SMiRT-12 / K. Kussmaul (Editor)

C01/2

MODELIZATION OF THE MECHANICAL BEHAVIOUR OF FRACTURED NUCLEAR FUEL PELLETS

C. Bernaudat

EDF/SEPTEN 12-14 avenue Dutriévoz, F-69628 Villeurbanne, France

ABSTRACT

The mechanical behaviour of fractured nuclear fuel pellets is far from simple. In order to take into account this behaviour correctly, a lot of phenomena must be examined, and, even in such case, it is rather difficult to assess physically all of them.

This paper deals with some mechanical and physical phenomena which participate to the total radial deformation of the fuel rod, during its in-reactor lifetime. These phenomena are mainly related to pellet fracturation, and, during power transients, gaseous swelling. Based on qualitative considerations and experimental data, empirical models for both pellet fracturation and gaseous swelling have been established, introduced into the TRANSURANUS thermo-mechanical fuel code [1] and calibrated against different experimental results.

I. INTRODUCTION

A lot of phenomena are involved in the radial deformation of nuclear fuel pellets, and their knowledge is necessary to predict accurately the overall behaviour of the fuel rod. This is of a great importance especially when pellet-clad mechanical interaction (PCMI) occurs, when the pellets and the cladding come into contact. As soon as this contact is established, the stresses in the cladding are strongly modified and, during a power ramp, cladding failure can be observed. So it is very important to know when and how PCMI occurs, and so, what is the contribution of each phenomenon to the overall deformation of the fuel pellets.

The phenomena which are accounted for in the paper are :

- pellet fragment relocation, which is directly induced by its fracturation ;
- relocation accommodation, which is the consequence of PCMI when the pellets are fractured ;
- healing and gaseous swelling, which both occur at high temperature, in off-normal conditions.

Chapter II is a qualitative description of all these phenomena, based on physical and mechanical considerations. On the basis of experimental results (rod profilometries and cladding strains observed during power ramps), empirical models have been established and introduced into TRANSURANUS code, as indicated in chapter III. Then (chapter IV), these models have been successfully validated on the basis of other experimental results.

II. DESCRIPTION OF THE PHENOMENA

II.1. Pellet fracturation and relocation

Pellet fracturation occurs at the very beginning of the in-reactor life of the fuel, i.e. during the first power rise : the heating of the central area of the pellet induces its thermal dilatation ; thus, a tensile hoop stress appears in the fuel periphery. When this tensile stress reaches a certain threshold, the pellet is fractured. The fracturation threshold has been examined by several authors [2]. During pellet fracturation the resulting fragments move outwards : this causes a pellet radius increase which is called relocation. The evidence that this relocation occurs very early is assessed by the fact that the effects of PCMI can be observed at relatively low burn-ups : for example, on some standard fuel rods, regular ridges, which reproduce the shape of the heated pellets ("bamboo effect"), appear during the second cycle of irradiation (burnup = 15000 MWd/tU), and zirconia is visible on the inner wall of the cladding, indicating that a pellet-clad contact has occurred.

II.2. Relocation accommodation

After the first pellet-cladding contact, cladding creepdown goes on, but with a slower rate than before the contact : the rod external diameter decreases then slowly. For instance, in standard fuel, this slow cladding creepdown occurs approximately during the second and third cycles of irradiation (15000 MWd/tU < burnup < 35000 MWd/tU). This phenomenon can be interpreted as follows : during PCMI, the cladding creepdown "pushes" the pellet fragments together again, and so the relocation is reduced : this is called relocation accommodation. But the gathering of the fragments is not an easy task : because the fracturation has freed thermal strains in the fuel, the fragments can be considered as a puzzle whose pieces are not very well adjusted. Moreover, the surface roughness of the fragments, which is of the order of magnitude of the grain size, cause frictions between neighbouring fragments. So it can be understood that the smaller the residual relocation, the more difficult its accommodation.

Figure 1 shows the evolution of rod deformation vs. burnup. As can be seen, this deformation presents three phases : the first corresponds to clad creepdown, the second is due to accommodation and the third one is governed by fuel swelling, when accommodation is completed.

II.3. Pellet healing

At high temperature (e.g. during a power transient), and when the pellet cracks are sufficiently closed, thermal diffusion can allow the build-up of "bridges" of material between neighbouring fragments : this is called healing. This phenomenon induces a particular crack pattern which can be explained as follows : during fuel cooling down, the central area of the fuel, where cracks have disappeared by healing, undergoes a thermal contraction. So a radial tensile stress develops between the center and the periphery of the pellet. Thus, a circumferential crack forms and connects the remaining peripheral cracks together. Figure 2 [3] clearly shows the effects of healing on the fuel : a cylindrical crack shares the center from the periphery, and the central cracks have partially disappeared.

II.4. Gaseous swelling

During experimental power ramps [4] [5] , large rod diameter increases have been observed and, at the same time, a strong increase of fuel porosity in pellet center and a large fission gas release occurred : this is gaseous swelling. A careful examination of the deformation measured on non-failed rods shows that this phenomenon depends on local temperature, open porosity and total amount of fission gas retained in the fuel grains before transient. Gaseous swelling can be roughly described as follows : when the fuel is heated, intragranular and intergranular bubbles form and grow very rapidly by coalescence. The high hydrostatic pressure in the bubbles causes grain boundary rupture, bubble interconnection with the rod free volume, so that almost the whole fission gas is released from the central parts of the fuel. Figure 3 shows a longitudinal ceramography of a fuel rod ramped during 1 minute : the complete dish filling indicates that large gaseous swelling and plastic strain occurred, with very fast kinetics.

III. MODELIZATION AND PROGRAMMATION

III.1. Fuel relocation

Fuel relocation induces an instantaneous pellet diameter increase, which is approximately 40% of the as-fabricated pellet-clad gap. Fuel hoop stress is calculated and when the fracture threshold is reached, the relocation model is activated. The resulting diameter increase is therefore limited by the actual gap, and the corresponding gap volume is transferred to the crack volume. At the same time, the mechanical properties of the fuel material are downgraded [6] [7] [8] .

III.2. Relocation accommodation

When PCMI occurs, relocation accommodation begins. Its kinetics is the result of an equilibrium between the pellet-clad contact pressure and the resisting friction forces between neighbouring fragments. So, accommodation is modeled by the means of a relocation reduction rate which is proportionnal to the contact pressure and depends on the residual relocation. The assumptions made in the previous chapter also suggest that the kinetics is "fast" when PCMI begins, and "slow" when accommodation is almost completed. The transition between "fast" and "slow" kinetics occurs when the residual relocation (whose order of magnitude is the same as that of the crack width) is half the grain size.

Figure 4 shows the flow-chart of the modelization of relocation-accommodation.

III.3. Crack healing

Crack healing has not been modeled as a separate phenomenon, but some of its mechanical effects have been accounted for, especially during power transients :
- restoring mechanical properties (Young's modulus and Poisson's ratio) of the uncracked fuel material ;
- stopping the accommodation of the relocation, when PCMI occurs.

III.4. Gaseous swelling

In normal steady-state conditions, the MATPRO [9] model has been used. But in transient conditions, this model gives too low values for the rod radial deformation. So we established an empirical model, based on the qualitative physical considerations mentioned above.

During a time-step dt, the gaseous swelling increment dv is given by :

$$dv = A(G).B(P).C(T).\exp(-(t-ttran)/\tau).dt/\tau \qquad (1)$$

where :
- G is the local fission gas concentration in the fuel (μmol/mm3) ;
- P is the open porosity before the transient (%) ;
- T is the local temperature (°C) ;
- t is the time (h) ;
- ttran is the time when the transient starts (h) ;
- A(G) is an increasing function of G ;
- B(P) is a decreasing function of P ;
- C(T) is an increasing function of T ;
- τ is the time constant of the gaseous swelling (h).

The evolution of the different function A, B, C is quite self-explanatory. An increasing quantity of retained fission gas will lead to a larger gaseous swelling. A large pre-existing open porosity (as is often the case in AUC fuels) leads to decreasing swelling, because the open porosity allows a large fission gas release without necessarily growth and interconnection of gas bubbles. A high temperature activates thermal diffusion of gas in grains and grain boundaries and increases their internal hydrostatic pressure, so that the growth, coalescence and interconnection of bubbles is accelerated. The following expressions have been chosen for the functions mentioned hereabove :

$$A(G) = Max(1., 28.1G-6.03) \; ; \qquad (2)$$

$$B(P) = 0.64/P^{1.25} \; ; \qquad (3)$$

$$C(T) = 1.10^{-27}\, T^{8}. \qquad (4)$$

The exponent of eqn.(4) has been chosen because the MATPRO model, even with a correcting factor, is too temperature-sensitive in the range of 1000-2000°C.

To simulate the kinetics of gaseous swelling, the time-constant τ has an order of magnitude of a few minutes.

III.5. Model programmation

All these models have been computed and introduced in the TRANSURANUS code, which simulates the whole behaviour of a fuel rod during its in-reactor lifetime. Thermal, mechanical and physical phenomena are taken into account in the code. Its modular conception makes the introduction of new models an easy task.

IV. MODEL VALIDATION

Relocation and accommodation have been calibrated against experimental profilometries of fuel rods irradiated in PWRs at various burnups (2, 3 and 4 cycles of irradiation). The calibrated models have then been applied to other rods, and especially the rods irradiated in the TRIBULATION program [10]. Figures 5 to 7 show the comparison between experimental and calculated profilometries of three rods with different designs. Figure 8 is the same comparison, for a fuel rod irradiated in a PWR during 3 cycles. In both cases the accuracy is quite good.

To assess healing and gaseous swelling models, a comparison has been made between the measured and calculated radial deformations during the ramps, for all the non-failed rods of the OVERRAMP and SUPERRAMP programs, for which such data are available. Both KWU and WESTINGHOUSE designs are considered. Figure 9 is a comparison between the measured and computed profilometries of PW3/2 rod. Figure 10 gathers the radial deformations (predicted vs. measured) for all the non-failed rods.

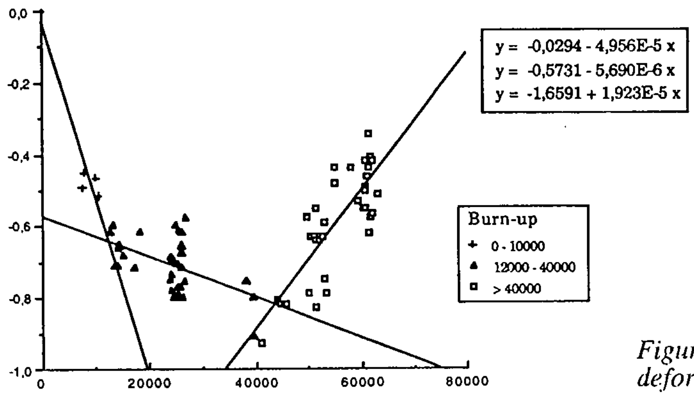

Figure 1 (left) : Radial fuel rod deformation (%) vs. burnup (MWd/tU)

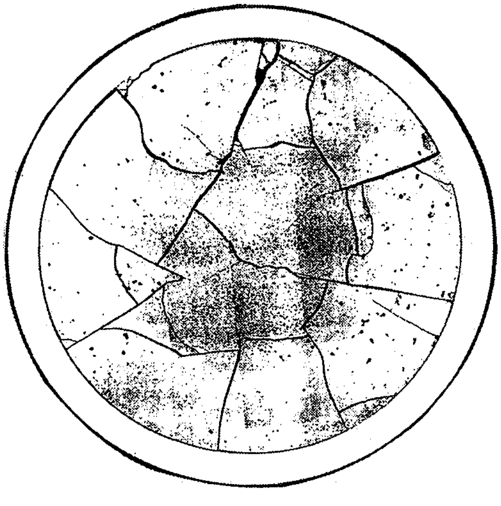

Figure 2 : Transversal crack pattern due to healing during a power ramp

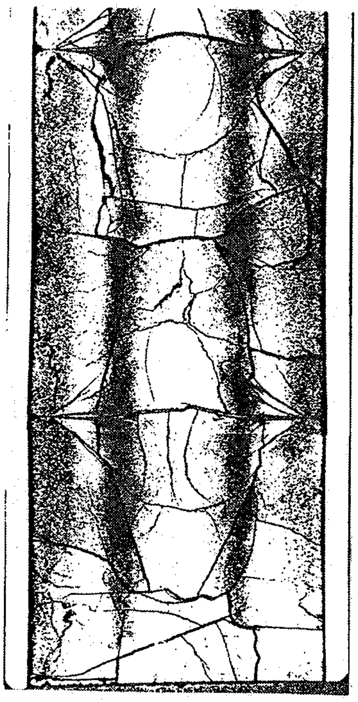

Figure 3 : Large gaseous swelling on fuel centerline after a power ramp

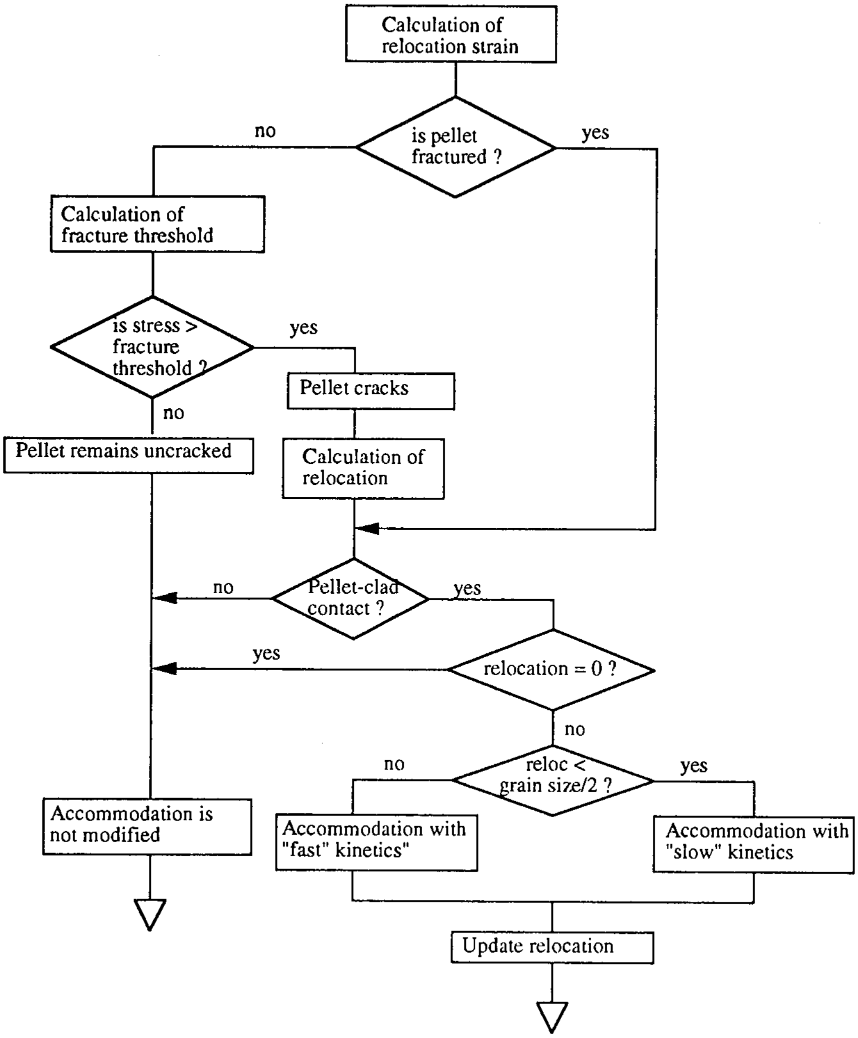

Figure 4 : Flow-chart of the relocation-accommodation model

N.B. : In figures 5 to 9 hereafter, the thick line represents the experimental profilometry, and the fine line is the calculated one.

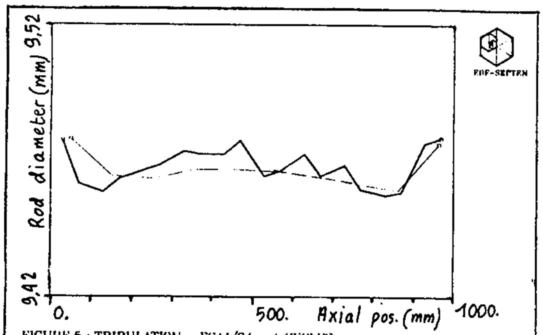

FIGURE 5 : TRIBULATION – FGA1/34 – 4 CYCLES

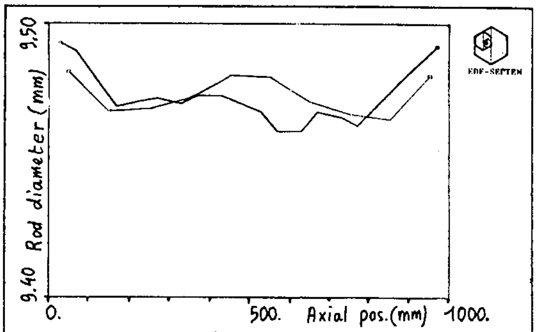

FIGURE 6 : TRIBULATION BN1/4 3 CYCLES

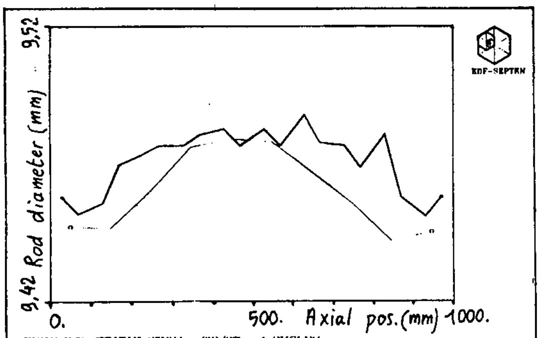

FIGURE 7 : TRIBULATION - W3/27 - 4 CYCLES

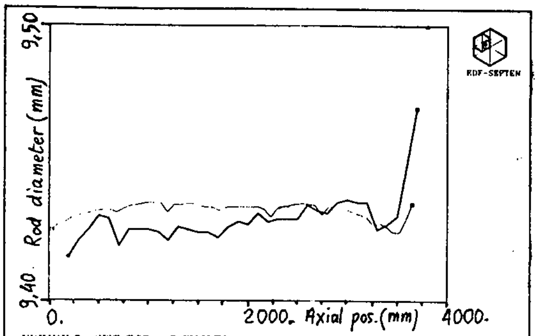

FIGURE 8 : PWR ROD - 3 CYCLES

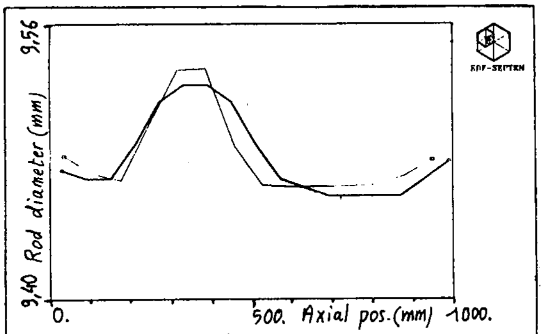

FIGURE 9 : SUPERRAMP - PW3/2

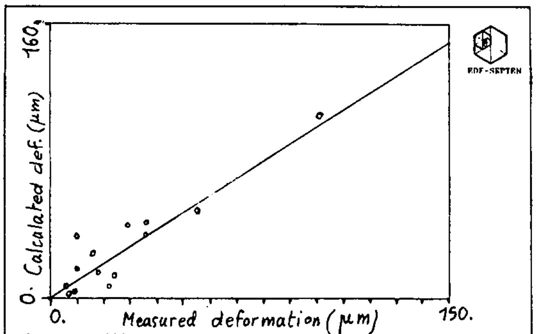

FIGURE 10 : ROD RAMP DEFORMATIONS

V. CONCLUSION

Relocation, accommodation and transient gaseous swelling have been modeled and introduced in the TRANSURANUS code. With these models, the behaviour of fuel rods in normal and off-normal conditions (power ramps), and especially their radial deformation, can be accurately predicted.

REFERENCES

[1] K. LASSMANN and H. BLANK, *Nucl. Eng. Des. 106 (1988) p. 291.*

[2] A.G. EVANS and R.W. DAVIDGE, *Jn. Nucl. Mat. 33 (1969) p. 249.*

[3] J.C. LAVAKE and M. GAERTNER : "High Burnup PWR Ramp Test Program : Final Report" *KWU-CE, Dec. 1984.*

[4] S. DJURLE : "Final Report of the OVERRAMP Project" *Studvisk STOR-37 - May 1981.*

[5] S. DJURLE : "Final Report of the SUPERRAMP Project" *Studvisk STSR-32 - Dec. 1984.*

[6] H.J. RITZHAUPT-KLEISSL and M. HECK :
"Modeling Fuel Cracking, Relocation and Crack Healing in the SATURN-FS Code"
7th International Seminar on the Mathematical Mechanical Modeling of Reactor Fuel Elements, La Jolla, Aug. 1989.

[7] R. ZIMMERMAN, *Jn. Mat. Sci. Letters 4 (1985) p. 1457.*

[8] E.D. CASE, *Jn. Mat. Sci. 19 (1984) p. 3702.*

[9] SCDAP/RELAP5/MOD2 Code Manual, Vol. 4 : "MATPRO : A Library of Material Properties for Light Water Reactor Accident Analysis" *NUREG CR-5273/EGG-2555 (Feb. 1990)*

[10] M. LIPPENS and D. BOULANGER : "TRIBULATION, Final Report", BN-TR-89179, Sept. 1989.