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# AN APPROACH TO WWER FUELS WITH BACO

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# An Approach to WWER fuels with BaCo

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## *Abstract*

*BaCo is a code for the simulation of the behaviour of a nuclear fuel rod under operation conditions. BaCo, a quasi 2D code based on a finite differences scheme, has been used for simulating PHWR, CANDU, PWR, BWR, MOX, WWER, and experimental fuel rods. We improve the performance of BaCo with a set of tools based on the method of finite elements for 3D analysis of the stress-strain state. We can simulate any* $UO_2$ *pellet geometry. Standard WWER-440 fuel assemblies irradiated in the Kola-3 reactor of the CRP FUMEX II of the IAEA were the first WWER simulations with BaCo. We find a very good agreement among our calculations, the experimental results and other qualified fuel codes. We present the BaCo code and our results for PWR and WWER fuels of the CRP FUMEX II, the 3D analysis of WWER fuel pellet and the projections of these results with the Argentinean nuclear fuels development.*

## 1. INTRODUCTION

Getting nuclear power generation supported by the security and economic criteria requires a deep knowledge of fuel behaviour under many different situations. The economics of the power generation might be greatly improved by means of relatively minor changes on the design, fuel processing and operating conditions, which its turn require checking carefully the fuel design, considering parts performance as well as their in service thermo-mechanical coupling. The classical tool, which has been used to study these changes, is reliable numerical simulation.

BACO is a code for the simulation of thermo-mechanical and fission gas behaviour of a cylindrical fuel rod under operation conditions. Our modelling approach is based on using effective models, which are however sustained on physically sound ideas and critical evaluation of their consistency. BACO has been used for simulating PHWR, CANDU, PWR, BWR, MOX, WWER, and experimental fuel rods. We enhanced the BaCo performance with a complete set of “ad hoc” software package named “MeCom”. The BaCo code is used for the simulation of the behaviour of a nuclear fuel rod under irradiation. The coupling of BaCo, a quasi 2D code based on a finite differences scheme, and the 3D MECOM tools, based on the method of finite elements, constitutes a complete system for 3D analysis of the stress-strain state of a nuclear fuel under irradiation. We calculate the 3D stress-strain state and the deformations of the $UO_2$ pellet at each time step of the BaCo code calculation. We find the stresses and the radial profiles of a fuel rod and the shape of the cracked pellet under irradiation. We can simulate any $UO_2$ pellet geometry including the dishing, the chamfers, a central hole and/or cracks.

The code performance was tested against other codes of similar capabilities. BACO was a participant in several co-ordinated round robin comparisons of fuel code predictions with experimental results (D-COM and FUMEX). At present we are participating in the last edition of the CRP FUMEX II of the IAEA (or "Improvement of Models Used for Fuel Behaviour Simulation FUMEX II", usually named as the "Co-ordinated Research Project of Fuel Modelling at Extended Burnup"). That project is under the last stage of development.

The CRP FUMEX II was the first official calculation of the BaCo code using WWER fuels. The cases 9 to 12 were standard WWER-440 fuel assemblies irradiated in the Kola-3 reactor. The operation of these assemblies was successfully completed in 1990-1991 with assembly average burnup of 46.2 and 48.2 MWd/kgU. We find a very good agreement among our calculations, the experimental results and other qualified fuel codes.

Predicting the thermal and mechanical performance of the WWER fuels is challenging for our computer code not designed "ad hoc" for those fuels. Nevertheless, the CARA Fuel Project and the CAREM Reactor Project of CNEA require a code with extended burnup capabilities where some characteristic of the WWER fuels could be adopted.

## 2. THE BACO CODE

The BACO code structure and models in its present versions have already been described in references [1], [2] and [3]. A complete application example of BaCo for PHWR fuel design is included in reference [3]. The strategy for the development of the code is presented in reference [2] with a brief description of the code. Statistical analysis, data post-processing and 3D tools improves the code's performance and analysis of results [4, 5].

On modelling the $UO_2$ pellet behaviour, phenomena such as elastic deformation, thermal expansion, creep, swelling, densification, restructuring, cracks and fission gas release, are included. For the Zry cladding, the code models the elastic deformation, thermal expansion, anisotropic plastic deformation, and creep and growth under irradiation. The modular structure of the code easily allows to add 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.

BACO assumes azimuthal symmetry in cylindrical coordinates for the fuel rod; the 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 [6]. 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 [1].

## 3. BACO TEST CASES

In order to illustrate the BaCo code capabilities with LWR fuel rods we present an exercise of comparison with experimental data. These irradiation tests are included in the CRP FUMEX II (Co-ordinated Research Project on "Improvements of models used for fuel behaviour simulation") organized for the IAEA (International Atomic Energy Agency) [7] where BaCo is one of the participants.

### 3.1. HBEP Test (Case 16 from the CRP FUMEX II of the IAEA)

The High Burnup Effects Programme (HBEP) was an international group-sponsored program managed by BNW (Battelle Pacific Northwest Lab.). The principal objective of the HBEP was to obtain well characterized data on FGR for typical LWR fuel irradiated to high burnup levels [8]. The data set produced for the code simulation contains a full irradiation history with clad temperature and local power. The selected cases include annular pellets. The data are particularly valuable for the evaluation of the FGR at EOL and the fission products radial distribution. The measurements for the code comparison were: FGR at EOL, fission products and Pu distribution with a burnup ~51 and 67~69 MWd/kg$UO_2$. The main results are included in the table 1.

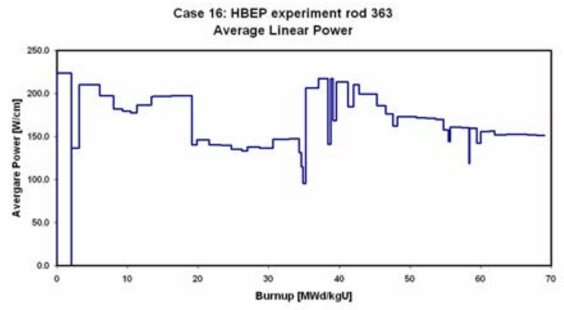


Figure 1: Average linear power of the fuel rod 363 from the HBEP experiment (Case 16). Burnup calculated with the BaCo code (time was the data).

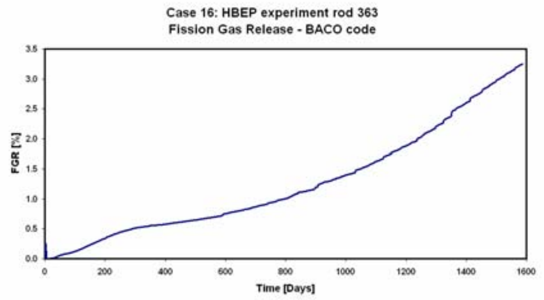


Figure 2: Fission gas release calculated with the BaCo code (Case 16). FGR data at EOL was: 3.80 %.

| **Case 16 (rod 363)** | **Data** | **BaCo** |
|---|---|---|
| Average Burnup at EOL [MWd/kgU] | 66.7 | 69.0 |
| FGR [%] | 3.80 | 3.25 |
| Hot Pressure [MPa] | | 3.29 |
| Pressure STP [MPa] | 2.06 | 2.84 |
| **Case 17 (rod 365)** | **Data** | **BaCo** |
| Average Burnup at EOL [MWd/kgU] | 69.4 | 65.7 |
| FGR [%] | 2.40 | 3.70 |
| Hot Pressure [MPa] | | 6.55 |
| Pressure STP [MPa] | 3.38 | 5.52 |
| **Case 18 (rod 370)** | **Data** | **BaCo** |
| Average Burnup at EOL [MWd/kgU] | 50.9 | 52.0 |
| FGR [%] | 1.40 | 2.00 |
| Hot Pressure [MPa] | | 6.31 |
| Pressure STP [MPa] | 3.28 | 4.62 |

Table 1: CRP FUMEX II of the IAEA – Cases 16 to 18 (HBEP)

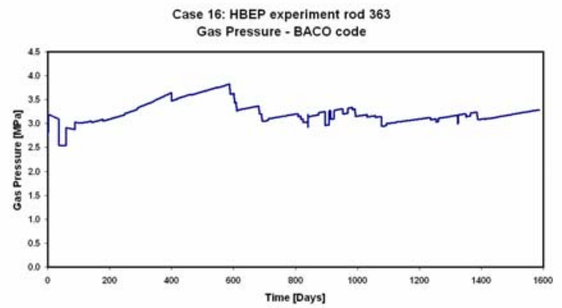


Figure 3: Inner gas pressure of the fuel rod 363 from HBEP experiment (Case 16). Pressure data at EOL was 2.06 (STP) and 2.84 MPa (STP) was calculated for BaCo.

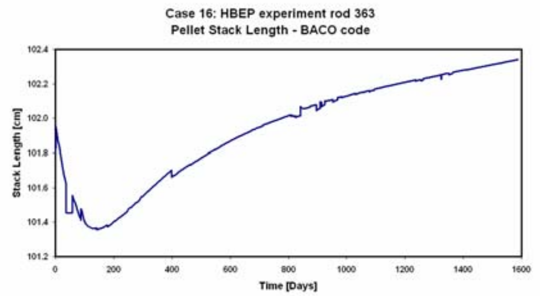


Figure 4: Pellet stack length calculated with the BaCo code for the fuel rod 363 from HBEP experiment (Case 16).

Figure 1 shows the power history of the case 16 of CRP FUMEX II. The burnup was calculated with BaCo using the time as input data. We find a good agreement between the calculated burnup and the data (see the table 1). The fission gas release calculation is included in figure 2. The release is thermally activated due to the limitation of our FGR model where the so-called HBS is not included. Nevertheless, the empirical approach used in the FGR model includes high burnup fuel irradiation results in their parameterization [9]. The FGR calculated agrees very well with the experimental result at EOL. Figure 3 shows the inner gas pressure calculated with the BaCo code. We find an acceptable correlation between our estimation and the data at EOL. The cases do not include the evaluation of pellet stack length data but we include that calculation with an illustrative purpose (see figure 4). Here we can identify a pellet densification up to a burnup of ~170 days; swelling is present after that date.

### 3.2. RISØ Test (Case 15 from the CRP FUMEX II of the IAEA)

The Risø National Laboratory in Denmark have carried out three irradiation programs of slow ramp and hold tests, so called 'bump tests' to investigate fission gas release and fuel micro structural changes. The third and final project, which took place between 1986 and 1990, bump tested fuel re-instrumented with both pressure transducers and fuel centreline thermocouples. The data from the project were particularly valuable due to the in-pile data on fuel temperatures and pressures as well as extensive PIE [10].

The bump testing originally named "AN3", case 14 of the CRP FUMEX II, was carried out in January 1988. The test fuel pin, CB8-R2, was refabricated from a segment supplied by Advanced Fuels Corporation (ANC) and instrumented with pressure transducer and fuel centreline thermocouple. The fill gas was 14.66 bar helium. The bump irradiation was performed in the test reactor DR3 at Risø under PWR conditions. Figure 5 shows the pellet centre temperature calculated with BaCo and the experimental measurement.

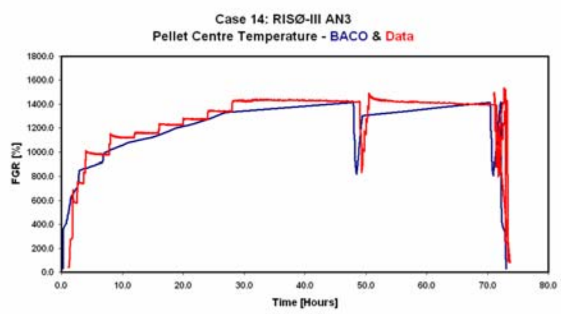


Figure 5: Pellet centreline data and calculation during the bump test.

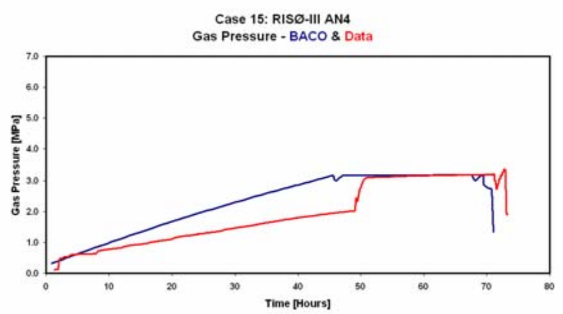


Figure 6: Experimental data and calculation of the inner gas pressure during the bump test at EOL.

Bump testing of AN4, case 15 of the CRP FUMEX II, was carried out in December 1987. The fuel pin was refilled with Xe during refabrication. This case is valuable for the comparison with the previous cases of fuel pins filled with He. Likewise the use of the Xe as filling gas reproduces the worst case of thermal conductivity in the gap pellet-cladding. Figure 6 shows the inner gas pressure calculation and data. The difference between data and BaCo at the first part of the experiment is done due to the position of the pressure transducer (at the top of the fuel), the shutdown after the first ramp and the axial power profile. The inner pressure at the bottom is higher than at the top of the fuel due to the power profile and PCI at the middle of the rod. As BaCo calculates an average gas pressure then we have that difference. Nevertheless we have a very good agreement between these experiments and the BaCo code results.

### 3.3. WWER cases (Case 9 from the CRP FUMEX II of the IAEA)

Two pre-characterised standard WWER-440 Fuel Assemblies (FA) with the identification numbers FA-198 and FA-222 were irradiated in the Kola-3 reactor for four and five fuel cycles respectively. The operation of these two assemblies was successfully completed in 1990-1991 with assembly average burnup of 46.2 (FA-198) and 48.2 (FA-222) MWd/kgU. The assemblies were manufactured in May, 1986 with the specific goal to validate fuel performance and design for WWER-440 High Burnup Fuel Cycles. The pre-characterisation of $UO_2$ fuel pellets, cladding material and fabrication procedures was carried out at the Russian Nuclear Fuel Company "Elemash" (Electrostal).

The PIE has covered all items of interest to fuel performance. In particular, cladding dimensions and mechanical properties, clad water side and fuel side oxidation, fission gas release, gas pressure and gaseous fractions in fuel rods were measured.

The fission gas release is recognised as an important aspect for the design of the WWER-440 high burnup fuel. The measurements on FGR show that in general the FGR was low, with measured average values of 0.9 and 2.2% after four and five years of base-load reactor operation, respectively. With reference to the overall and safety criteria, the observed FGR is rather normal for the operation conditions currently applied for WWER-440 four year fuel cycles and should not lead to major feedback effects at the end of life by the fuel temperature response to the FGR.

The PIE data are restricted to FGR measured by puncturing, rod internal pressure at the EOL and clad creep-down over the active part of the fuel. The data are particularly valuable for modelling WWER fuels, dimensional changes and FGR taking into account the presentation of the values of the gas pressure at EOL. It is valuable the study of the influence of the presence of a central hole by design on the stress release of the fuel rod (less diametral deformation in the pellet and lower values for the hoop stress at the cladding, see bellow) plus the stability of the calculations when a central hole is done at BOL. It was plausible the use of these set of irradiations with BaCo al least for the mentioned items.

Measurements made for comparison: FGR, pressure and creepdown at Burnup ~60 $MWd/kgUO_2$. The fuel length at EOL, grain size and central hole changes are available.

We calculated using the normal parameters and laws of BaCo for Zry4. We include a sensitivity analysis for the Case 9 (rod 7 from FA222). We found an excellent agreement between calculations and experimental data in all the cases including the evaluation of the fuel burnup (see the table 2 and 3).

The figure 7 shows the average lineal power for the rod 7 of Kola-3 (case 9). The figure 8 includes the local lineal power for each axial section of the fuel rod. A strong axial profile is present at BOL.

The figure 9 shows the inner gas pressure. The value at EOL compares very well with the experimental data (see the tables 2 and 3). A statistical analysis is performed in the figure 10. We used all the geometric numerical standard deviations presented in the data for that analysis. We find a small deviation from the normal calculation.

The figure 11 shows fission gas release. The value at EOL compares very well with the experimental data (see the tables 2 and 3). A statistical analysis is performed in the figure 12. We find a very small deviation from the normal calculation. As we do not include the modelling of HBS we assume that the FGR is enhanced by the hot regions of the fuel pellets.

The figure 13 shows the average creepdown of the cladding and the figure 14 includes the creepdown of each axial sections of the fuel rod. The figure 15 shows the fuel pellet stack and the cladding lengths. We have a close pellet-cladding gap in all the axial sections of the rod after the first power ramps at approximately 250 days (~10 MWd/kgU) (see the figures 13 and 14). The figure 15 shows the evolution of the lengths of the cladding and the stack pellets.

We find that their length evolutions are different up to the complete gap closure. After that point both curves look as parallel ones. The grain size and the pellet hole calculations agree very well with the experimental observations (see the table 2 and 3). We did not find numerical instability due to the presence of a central hole in the WWER fuel pellets.

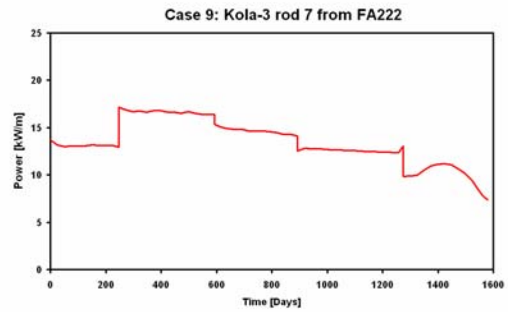


Figure 7: Average linear power for the rod 7 from FA222 (Case 9).

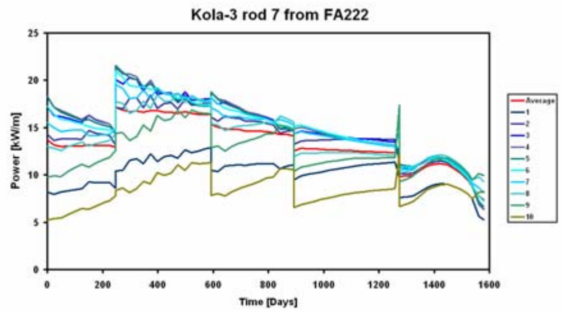


Figure 8: Linear power at ten axial sections of the rod 7 from FA222 (Case 9).

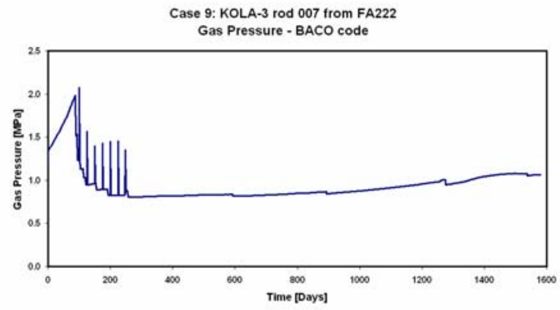


Figure 9: BaCo calculation of the gas pressure during the irradiation of the rod 7 (Case 9). Experimental data: 1.40 MPa at EOL.

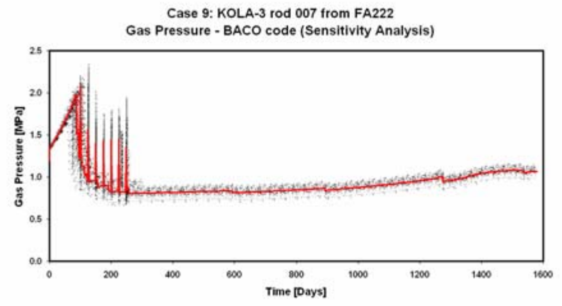


Figure 10: Statistical analysis of the gas pressure during the irradiation of the rod 7 (Case 9). We use the standard deviations of pellet and cladding data for these calculations. The red curve is the normal calculation.

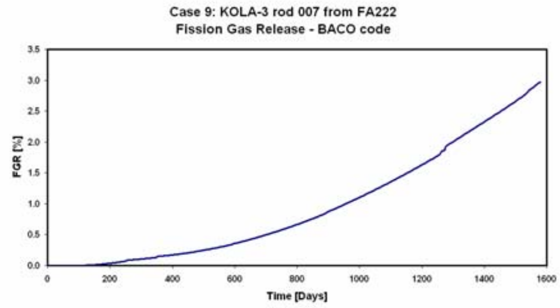


Figure 11: BaCo calculation of the fission gas release during the irradiation of the rod 7 (Case 9). Experimental data: 3.71 % at EOL.

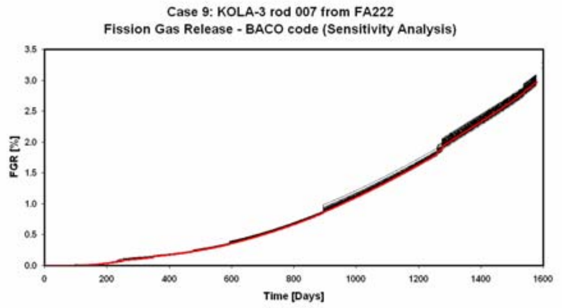


Figure 12: Statistical analysis of the fission gas release during the irradiation of the rod 7 (Case 9).

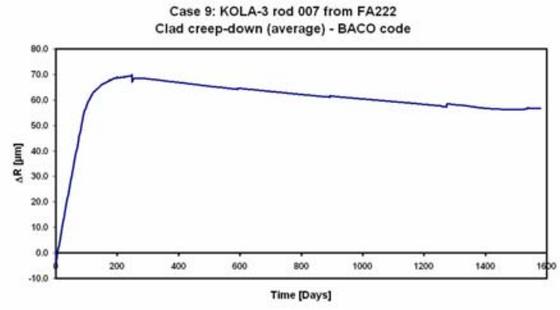


Figure 13: BaCo calculation of the cladding creep-down (average) during the irradiation of the rod 7 (Case 9).

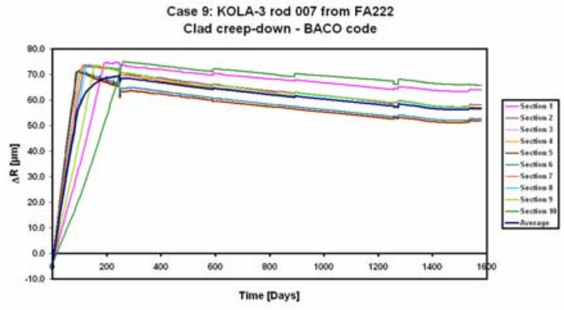


Figure 14: BaCo calculation of the cladding creep-down for each axial section of the rod 7.

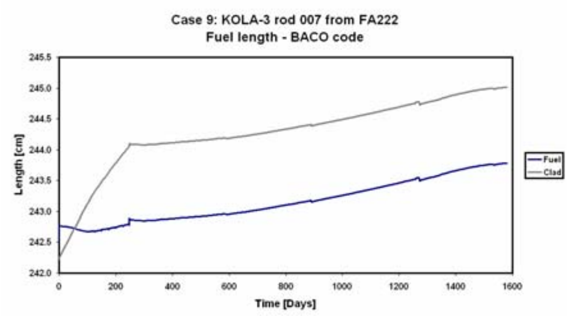


Figure 15: BaCo calculation of the fuel pellet stack length and cladding length during the irradiation of the rod 7 (Case 9).

| | Case 9 (BC 7) | | | Case 10 (BC 52) | | | Case 11 (BC 86) | | | Case 12 (BC 120) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Exp.** | **BaCo** | **TRANS** | **Exp.** | **BaCo** | **TRANS** | **Exp.** | **BaCo** | **TRANS** | **Exp.** | **BaCo** | **TRANS** |
| **Burnup at EOL [MWd/kgU]** | 55,3 | 54,2 | 53.43 | 46,2 | 47,6 | 46.86 | 44,4 | 45,8 | 45.2 | 50,4 | 50,4 | 49.7 |
| **Maximum burnup [MWd/kgU]** | 63,8 | 61,2 | 60.0 | 54,0 | 53,3 | 52.23 | 52,1 | 51,0 | 50.3 | 57,8 | 56,3 | 55.23 |
| **FGR [%]** | 3,71 | 2,97 | 3.71 | 0,99 | 2,33 | 0.87 | 0,69 | 2,07 | 0.72 | 2,26 | 2,39 | 1.25 |
| **Pressure [MPa]** | 1,40 | 1,07 | 1.03 | 1,01 | 1,00 | 0.87 | 0,95 | 0,96 | 0.84 | 1,10 | 1,05 | 0.94 |
| **ΔR [μm]** | (40~43) | 56,7 | 40.3 | 80,0 | 60,5 | 53.4 | 60,0 | 61,4 | 55.2 | 50,0 | 58,7 | 49.7 |
| **ΔL [mm]** | ~12 | 30,1 | 12.83 | ~12 | 25,6 | 12.24 | ~12 | 24,3 | 12.01 | ~12 | 32,7 | 12.43 |

Table 2: CRP FUMEX II Cases 9 to 12, WWER-440 fuels.
Comparison among experimental data, BaCo and TRANSURANUS-WWR.

| ***Experimental observation*** | ***BaCo*** |
|---|---|
| No grain changes were registered in the centre of the fuel pellets. | No grain changes were calculated in the centre of the fuel pellets. |
| Grain size was 6-15 mcm, where the average was 6-8 mcm. | Grain size was calculated with an average size of 6.6 μm. |
| The central hole diameter was not changed. | The central hole diameter was not changed. |

Table 3: Experimental observations vs. BaCo for the CRP FUMEX II. Cases 9 to 12, WWER-440 fuels.

The tables 2 and 3 resume the present performance of BaCo in comparison with the experimental data and the results of the TRANSURANUS code for the WWER cases of the CRP FUMEX II [7]. We find an excellent agreement with experimental data for the calculation of burnup, fission gas release and inner gas pressure. A good agreement is found for dimensional changes as the diameter and the length of the fuels. Then we can assume that the physical laws included in BaCo and the boundary conditions constitute a reasonable approach as a seed for the 3D calculations of hollowed pellets with the MeCom tools.

### 3.4. Overview of the BaCo code test cases

We were pushing the limits of the BaCo code in order to estimate the present range of applicability of the code. We need to keep the compatibility with the "Argentinean" fuels defined above, to test the real capabilities of our code and modelling in order to prepare BaCo for the challenge of the near future as the fuels for the CAREM reactor [11] and the Atucha II [12], the CARA fuel for the Argentinean reactors [13] and the next CRP FUMEX III of the IAEA, among others.

## 4. A 3D ANALYSIS - THE MECOM TOOLS

We enhanced the BaCo performance with a complete set of "ad hoc" software package named "MeCom". The 3D finite element (FEM) calculations were performed with a set of tools developed at the Computational Mechanics (MeCom) Division at the Bariloche Atomic Centre (CAB), CNEA. Basically, these are grouped in two software packages, "acdp95" [14] and "gpfep99" [15]. The package "acdp95" includes tools for mesh generation and optimization [16] and a complete collection of visualization programs. Non structured meshes composed of tetrahedral elements for arbitrary geometries can be obtained. Visualization tools for viewing meshes and the FEM solutions over these meshes (scalar and vectorial) are available. The package "gpfep99" is the FEM solver. The solutions obtained with "gpfep99" can be visualized with the "acdp95" tools.

### 4.1. BaCo + MeCom

The coupling of BaCo, a quasi 2D code based on a finite differences scheme, and the MeCom tools, based on the method of finite elements, constitutes a complete system for 3D analysis of the stress-strain state of a nuclear fuel under irradiation. We calculate the 3D stress-strain state of the $UO_2$ pellet at each time step of the BaCo code. We obtain the stresses and the radial profiles of a fuel rod and the shape of a fuel pellet under irradiation. By using an appropriate set of boundary conditions, based those calculations and data we obtain a good agreement between experiments of irradiation and calculations particularly for the pellet radial profile after irradiation [19]. We can define an "ad hoc" 3D pattern of cracks based on BaCo calculation and experimental data in order to enhance the results [23].

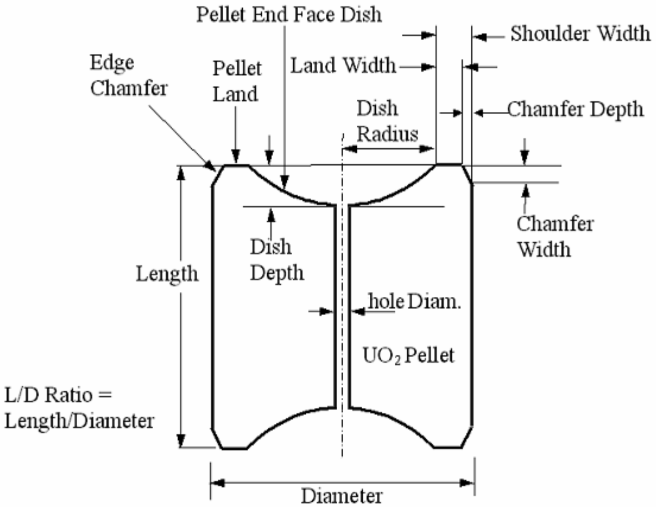


Fig. 16: A fuel pellet and its main geometric parameters

The BaCo code includes time dependent phenomena as creep and the opening, closure and healing of cracks in the fuel pellet during the irradiation among others. The creep of $UO_2$ and the dynamics of the cracks are the main mechanisms in BaCo to release stresses at the fuel pellet. The MeCom tools include the same laws for elasticity and thermal expansion than the BaCo code. A first approximation of the fuel rod behaviour is made by using the BaCo code. The treatment is quasi-bidimensional at this stage but using the complete set of models and options of BaCo. We generate the input data for the MeCom tools, in particular the geometry of the pellets and the boundary conditions for a particular time of the irradiation.

The geometry of the pellet includes the evolution of the shape of the dishing, the shoulders, central hole and the deformations calculated by BaCo (see figure 16), and also we can included a crack pattern.

We assume that the cladding follows the pellet deformation at the points where we find contact between pellet and cladding. Here the assumption is that the cladding deformations are irreversible ones and the cladding do not return to its previous shape when the radial pellet deformation is reduced due to thermal changes (or power rate changes). Then the fuel rod profile is the cladding profile at the end of the irradiation. Nevertheless a good approach is done if we consider just the pellet radial profile and we assume a direct translation of the pellet shape to the cladding surface. This approach is a very good model for CANDU fuel where the cladding is collapsible by design and a pellet-cladding contact is done during all the irradiation.

The boundary conditions for the pellets are: *1*) the pressure of the free inner gases in the fuel rod calculated with BaCo (also for the dishing of the pellet, the central hole and the inner surface of the cracks), *2*) the coolant pressure, a datum for the lateral surface of the cylindrical pellet, and *3*) the axial stresses calculated by BaCo for the pellet shoulders (see the Figure 17).

The temperature field is an input data. Porosity, crack pattern and thermal conductivity can be included into MeCom for a best estimation of its thermal behaviour. The result is the 3D deformed geometry of the pellets and cladding and the 3D maps of stresses and strains. At present, we are including elasticity, thermal expansion and cracks into the FEM solver (Finite Element Method solver included in the MeCom package).

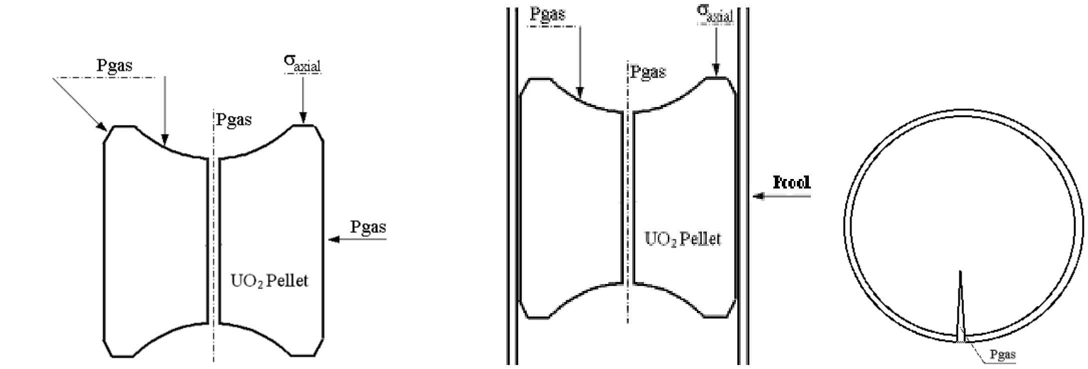


Fig. 17: On the left we show the boundary conditions condition of a fuel pellet without contact with the cladding and at the middle the conditions when pellet-cladding are in contact. Where, $P_{gas}$ is the pressure of the inner gases of the fuel rod, $P_{cool}$ is coolant pressure and $\sigma_{axial}$ is the axial pellet to pellet stress. At the inner surface of a crack the boundary condition is the gas pressure. We can include several radial cracks as the previous one in the pellet.

Taking into account the 3D simulation of a fuel pellet we perform a parametric analysis of the influence of the boundary conditions in the final result of the calculations. We vary the radial stresses at the lateral surface of the pellet among reasonable values over and under the inner gas ($P_{gas}$) and the coolant ($P_{cool}$) pressures. Likewise, we included the influence of an axial constrain, we do not allow the axial deformation of the pellet. We found that the influence of those variations produces a negligible influence in the pellet shape. The values of the ridging and the radial deformations show a small variation, for example the pellet ridge height results less than 1 μm of difference respect the original boundary conditions.

## 4.2. Analysis of the Fuel Pellet Geometry

We can find the stresses and the radial profiles of a fuel rod and the shape of the cracked pellet under irradiation showing the bamboo effect and others 3D effects as the presence of the secondary ridge. Figure 18 shows four different pellets. The first one is the WWER fuel pellet used in the previous calculation of the cases 9 to 12 of the CRP FUMEX II. The second one is the same cylinder without the central hole. The third is the previous one with dishing and chamfers at the top and at the bottom. And, finally, we repeat the third pellet including a central hole.

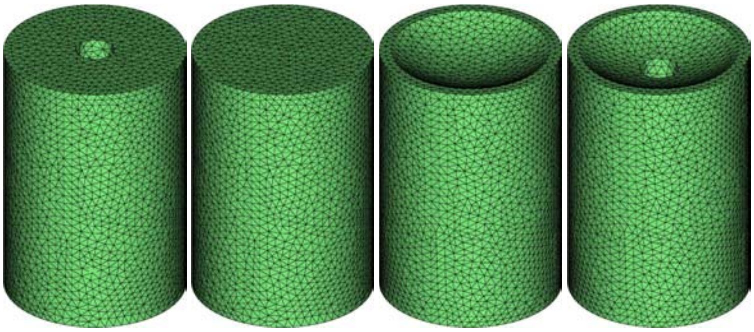


Fig. 18: Meshes for different pellets in order to start the analysis of the best geometric shape for a WWER fuel.

As interesting examples by using BaCo + MECOM we find the mentioned secondary ridge and the "bamboo" effect plus (see figure 19): *a)* the reduction of the deformation when a hole is included in the centre of the pellets, and *b)* the increment of ridging when a dishing is present. The WWER fuel pellet appears with minor ridging and radial deformations.

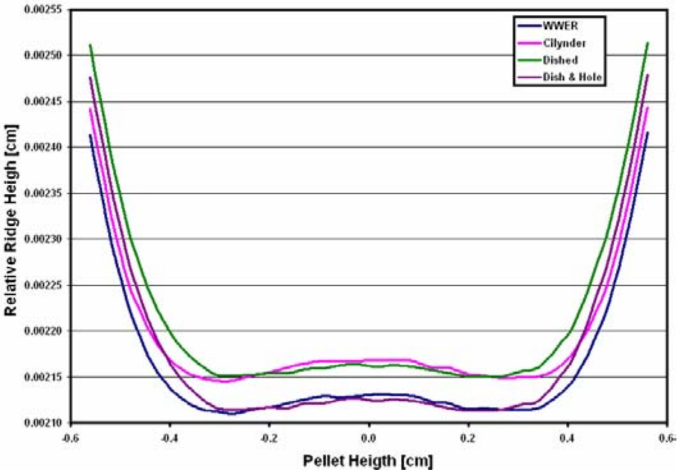
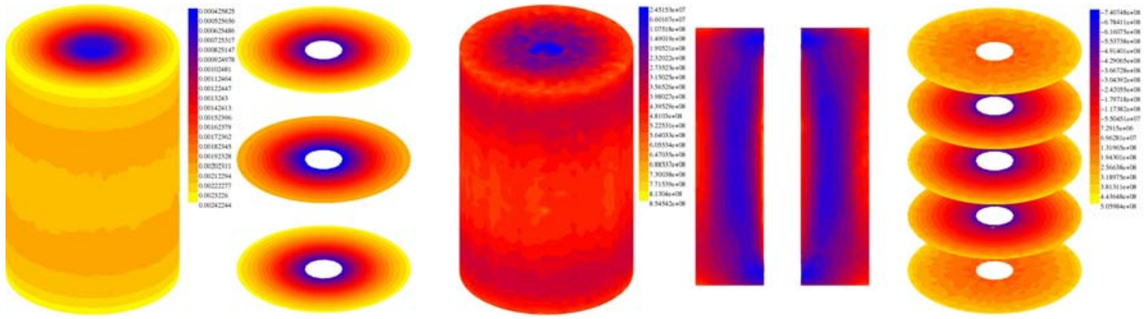


Fig. 19: Radial deformations for the pellets of figure 18.

Figure 20 includes several cuts of the 3D maps for the deformations and the stresses of the same WWER fuel pellet. Here we see more clearly the reduction in the radial deformation, the reduction in the riding among a decrement in the radial stresses between pellet and cladding and the secondary ridge. The von Misses equivalent stresses are greater at the lateral surface and at the hole of the pellet. Positive values of the tangential stresses (that means traction) are found at the periphery of the pellet (top, bottom and lateral surfaces with light colours) and negative ones (compression) at the central zone of the pellet (dark colours).



***Radial deformations*** ***von Misses stress*** ***Tangential stress***

Fig. 20: Radial deformation from two different options of viewing, von Misses stresses (two point of view) and tangential stresses of a WWER fuel pellet.

We mentioned above that the optimization of fuel pellet geometry could be approached with the finding of the best *l/d* relation (length/diameter). It is confirmed by the agreement with several experiments present in the literature [17, 18]. We could find as a result of BaCo that the ridging is reduced when *l/d* is reduced with a perfect agreement with experimental observation [19]. The curve of figure 21 includes the experimental values and our calculations with different *l/d* values. There is not a clear correlation between experimental results and BaCo calculations because the experimental evaluation of the fuel ridging was not clearly explained in the measurements performed in the references; however for a qualitative purpose we see that the global trends of the measurements of the mean ridge height are the same than the radial deformations of the pellets. We extend the qualitative agreement by varying shoulders and chamfers as it is shown in figure 21. The increment of *l/d* over more than 1.3 produces the maximum value of deformation. The decrement of *l/d* produces a convergence to the lowest values for the radial deformation. These trends are present in all the BaCo calculations.

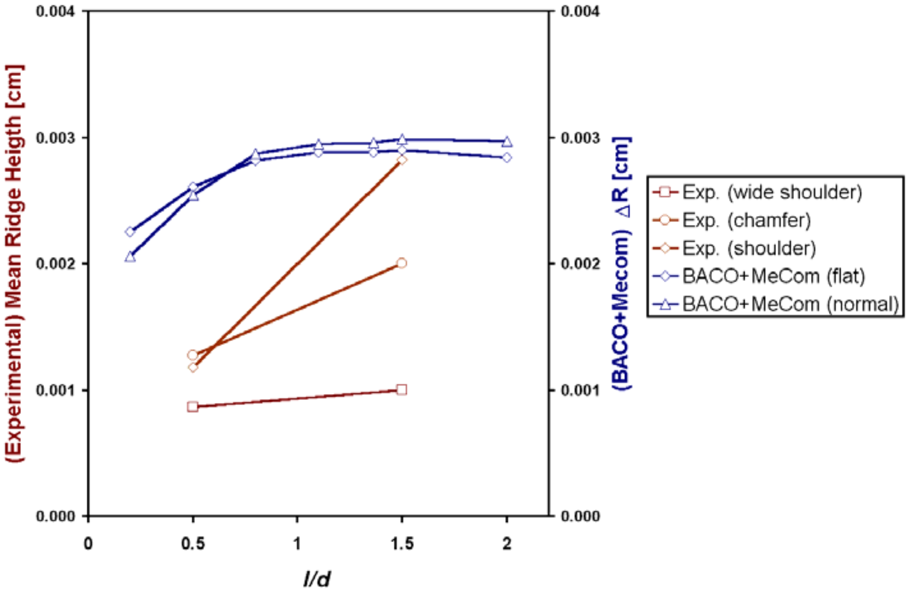


Figure 21: Correlation between experimental mean ridge height and radial deformation (ΔR) calculated by varying the *l/d* relation.

### 4.3. 3D Test Cases

As an exercise of validation of our calculation we show in the figure 21 the radial profile of two experimental fuel rods irradiated at the Halden reactor [19]. Those rods have some hollowed pellets at the top of the fuel with the purpose to include a thermocouple. The figure includes the power profile of the rods. We see that the power is slightly greater than in the rest of the rod. Nevertheless we observe a reduction of radial deformation of the fuel diameter and a reduction of the ridges height as we calculate with BaCo. It is interesting to mention that this validation test is obtained by using a non specific experiment. We observe the same behaviour at the figure 22 where an experimental comparison of hollow and solid pellets is included. Here PCMI is much reduced in the hollow pellet rod and, unlike the solid pellet rod, results in no plastic permanent deformation of the clad [21, 22].

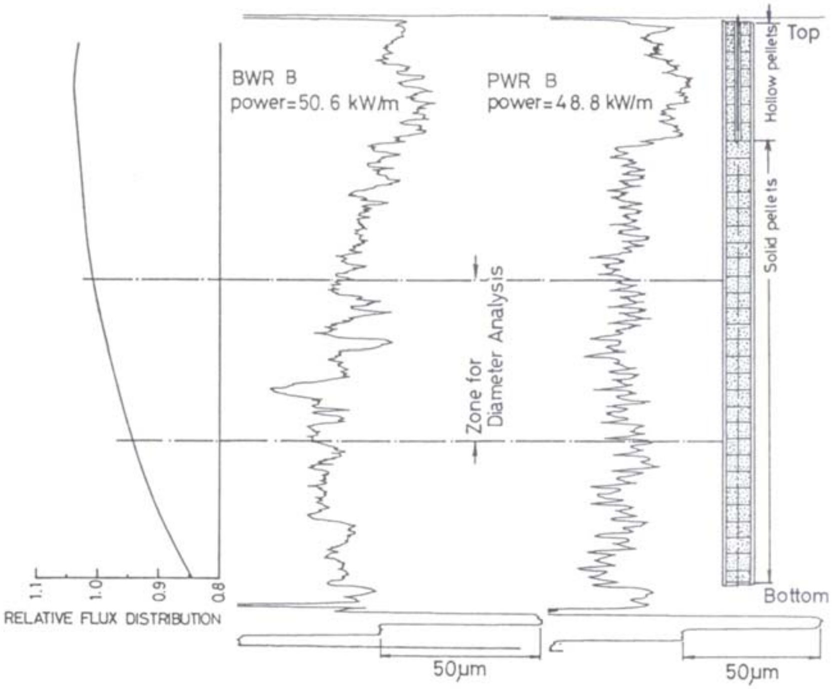


Fig. 21: Rod profile of an experimental fuel at the Halden Reactor. At the top hollowed thermocoupled pellets are present [20].

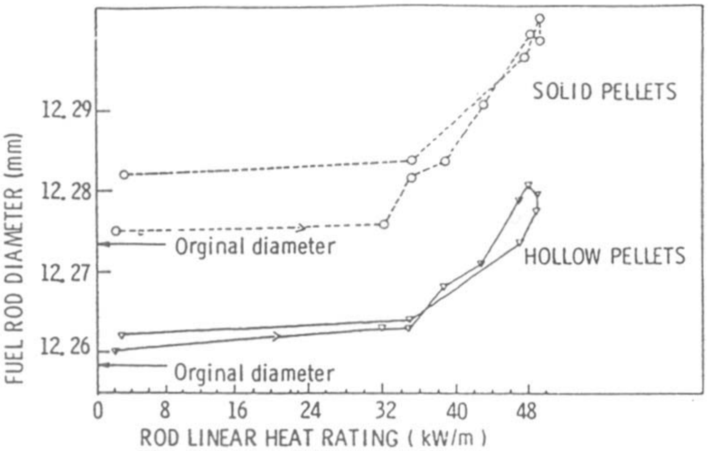


Figure 22: Clad average diameter versus linear heat rate for hollow and solid pellet rods in IFA-509 during a ramp at 3.0 MWd/kgUO$_2$ [21, 22].

## 4.4. An Approach to a 3D Fuel (Present situation)

At present we are starting to include the cladding of the fuel rod. Our simulation assumes that the cladding is around the pellet with the geometry calculated with BaCo. Due to the radial deformation the pellet can touch the cladding. The main assumption is the direct translation of the pellet to the cladding surface. That is exactly for normal CANDU fuel where the PCI is done due to its collapsible cladding and the low inner pressure. For a PWR that is a good assumption at high power or with high swelling when we can find PCI. Our first approach in order to include the treatment of the cladding in our 3D environment is to consider that the cladding follows the pellet deformation when we have PCI. We include the same laws for cladding elasticity and thermal behavior than we include in the BaCo code. We model a pellet stack (at present with 3 or 5 pellets) and the cladding. The boundary conditions are provided by BaCo (see the figure 17): $P_{gas}$ for the inner surface of the cladding, $P_{cool}$ for outer surface of the cladding and the pellet to pellet axial stress for the pellet shoulders. The first calculation belongs to BaCo. The second one is produced just for the pellets by using MeCom and the last is the 3D calculation of the cladding behaviour as we mentioned previously. Nevertheless there is not feedback from the cladding to the pellets.

Figure 23 shows the meshes used for the pellets and the cladding for the simulation of the pellet-cladding behaviour and the 3D radial deformation of pellet and cladding. We find a good solution for the radial deformation where the ridging appears at the top and at the bottom of the pellet and it presents a very good qualitative and quantitative agreement with experimental results.

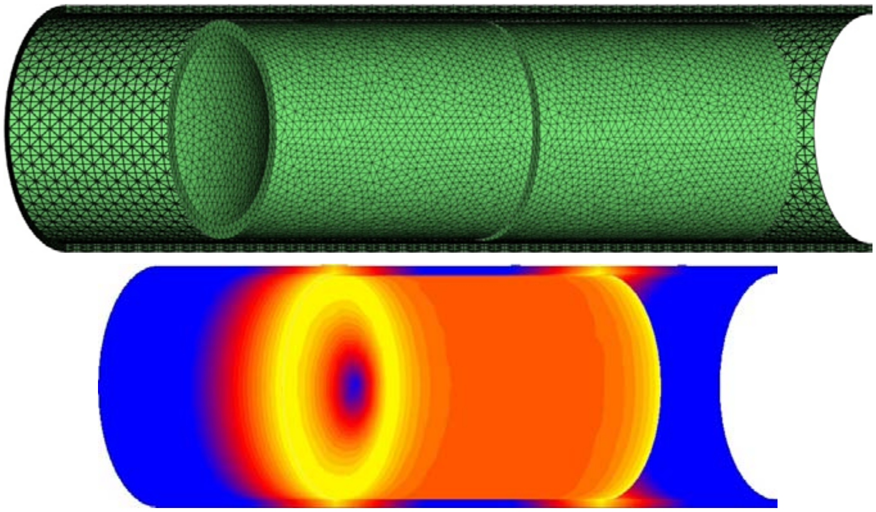


Fig. 23: Detail of the meshes for the cladding and the column of pellets (at present just 3 o 5 pellets are used for calculation). At the bottom there is a detail of the radial deformations of one of the pellets and the cladding.

## 5. CONCLUSIONS

We find an excellent agreement with experimental data for the calculation of burnup, fission gas release and inner gas pressure. A good agreement is found for dimensional changes as the diameter and the length of the fuels. At this step we want to remark the extraordinary help of the IAEA due to the coordination of projects for nuclear fuel rod simulation and modeling as the CRP FUMEX II. Then we can assume that the physical laws included in BaCo and the boundary conditions that we will use constitute a reasonable approach as a seed for the 3D calculations of fuel rods with the MeCom tools.

The main assumption for the analyses of the 3D pellet simulation is that we have a direct translation from the pellet profile to the cladding one. Here we find an excellent qualitative agreement in particular for the pellet ridging and the secondary ridge. The inclusion of a pattern of crack in order to release stresses in the pellet enhance our simulation providing an excellent agreement with the experimental data due to the increment of the pellet ridging. We are obtaining a very good dimensional agreement taking into account experiments of irradiations from the Halden Reactor Project as we show in section 5.2. We mentioned that non specific test of irradiation could be used for code validation.

It is interesting to mention that the variation of the classical WWER fuel pellet shape, as dishing and a solid centre does not mean an improvement of the stress-strain behaviour. This analysis is taking into account in the design of our CARA and CAREM fuels for argentine reactors as Atucha I, Embalse and CAREM NPPs.

At present our effort in order to include pellet and cladding is producing good qualitative results. Here the assumption is that the clad follows and it keeps the deformation of the pellet.

The BaCo code + the MeCom tools appear as good tools for the fuel rod design. BaCo + MeCom predict very well the WWER fuels behaviour.

## ACKNOWLEDGMENTS

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