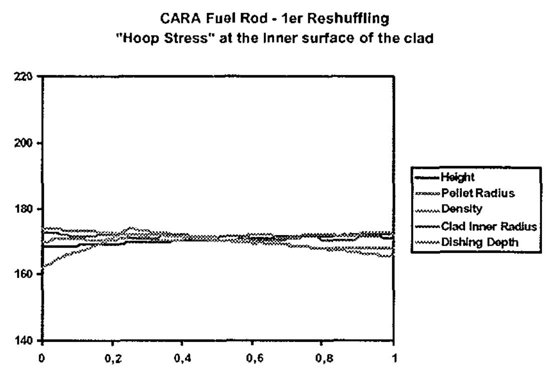

Figure 19: Parametric analysis of the susceptibility on the "hoop stress" after tuning parameters of the CARA fuel and "feedback" with the manufacturer.

With these results we tune up the parameters and we obtain a new set of parameters with a new response. The Figures 17, 19 and 20.b show the new calculation after tuning the parameter of the CARA fuel and including "feedback" with the manufacturer.

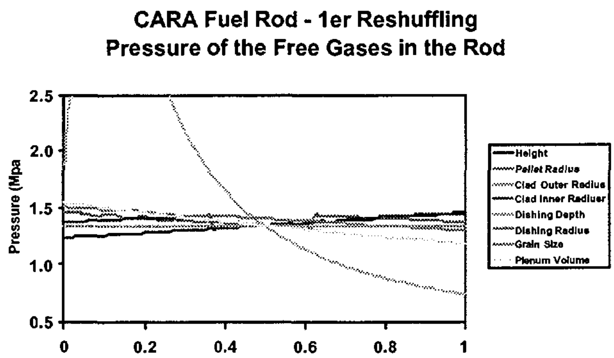

Figure 20.a: Parametric analysis of the susceptibility on the gas pressure of the free gases.

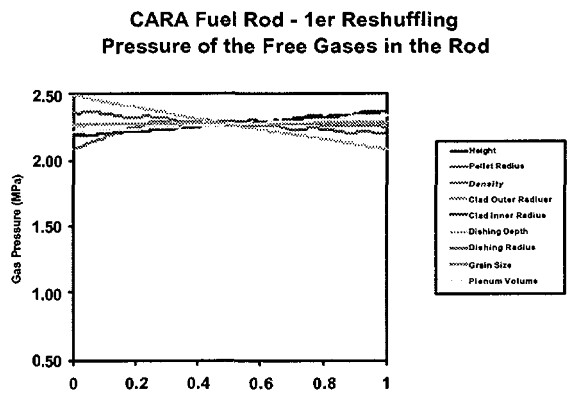

Figure 20.b: Parametric analysis of the susceptibility on the gas pressure of the free gases after tuning parameters of the CARA fuel and "feedback" with the manufacturer.

A realistic definition of some results could be an increment of its values. Nevertheless, those increments produce a stable solution within safety levels. These are the output shown in Figures 20.a and 20.b (gas pressure of the free gases in the fuel rod).

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) with an engineering point of view.

5.3. 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 21.a shows the pellet centre temperature for that fuel at the most demanding position into the core. The same happens with Figure 22.a for the "hoop stress" and Figure 23.a for the pressure of the filling gases (plus released gases during irradiation). We find conservative curves in the three plots. The Figures 21.b, 22.b and 23.b includes the average curve, the curve of the standard calculation and the curves of the average plus and less the standard deviation.

The temperature calculation shows a small dispersion during irradiation and converges of curves at EOL (End of Life). The average (of the random calculation) curve and the standard curve look equivalent (See Figures 21.a and 21.b).

The "hoop stress" calculation (Figures 22.a and 22.b) shows a great dispersion between 6000 and 14000 MWd/tonUO_2. This situation is emphasised in the Figure 22.b; here there is a strong difference between average curve and standard curve and a wide field between the curves plus and less deviation. The average curve does not reproduce a real situation. That curve is included with illustrative purposes. Nevertheless, the appearance of an increment of the dispersion of the curves could be the key to understand this kind of situation. The different size of gap pellet-cladding at BOL (Beginning of Life) produce the contact at different time. The coupling of results with and without contact is the responsible of that increment of dispersion. An equivalent analysis can not be reproduced with the calculation of gas pressure of the free gases. The increment of the dispersion is not easy to explain due to the coupling of all the process during irradiation were the gases pressure calculation is embedded.

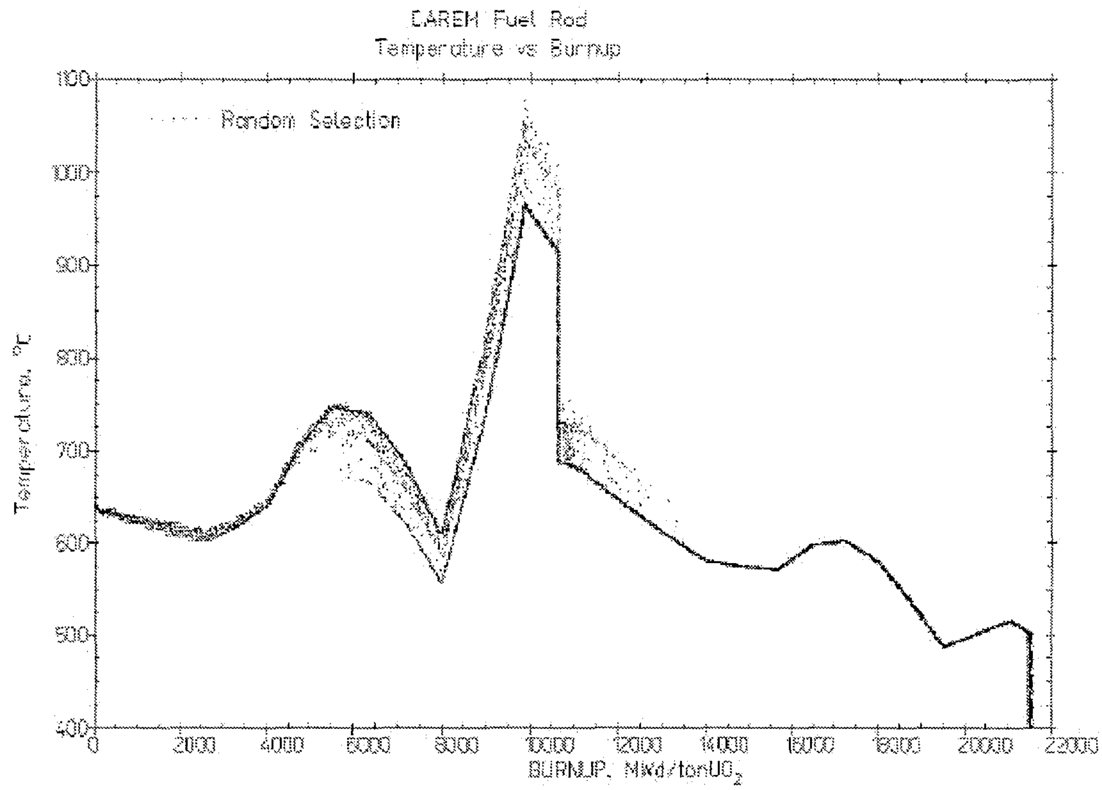

Figure 21.a: Probabilistic analysis for the pellet centre temperature of a CAREM fuel rod.

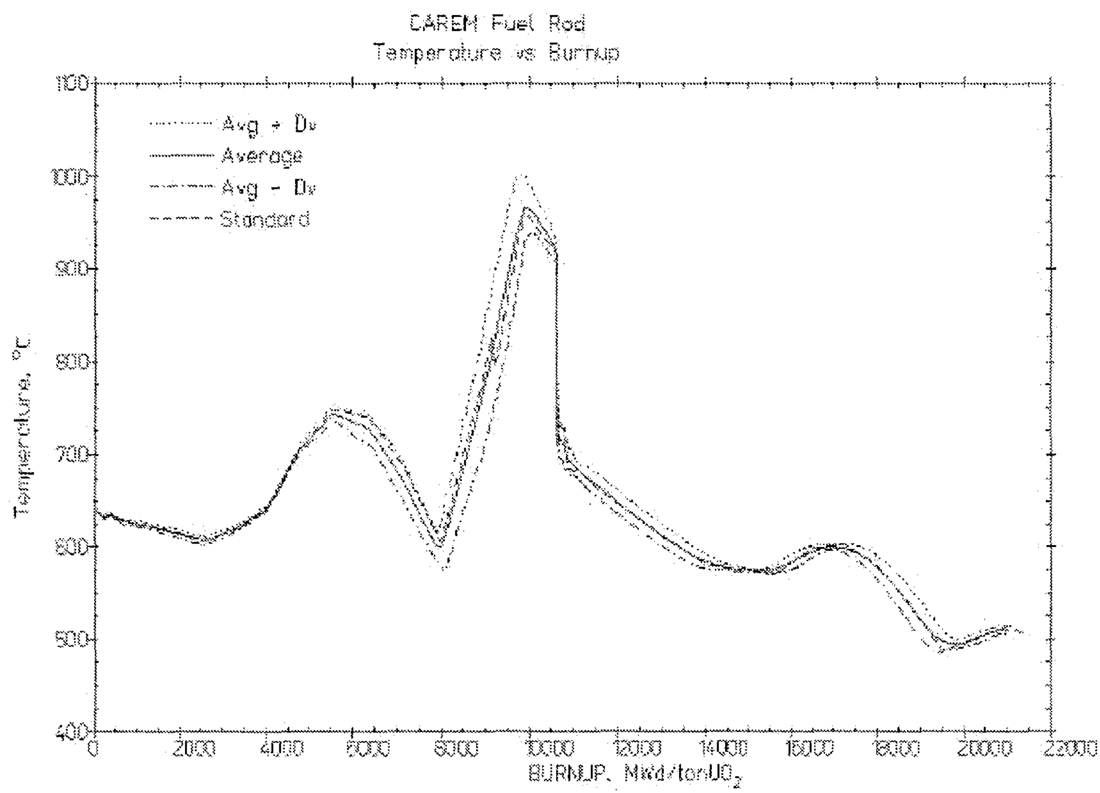

Figure 21.b: Probabilistic analysis for the pellet centre temperature of a CAREM fuel rod.

Further study could analyse the influence in the behaviour of the stress reversal at the maximum power during irradiation or the increment of the dispersion with burnup of the gas pressure.

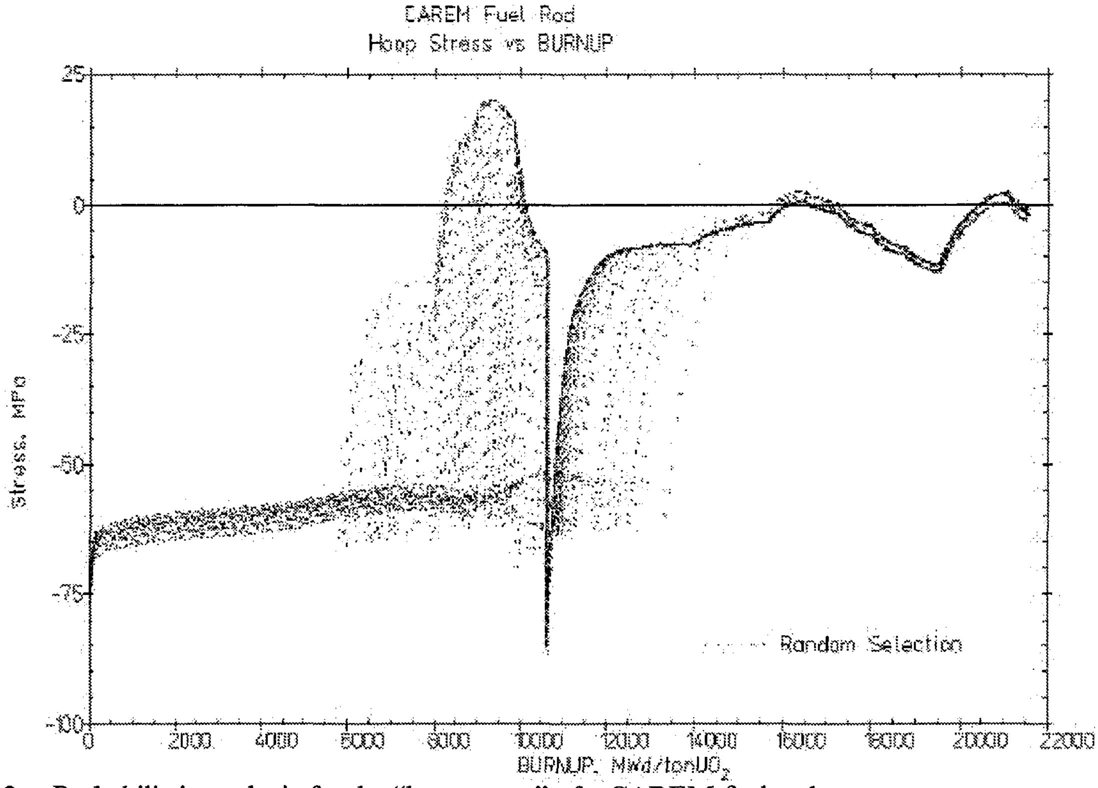

Figure 22.a: Probabilistic analysis for the "hoop stress" of a CAREM fuel rod.

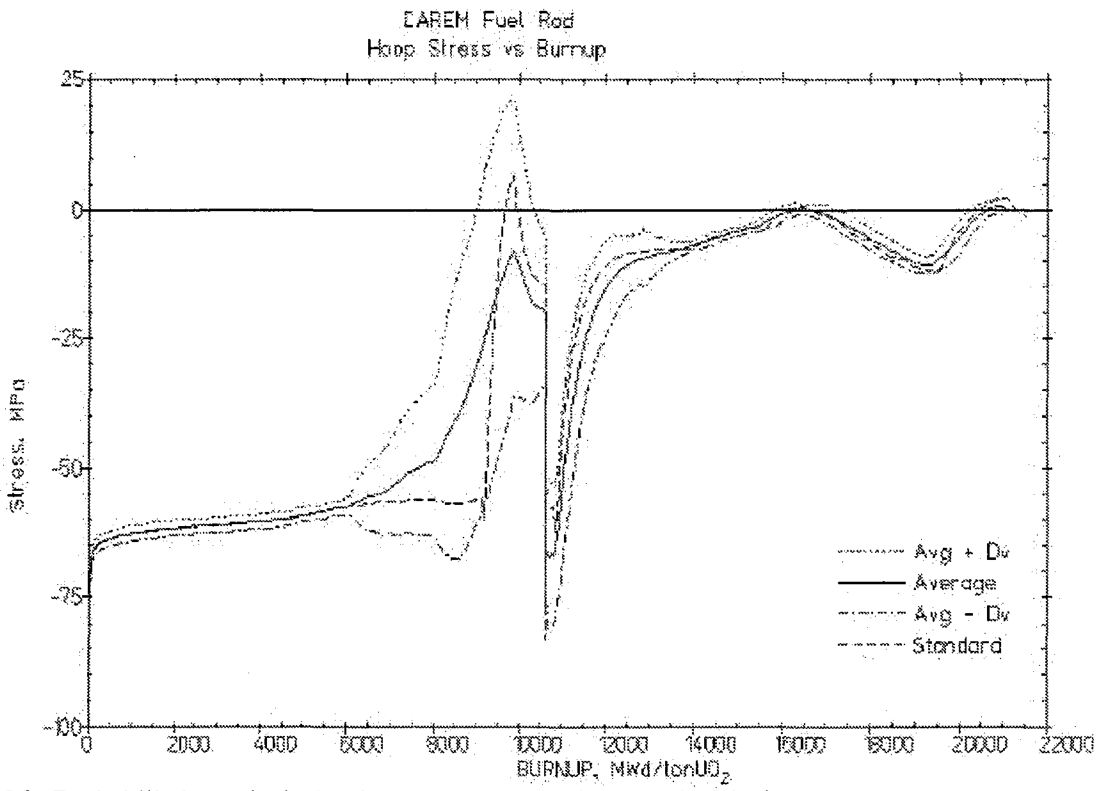

Figure 22.b: Probabilistic analysis for the "hoop stress" of a CAREM fuel rod.

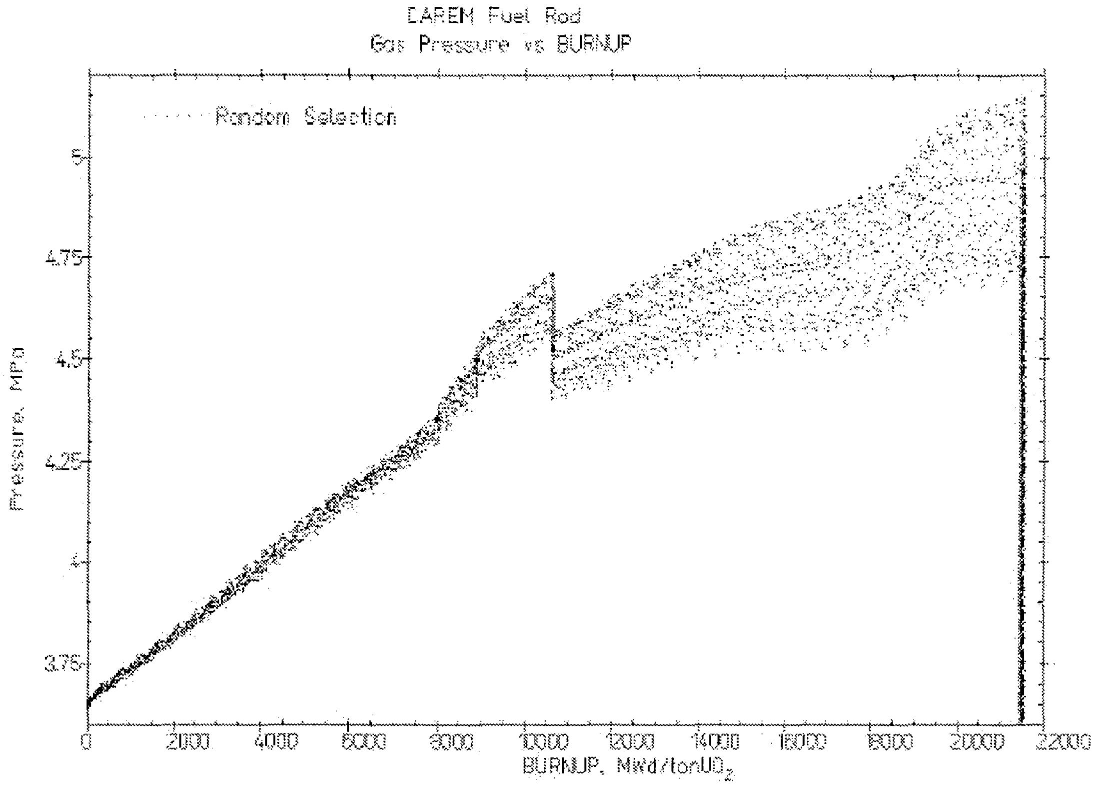

Figure 23.a: Probabilistic analysis for the gas pressure of a CAREM fuel rod.

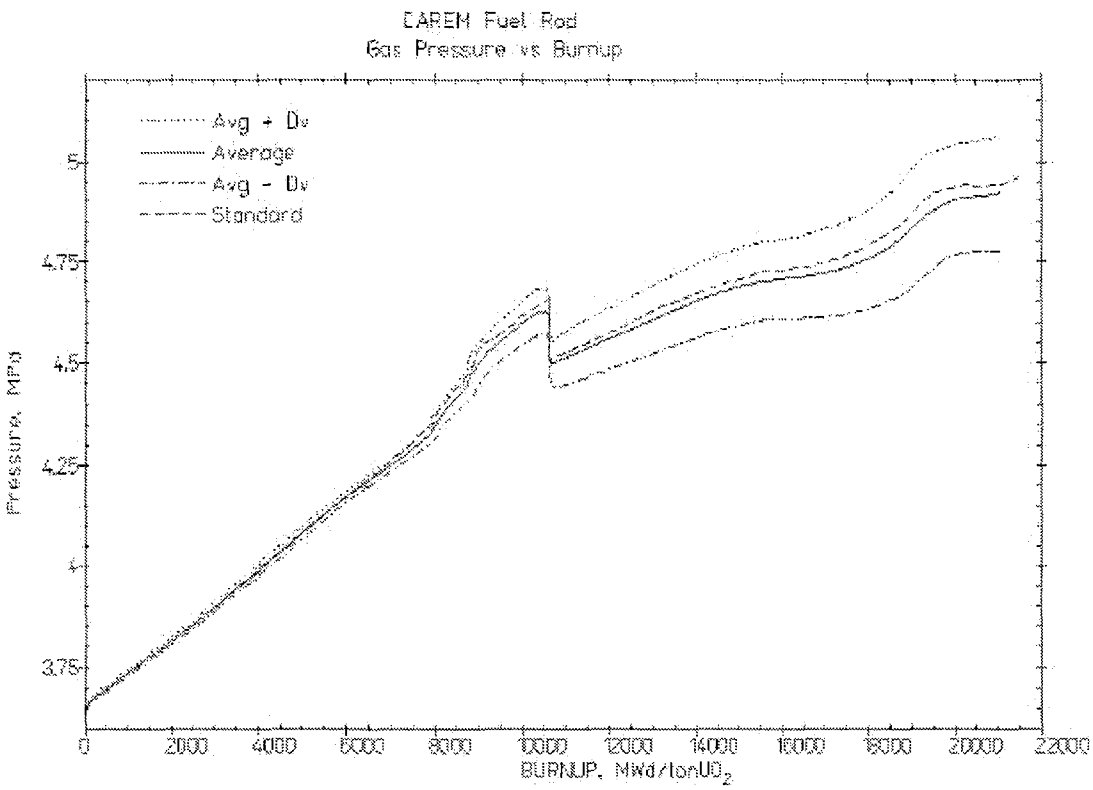

Figure 23.b: Probabilistic analysis for the gas pressure of a CAREM fuel rod.

6. CONCLUSIONS

The schedule sketched in this paper begins with a validated code for the simulation of the fuel rod behaviour 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 modelling.

A MOX fuel rod failure due to PCI-SCC was presented. The BACO code was the 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). An additional developing was the induction of fuel failures due to SCC mechanism and the simulation of burnup extension with synthetic products (CsI and Iodine).

We have showed that is not enough a simple running code in order to simulate the behaviour 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 rod design related to fabrication uncertainties must be tested. This exercise shows, on one hand, the sensitivity of the predictions concerning such parameters and, on the other hand, the potentiality of the BACO code for a probabilistic study.

The increment of the dispersion with burnup that we find in the calculation performed with BACO is an advice that we must include probabilistic safety criteria in the design of fuel elements. The design of both the CARA fuel and the CAREM reactor fuel are being developed using strongly the techniques of calculation and criteria sketched in this paper.

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