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EDF FRAGMENT RELOCATION MODEL BASED ON THE DISPLACEMENT OF RIGID BODIES

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Abstract

In order to release the restricting conditions imposed to the reactor operations with regards to PCMI (Pellet-Cladding Mechanical Interaction), the simulation of a fuel rod thermomechanical behavior has to be improved. The computer programming has to cope with the more and more sophisticated mathematical modellings induced by the complexity and the interdependance of the phenomena. Therefore EDF is developping a new code - CYRANO3 - since 1990 putting emphasis on its evolution capacities.

Concerning more precisely the PCMI simulation, the pellet fragmentation and the fragments relocation is one of the major aspect one must account for. Thanks to recent analytical experiments, EDF developped a new modelling based on the displacement of rigid bodies and on the calculation of the interaction efforts between the fragments.

This paper presents the basis of the model, its introduction within the CYRANO3 code and its calibration on a specific analytical experiment. The modelling is then tested against PWR fuel rods deformations from the EDF data base. The results are presented and discussed.

INTRODUCTION

The fuel rod design work has to ensure the integrity of the cladding under normal, off-normal and as far as possible accidents conditions. The Pellet Cladding Mechanical Interaction (PCMI) is one of the potential cause of cladding failure during severe power transients in Pressurized Water Reactor (PWR). Once the mechanical behavior of the cladding material (zircaloy-4) has been accurately modelled [1], the loading induced by the cracked pellets remains the major field of investigation. The two- and three- dimensionnal effects of the fractured pellet have then to be modelled.

This paper deals with the pellet fragment relocation induced by the fracturing and with the relocation accommodation. Indeed, these phenomena have a major influence on the pellet-clad gap width. The knowledge of the time to closure gap is primordial because the stress profile in the clad is modified as soon as contact occurs. Moreover, the gap width has a major importance in the thermal behavior of the rod because of the gap conductance calculation, and in the internal pressure prediction which is one of the design criterion.

The first part of this paper is then devoted to the description of the fuel relocation phenomena and of the assumptions made for the mechanical modelling which was developped within the CYRANO3 code.

Accounting for the intricate phenomena, the validation of the relocation model is dependant on the whole code behavior. Thus the logic flow and the main characteristics of this one dimensionnal non linear finite element code are presented in the second part.
The comparison of predicted results against several experimental results finally validates the fuel fragment relocation modelling.

1 - FUEL CRACKING AND PELLET FRAGMENTS RELOCATION MODELLING

1.1 - Description of the phenomena

Figures 1,2 present a qualitative description of the phenomena and the way they affect the evolution of cladding radial deformation.

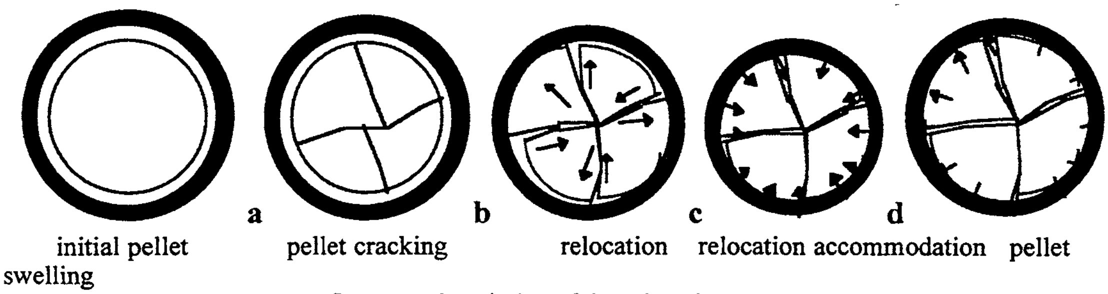


figure 1 : description of the relocation process

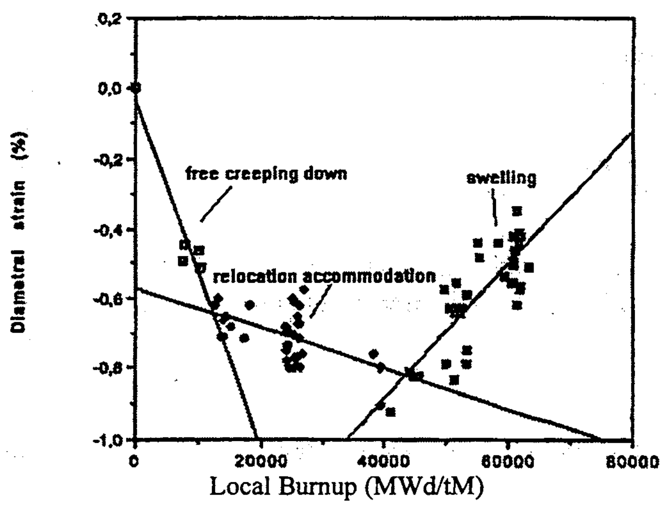


figure 2 : Evolution of cladding deformation

a) Pellet cracking

Because of the thermal properties of the uranium dioxyde and due to the cylindrical geometry, the radial distribution of temperature in the pellet has a parabolic shape with a large radial gradient. Therefore a tensile hoop stress appears in the fuel periphery which may reach the fracture threshold. The typical crack pattern observed on a rod irradiated under normal conditions (figure 3) shows several radial cracks the number of which mainly depends on the linear heat generation rate (LHGR).

b)Pellet relocation

As long as the pellet-cladding gap is open, the cladding creeps down as a consequence of the external pressure of the reactor coolant. The pellet-cladding mechanichal interaction (PCMI) is experimentally detected as regular ridges, that reproduce the heated pellets shape, first appear on the cladding (during the second cycle of irradiation for standard fuel rods). The one dimensional description which considers thermal expansion, densification and swelling, always over-estimates the burn-up when the PCMI occurs. The fractured pellet diameter is then much larger than the calculated one with the previous hypothesis. Indeed, fracturing has freed thermal strains, the shape of the fragment is then modified as shown in the figure 9. Moreover, the fragments move outwards because of gravity and rodlet vibrations. Obviously there is a random nature of this movement. The combination of these two phenomena is called relocation.

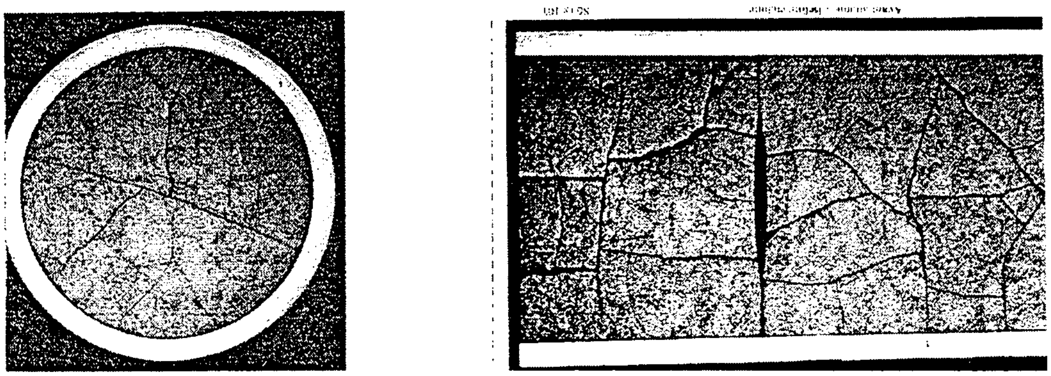


figure 3 : Typical radial and axial crack patterns

c) Relocation accommodation

As irradiation proceeds, the cladding keeps on creeping down radially while the fragments increase in volume due to the swelling. As the cladding comes in contact with the pellet fragments, it pushes back the pieces inwards. This is called relocation accommodation or soft contact. The gathering of the fragments is more and more difficult as their free play is decreasing, because of the fragment-fragment mechanical interaction. This resistance can be best visualized as an hardening process. Thus the down-creeping rate decreases until the pieces are almost completely in their initial place. Nevertheless, the accommodation is never totally completed, the apparent pellet diameter always remains larger than the theoretical one because of the shape of the fragments.

d) Pellet swelling

When the accommodation is completed, the volumetric increase of pellet fragments due to swelling has to be supported entirely by straining the cladding. The cladding creepdown is then reversed. The pellet-cladding interaction condition is now defined as "hard contact".

1.2 - Experimental results

Lots of experimental data are available from standard PWR fuel rods irradiated in PWR under standard conditions. End-of-life profilometries, pellet stack and rod lengths are available for different burn-up. The comparison (calculated vs measured) leads to whole code behavior validation rather than to the relocation model validation only because the calculated diameter depends on many other models such as fuel densification or cladding creep laws. However, assuming all the other phenomena are accurately predicted, the calibration of the modelling is possible considering especially the fuel rods irradiated during two and three cycles. Indeed, during this phase called "soft contact", the cladding diameters predicted without the modelling of the relocation phenomena were too much small because the creeping down of the cladding was not pertubed by the location of the fragments.

In order to have access to the real strains induced by PCMI, CEA has developped specific experiments with an original device [2]. In these experiments, cladding deformations can obviously be measured after irradiation and power transient and the cladding diameter evolution can especially be followed in-situ during irradiation all along the fuel rod. A specific short fuel rod has been designed with especially large diameter pellets so that the pellet-cladding gap can be closed at a LHGR of about 17 $W.mm^{-1}$. Thus the use of fresh fuel prevented one from burn-up related phenomena and the effects of thermal expansion and of relocation were singled out. Several power transients induced large diameter changes that proved the relocation of the cracked pellets. Kinetics data have been obtained during power levels. Effects of power cycling were also highlighted.

1.3 - Modelling and programming

a) Framework of the model

The framework of this modelling is described in the flow chart presented in figure 4.

Using a semi-empirical process, the location of the pellet fragments is defined by its quasi-static equilibrium. Therefore, the fragment number and the various interactions have to be estimated.

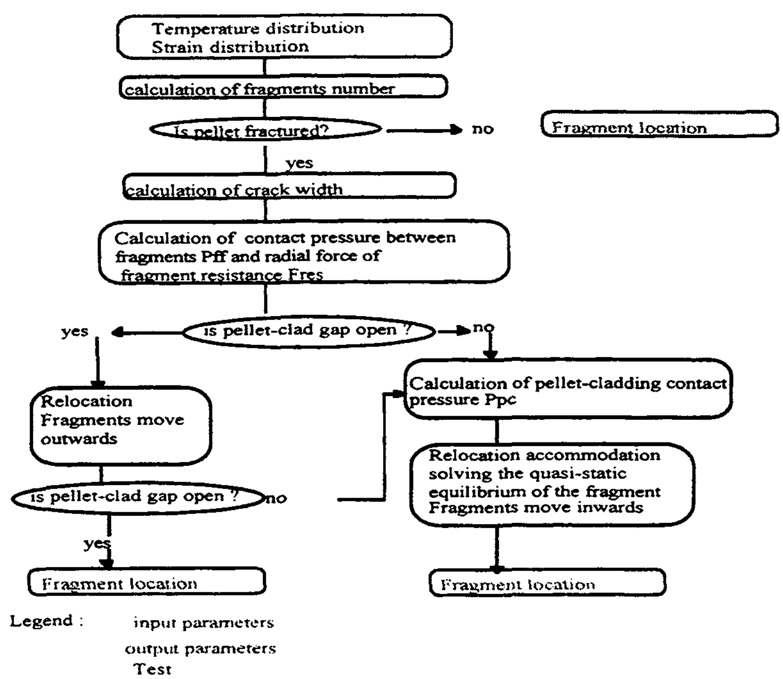


figure 4 : fuel relocation modelling flow chart

b) modelling

As explained before, the pellet cracking mainly depends on the LHGR. Different authors (OGUMA [3] for instance) tried to predict the number of cracks thanks to FE calculation and proposed, the evolution shown in figure 5 . However, the circumferential crack predicted is not experimentally observed at this level. Such calculations are difficult because of boundary conditions.

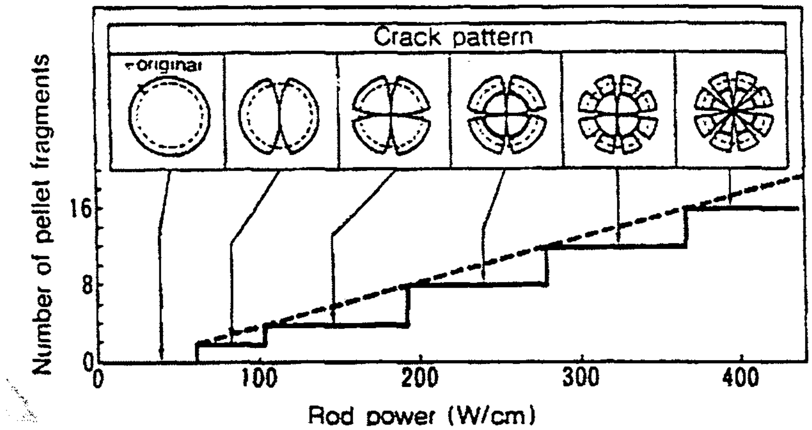


Figure 5 : changes in crack pattern during rise to power

In the present modelling, the number of radial cracks is defined as a fonction of the radial gradient of temperature and the saturation value is supposed to be 8 radial cracks. The cracking pattern considered is regular. The fragments have an ideal symmetric shape.

Once the number of fragments is known, one estimates the heated shape of the fragments in order to calculate the interaction forces between neighbouring fragments. The bulging of the fragments induced by different radial gradients is easily calculated [4] with the following hypothesis : elastic behavior, fragment is not restraint in any direction, the radial distribution of thermal temperature is not changed by the fractured geometry.

Considering a half fragment, the length of the heated pellet arc $A_1(ir)$ for ir-mesh is given by (figure 6) :

$$A_1(ir)= \frac{\alpha}{2} r_o(ir).(1+\varepsilon_{\theta\theta}^{therm}(ir)+\varepsilon_{\theta\theta}^{perm}(ir)) \qquad (1)$$

where $\varepsilon_{\theta\theta}^{therm}$, $\varepsilon_{\theta\theta}^{perm}$ are respectively the thermal circumferential strains and the permanent circumferential strains (densification,swelling) calculated with CYRANO3 ; r_o is the average as-fabricated radius of the ir-mesh considered and α the angle of the fragment defined by the number of cracks $\alpha = \frac{2\Pi}{N_{frag}}$.

Due to pellet cracking, the newly created surfaces present a roughness of the magnitude of the grain size. This rouhgness (ρ) has then to be added to the length of the arc in order to estimate the local width of the fragment A(ir) :

$A(ir)=A_1(ir)+\rho(ir)$ (2)

Facing the effect of power cycling in the analytical experiment, the following assumptions are made : the fragments movements induced by the action of the cladding cause the roughness wear because of friction forces. This wear is supposed to be proportionnal to the contact pressure between fragments and to the fragment displacement. The wear coefficient also depends on the displacement rate and on the local burn-up.

Let us calculate the available place for the fragment (B(ir)) :

$$B(ir)=\frac{\alpha}{2}(r_a(ir)+\Delta_{frag}) \quad (3)$$

where $r_a(ir)$ is the heated average radius of the mesh calculated with $r_a(ir)=r_0(ir)x(1+\varepsilon_{rr}^{tot}(ir))$ where $\varepsilon_{rr}^{tot}(ir)$ is the total radial strains calculated with CYRANO3. Δ_{frag} is the fragment location.

The crack width is then calculated with :

$$w(ir) = 2\,B(ir)-2A(ir) \quad (4)$$

If the crack width is negative then the contact pressure between two neighbouring half fragments is given by :

$$Pff(ir) = -\frac{w(ir)}{A(ir)}E(ir) \quad (5)$$

with E(ir) the local Young modulus depending on temperature and burn-up.

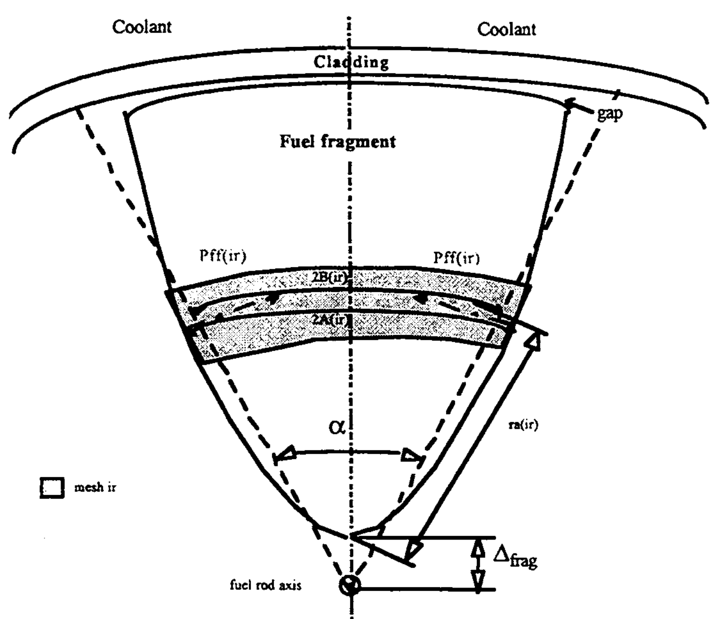


figure 6 : fragment fragment contact pressure calculation

Fragment relocation :

When the pellet-cladding gap is open, the minimum fragment displacement (Δ_{frag}^{1})is defined by the location where the cracks between neighbouring fragments is open. However, in order to include the random nature of the phenomena the effective location is:

$$(\Delta_{frag}) = \max[\Delta_{frag}^{1} \ ; \ 0{,}3\ Jc]$$

where Jc represents the hot pellet-cladding gap calculated with CYRANO3.

Fragment relocation accommodation :

When the cladding fragments contact is established, the pellet cladding contact pressure (Ppc) is calculated.

Using the previous equations (1) to (5), the resistance force induced by contact (Fres) is calculated.

$$Fres = \sum(Pff(ir).L(ir)) \text{ with L(ir) the mesh length.} \qquad (6)$$

In order to take into account the random effects of relocation, a resistance force (Fkin) that is proportional to the fragments velocity is introduced. It represents the resistance of the fragments induced by the non uniform displacement of the fragments in the (r, θ) plane.

The solution of the following equation defines the fragment location (Δ_{frag}) :

$$2.Fres.\sin(\frac{\alpha}{2}) + Fkin + \alpha.rclad.Ppc = 0 \qquad (7)$$

with rclad the internal heated cladding radius.

2 - IMPLEMENTATION IN THE CODE CYRANO3

This modelling has been introduced in the CYRANO3 code [5] and [8]. Accounting for the intricate phenomena, the development of a new model clearly affects the other calculations. A short description of the code structure is proposed in order to clarify in the second part the effects of the relocation model.

2.1 - General CYRANO3 Code structure

The improvement of the fuel rod overall behavior prediction requires more and more sophisticated modelling that needs consistent mechanical/mathematical concepts. Because a pertinent framework was necessary to integrate in a well-considered way the physical behavior models, a new computer modelling has been developped by EDF during the last six years. It provides a hierachical and flexible structure that offers all features necessary to be used as tool for research or design applications. It was developped in the respect of the Quality Assurance rules.

Considering the complexity and the intricate physical and mechanical phenomena involved, simplifications have to be assumed. The most common assumption concerns the geometric modelling of the fuel. In order to limit the computer storage and the running time costs, the structural analysis is performed with a quasi-two-dimensionnal description. The whole fuel rod is then represented by a stack of one-dimensionnal radial calculations coupled axially by the coolant energy equation, a common internal fuel rod gas pressure and by axial forces modelling. The rough logic flow of CYRANO3 is presented above.

The structure of the program is quite similar to the last fuel performance codes being developped [6]. The major specific phenomena due to non axisymmetric conditions and axial effects are included in CYRANO3 : mechanical axial coupling, hourglassing effects, ridging formation, cracked pellet effects.

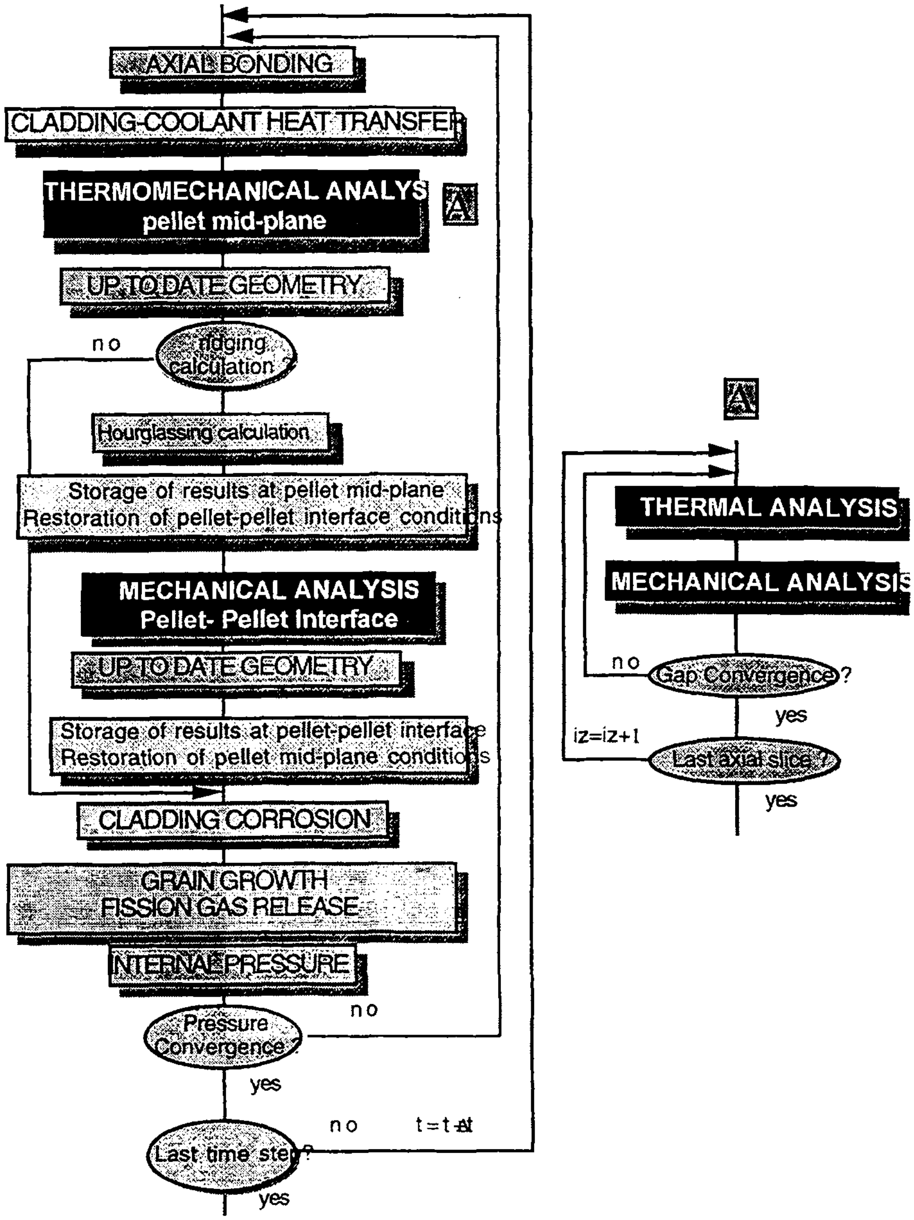


Figure 7 : CYRANO3 general flow chart

2.2 - Consequences of this modelling

a) internal pressure calculation

As the pellet fragments move outwards, part of the void volume, which was initially located only in the pellet cladding gap, is redistributed in the opened cracks between the fragments and in the remaining pellet-cladding gap. This volume transfer is introduced in the rod internal pressure calculation .

b) thermal analysis

The pellet-cladding gap decrease induced by the movements of the fragments has a major influence on the thermal behavior of the rod. Indeed, the gap conductance depends on the gap width. However, the gap conductance modelling in CYRANO3 already takes into account this effect thanks to the Mac Donald et Weisman modelling [7]. So it has been decided to keep this formulation and to define two values of the gap width depending whether we calculate thermal or mechanical behavior.

c) mechanical axial coupling

At each time step, the axial forces are calculated resolving the axial equilibrium between the pellet stack and the cladding with localized or uniform contacts accounting for the fuel column weigth above each axial location. The calculated axial forces are then introduced as imposed stresses in the radial axisymmetrical calculation.

The four differents modes of axial interaction between pellets and cladding are presented in the figure 8. If the radial gap is open the fuel may slip in the cladding without axial stresses. As the gap is closed, the pellets might be completely wedged to the cladding so that they have the same displacements (bonding conditions) or the contact pressure is small enough to allow relative axial displacement (sliding friction). Moreover section without radial contact may be trapped by sections above them having radial contact. The main problem is to describe the criteria that define whether the interaction conditions are sliding or bonding conditions. The sliding condition is not yet introduced in the present version of the code. The criteria of bonding conditions were improved thanks to the relocation modelling.

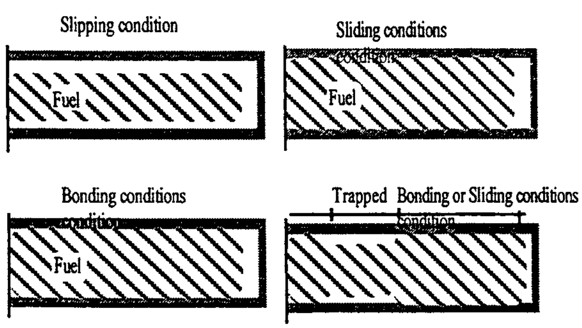


figure 8 : axial interaction modes

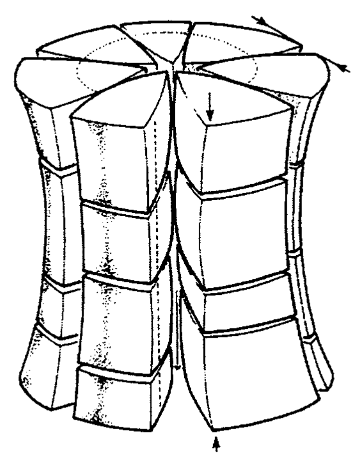


figure 9 : pellet hourglassing

Indeed, axial bonding is supposed to occur as soon as hard contact between pellet and cladding is established. The hard contact definition is now based on the following assumptions : the pellet-cladding contact pressure is greater than a calibrated threshold and the pellet fragments displacement rate is lower than a given value. Pellet and cladding are assumed to remain bound until the pellet gap reopens.

d) pellet ends effects

As soon as pellet cladding mechanical interaction occurs, ridges induced by the hourglassing shape of the pellets (figure 9) are observed on the cladding. Using two- and three-dimensionnal finite element modelling, a semi empirical formulation has been established. The pellet radius increase induced by hourglassing is calculated and is added to the permanent strains calculated at pellet mid-plane. This option allows to estimate the maximal strains and stresses in the cladding at ridges location where cladding failures occur.

In the analytical experiment, the variation of cladding diameter during power level was greater at pellet-pellet interfaces than at pellet mid-planes. This observation is consistent with the process developped which assumes that the fragment location depends on the pellet-cladding contact pressure. Considering the specific calculation of the ridges with CYRANO3 ,the fragments location is assumed to be calculated independently at pellet-pellet interfaces and at pellet mid-planes.

3 - CALIBRATION AND EVALUATION OF THE MODEL

The relocation model has been calibrated on the basis of the CEA analytical experiments. The figures 10 and 11 compare the measured diametral evolution of the cladding and the calculated one at pellet mid-plane and pellet-pellet interface. Both calculated kinetics and magnitudes are in good agreement with the measurements.

Analytical experiment
Average cladding diameter evolution

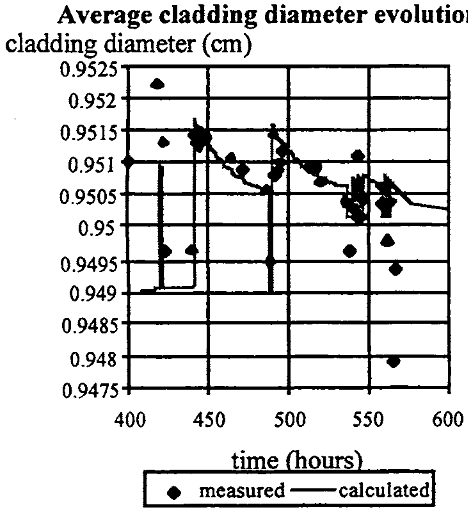


figure 10

Analytical experiment
Average cladding diameter evolution
at pellet-pellet location

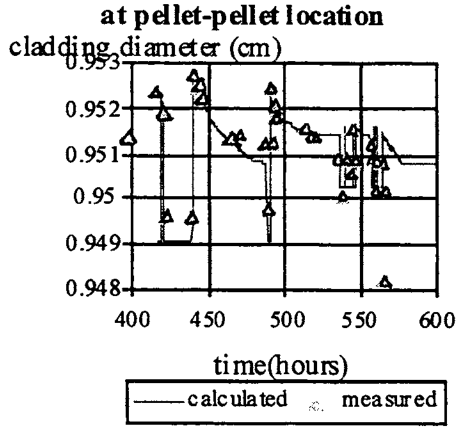


figure 11

Once the model was calibrated on this base, it has been applied to the standard rods irradiated under normal operating conditions.

Figures (12 to 16) show the comparison between the calculated profilometries and the measured one for fuel rods irradiated respectively during one to five cycles in a PWR. The first one is presented in order to prove that the creeping down is correctly predicted. The predicted profilometries are in good agreement with the measured one whatever the burn-up.

Considering the fuel stack length and the rod length, the comparisons calculations vs measurements validate the axial bonding modelling (figures 17 and 18). Nevertheless, this modelling should be modified to take into account axial sliding conditions between pellet and cladding. Moreover, axial relocation induces an increased length which might be hidden at the present time by the swelling modelling. Further work has to be done including density comparison in order to validate separetely the different models. Lastly, the major importance of the definition of the axial bonding criteria has to be noticed. Indeed, as far as high burn-up fuels are concerned, the axial interaction increases the rod length so that the internal pressure is directly influenced. Considering the PCMI, the axial interactions strongly modify the circumferential stress calculated in the cladding. The time where the axial bonding occurs has to be accurately predicted especially during the power increase.

Diametral profilometry of a rod irradiated during 1 cycle in a PWR

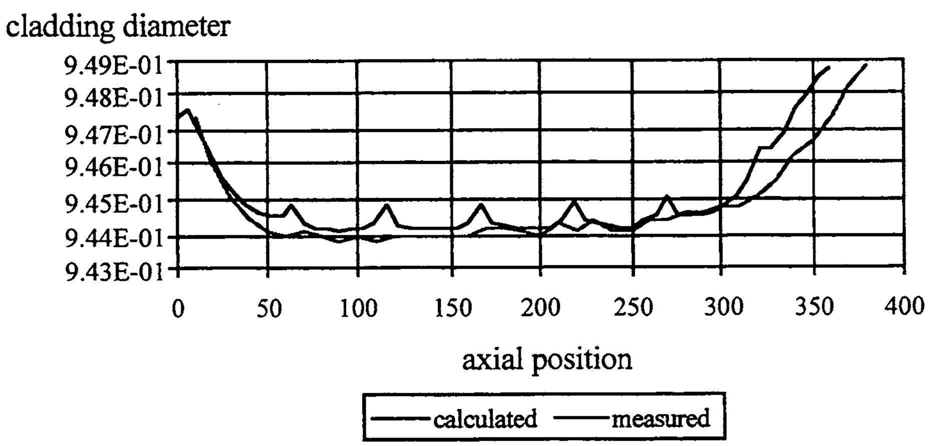


figure 12 :

Diametral profilometry of a rod irradiated during 2 cycles in a PWR

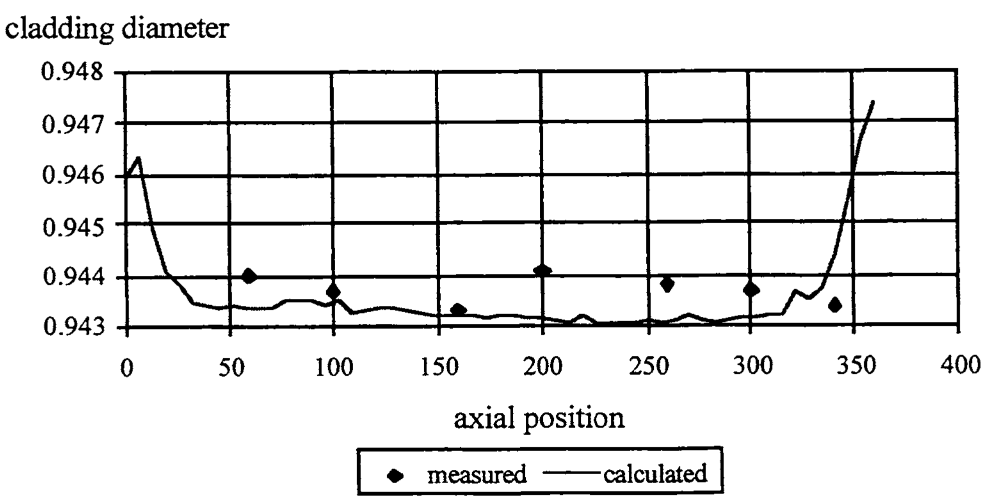


figure 13

Diametral profilometry of a rod irradiated during 3 cycles in a PWR

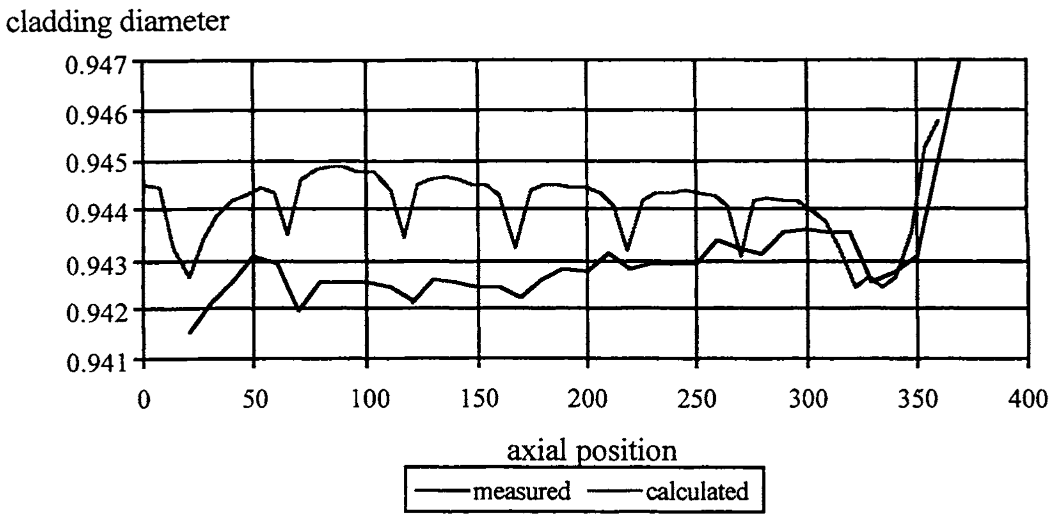


figure 14

Diametral profilometry of a rod irradiated during 4 cycles in a PWR

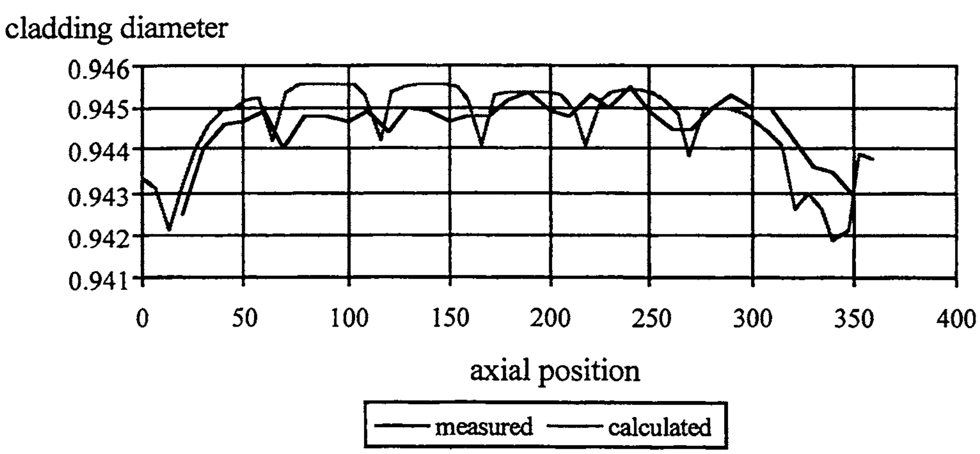


figure 15

Diametral profilometry of a rod irradiated during 5 cycles in a PWR

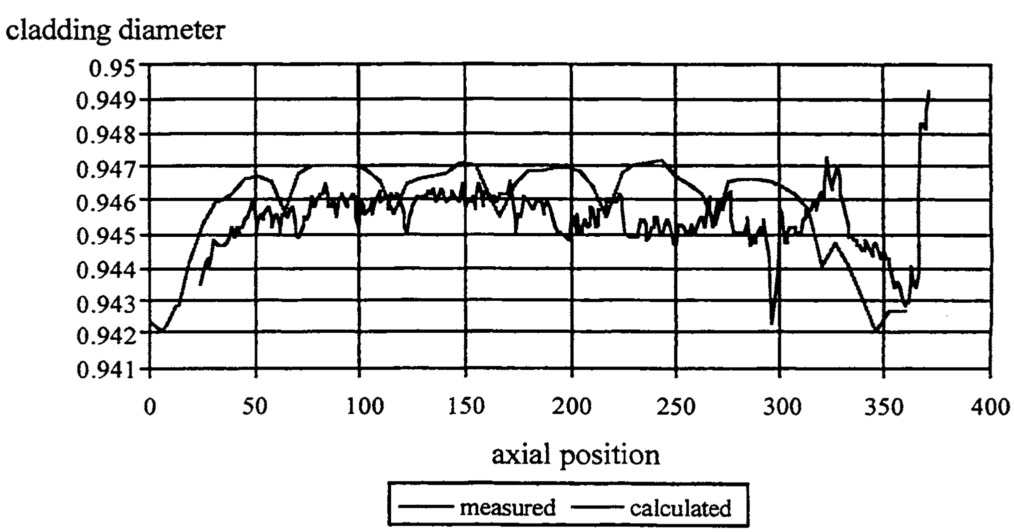
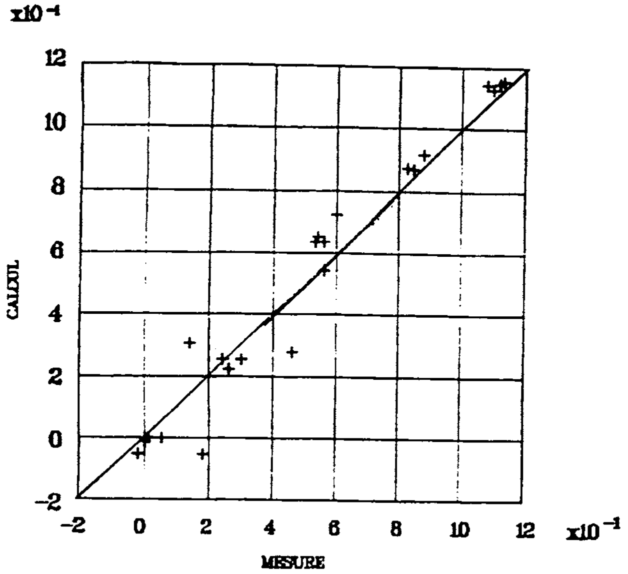
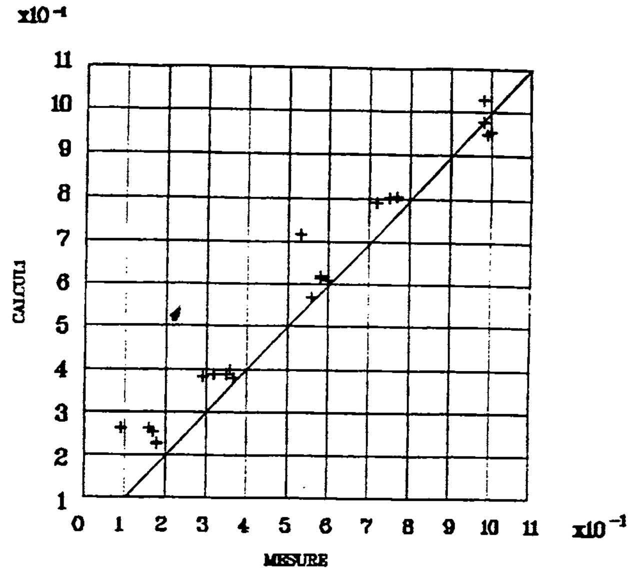


figure 16



Fuel stack elongation (measured against predicted)
figure 17



Fuel rod elongation (measured against predicted)
figure 18

A first evaluation has then been performed in order to estimate the modelling behavior during theoretical power ramps. Assuming a constant power level of 200 W/cm, a power increase is modelled at the rate of 125 W/cm/mn with a peak power of 450 W/cm for various burn-up levels. The average stresses in the cladding are strongly increased for the fuel rods with a burn-up from 10 to 30 GWd/tU, that is, during the "soft contact" period.

In order to validate this modelling, the comparisons between measured and calculated diametral deformations have to be performed on the basis of the fuel rods irradiated during the OVERRAMP and SUPERRAMP programs.

4 - DISCUSSION AND CONCLUSIONS

The model presented in this article provides correct average strains of the cladding at mid pellet as well as at pellet ends for fuel rods irradiated under normal conditions. The pellet-cladding gap time to closure is also more accurately predicted. Moreover the fictive power ramp calculation showed that in spite of an increased contact pressure, the fragments do not move inwards thanks to the increased pressure between the neighbouring fragments. PCMI effects can thus be accurately predicted in normal and off-normal operating conditions.

However several assumptions and choices that have been made, remain open for discussions. For instance, the empirical equations proposed for the wear of the fragment roughness could be improved and based on more physical grounds. To this aim, several types of experiments that were not available at the time this study was performed, are required in order to characterize the effect of the power ramp rate upon the wear and to developp physical formulations. Another important assumption has been made to simplify the modeling : the distinction between the thermal and the mechanical gaps. Indeed, from the purely physical viewpoint, it does not seem satisfactory to deal with two values of the same physical quantity. Nevertheless the axisymmetric description of the finite element calculations prevents from following another way. The only possibility to cancel this assumption is to perform 2D calculations in the (r, θ) plane.

ACKNOWLEDGEMENTS

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REFERENCES :

[1] I. SCHÄFFLER ; Modelling of the mechanical behavior of zircaloy-4 cladding tubes from unirradiated state to high burn-up ; International Topical Meeting on Light Water Reactor Fuel Performance, 1997, p 219-225.

[2] L.CAILLOT, G.DELETTE, B.JULIEN, J.C.COUTY ; Impact of Fuel Pellet Fragmentation on Pellet-cladding Interaction in a PWR Fuel Rod : Results of the RECOR Experimental Programme ; SMIRT 97, communication C02/4, Lyon - August 17-22, 1997

[3] M. OGUMA ; Cracking and relocation behavior of nuclear fuel pellets during rise to power; Nuclear Engineering and Design, 1983, 76, 35-45.

[4] L.A. WALTON, J.E. MATHESON ; FUMAC- A new model for light water reactor fuel relocation and pellet cladding interaction, Nuclear Technology, février 1984, vol. 64, 127-138.

[5] D.BARON ; Les apports du logiciel CYRANO3 dans la simulation du comportement thermomécanique des crayons combustibles REP, Séminaire Mécanique EDF 1996.

[6] K. LASSMANN ; The structure of fuel element codes ; Nuclear Engineering and Design, 1980, 57, 17-39.

[7] P.E. MAC DONALD, J. WEISMAN Effect of Pellet Cracking on Light Water Reactor Fuel Temperatures, Nuclear Technology 31, december 1976, p 357.

[8] D.BARON et al ; CYRANO3 : Un logiciel de nouvelle génération pour simuler le comportement des crayons combustibles en réacteur ; Journal EPURE (EDF Etudes et Recherches) n°55, Juillet 1997.