and the maximum temperature which has been endured in the fuel section. The relocation is obtained by a fuel volume expansion constant along the radius. This fuel expansion and the void so introduced in the fuel yields in case of mechanical interaction with the cladding.

V.6.- Void and plutonium migration

Taking into account the local temperature, oxygen and plutonium content, we calculate with the help of out of pile thermodynamical data the vapor pressure of the plutonium and uranium oxyde species along the radius. We also calculate a diffusion coefficient in vapor phase based on gas kinetics. We then obtain the material fluxes through the thermal gradient. They are considered as mean fluxes through a homogeneous medium and it is necessary to introduce an empirical limit to fuel density in order to take into account the remaining porosity which actually cannot be dragged out from the fuel.

This procedure allows by the way the calculation of the demixion between uranium and plutonium through gas transport which is the only way we retain as we have no definite experimental evidence of plutonium migration through solid phase.

[1] M. de FRANCO J.P.G.
The thermodynamic properties of $UPuO_{2\pm x}$ described by a cluster model.
Pu and other activities . 1976

[2] Y. GUERIN. G. MARBACH
Experimental results on cladding plastic deformation.
I.W.G.F.R. meeting. CENFAR. 28 May. 1 of June.

MIXED OXIDE THERMAL BEHAVIOUR AT BOL: COMETHE III-J MODELS AND IMPACT ON POWER-TO-MELT

J. VAN VLIET
BELGONUCLEAIRE,
Brussels,
Belgium

SUMMARY

The mixed oxide thermal behaviour at beginning of life is very important because it can impose a limitation to the fuel pin peak power, and therefore to the reactor thermal output.

The relevant physical processes leading to fuel restructuring are modelled in COMETHE III-J in a kinetic way. This ensures that the temperature and power history are properly taken into account.

These models are described and their impact on the calculated power to melt early in life is analysed.

1. INTRODUCTION

High linear ratings are an essential requirement for designing a performant FBR fuel. In order to improve core thermal output and to reduce the fuel cycle cost, fuel pin linear power has to be increased near the corresponding technological limit which is the well known non melting design criterion.

Satisfying this criterion, i.e. holding the fuel peak temperature under melting point, must be maintained throughout the fuel pin life, but is difficult at start of irradiation : due to the fabrication clearance, a high thermal resistance between fuel and cladding increases fuel surface temperature and therefore the fuel overall temperature conditions.

These high temperatures, together with fission, lead to important and irreversible changes of the fuel pellet structure through such processes as cracking, sintering, equiaxed and columnar grain growth, fission gas bubble swelling, and so on.

Due mainly to fission gas bubble swelling, the fuel clad gap closes progressively, improving thereby the heat transfer between pellet and

cladding. The resulting decrease in fuel temperature quenches the still acting restructuring processes, and a quasi steady-state fuel pattern is obtained which is only modified by long term burnup effects.

The power which can be achieved in this pattern is usually significantly higher than the maximum allowable power achievable on as-fabricated fuel. In order to avoid any long term penalization on core thermal output due to early fuel behaviour, the start-up of fresh fuel should be optimized to avoid excessive central temperatures.

This optimization requires a good prediction of the transient fuel temperature evolution which occurs during restructuring. This requirement can be fulfilled by a well calibrated set of restructuring models, as those included in the COMETHE III-J computer code .

The fuel restructuring models included in COMETHE III-J are discussed in the first part of this presentation. The second part provides an illustration of those models capabilities related to the calculation of the centerline temperature at start-of-life.

2. RESTRUCTURING MODELS INCLUDED IN COMETHE III-J

2.1. Introduction

Before describing the restructuring models included in COMETHE III-J, it is useful to mention some ideas that have led to their selection.

The processes leading to fuel restructuring are quite complicate and numerous. On the other side, the models aiming at their simulation must remain simple enough to avoid excessive computing time, and sufficiently sophisticated to describe in a realistic manner what actually happens during the first days of irradiation.

Another important remark is that many fundamental features such as e.g. oxygen redistribution are not clearly understood /1/, even if it has been demonstrated that they can play a significant role. In this aspect, the development of empirical models remains possible, but has to rely on a wide enough calibration data base.

The individual model calibration and the global code benchmarking are the most important parts of code development. In the case of B.O.L. fuel behaviour, this requires a lot of very short and well instrumented experiments which are obviously rare, but essential to reduce the uncertainties on early pellet temperature distribution.

In COMETHE III-J, the most important models during fuel restructuring are related to :

- fission gas bubble swelling ;
- in-pile sintering ;
- equiaxed grain growth ;
- columnar grain growth ;
- fission gas release.

Other models devoted mainly to early chemical behaviour (oxygen and Pu redistribution) are under development and calibration /2/ but good agreement between calculation and experiment is already obtained in most situations.

2.2. Fission gas bubble swelling

Fission gas atoms generated within the fuel grains diffuse through the mixed oxide matrix, eventually being trapped by defects or going back in solution by fission fragment damage. As irradiation proceeds, fission gas atoms are trapped at grain boundaries or escape through open porosities. If temperature is high enough, the trapped atoms form bubbles which grow progressively depending on temperature, burnup and hydrostatic pressure. This phenomenon becomes significant above 1300 - 1400°C. Once bubbles are large and numerous enough, they begin to coalesce and progressively form "tunnels" which communicate with external voids through cracks or open porosity. The tunnel formation liberates the gas contained in the bubbles, the inner pressure of these bubbles decreases and the tunnel is interrupted. A dynamic equilibrium situation is reached and tunnels are in continuous process of creation and interruption. This corresponds to a saturation in the fission gas swelling which depends on temperature and hydrostatic stress.

By lack of experimental data it has been assumed that the burnup required for reaching such a saturation is temperature independent. The model equations are, if b is the local burnup, and P_o the initial pellet porosity :

$$\frac{d}{db}\left(\frac{\Delta V}{Vo}\right)_{fgb} = \frac{1}{b_s}\left[\left(\frac{\Delta V}{Vo}\right)_L - \left(\frac{\Delta V}{Vo}\right)_{fgb}\right] \quad ; \qquad (1)$$

$$\left(\frac{\Delta V}{Vo}\right)_L = \frac{P_L - P_o}{1 - P_L} \quad ; \qquad (2)$$

$$P_L = C\, f_1(T)\, f_2(\alpha_H) + P'_o \quad ; \qquad (3)$$

$\left(\frac{\Delta V}{Vo}\right)_{fgb}$ is the fission gas bubble swelling ;

$\left(\frac{\Delta V}{Vo}\right)_L$ is the temperature and stress dependent f.g.b. swelling saturation level ;

P_L is the corresponding saturation porosity ;

P'_o is the porosity that should exist without any f.g.b. swelling ;

C is the maximum saturation porosity in a stress-free 100 % dense fuel ;

$f_1(T)$ is the temperature dependence, chosen to be linear between O for a treshold temperature T_1 and 1 for a saturation temperature T_2 ;

$f_2(\sigma_H)$ is a function of the local hydrostatic stress σ_H (hot pressing) which is equal to unity under a treshold stress σ_t and which then decreases exponentially with a stress constant σ_c ; i.e.

$$f_2(\sigma_H) = \exp(\sigma_t - \sigma_H)/\sigma_c \text{ ;}$$

b_s is the burnup constant for reaching saturation.

This model is essentially empirical, and its parameters have been selected by comparison mainly with LWR experimental data which are much more numerous than FBR ones. The most important coefficients are C and b_s.

From LWR irradiation data (see e.g. /3/), the peak swelling in a stress-free oxide can be shown to be as high as 20 to 40 %, which gives an order of magnitude for C. The question related to b_s is more difficult, as it can only be deduced from parametric experiments where fuel swelling has been measured as a function of burnup (see e.g. /4/). Calibration of the model on such experiments has shown that b_s is usually about 1 at % burnup.

Concerning the hydrostatic stress effect, it must be mentioned that fission gas bubble swelling is acting in the hot part of the fuel where fuel creep modulus is rather low. Therefore the assumption of instantaneous hot pressing is well justified, except in fast power transients.

Finally, the kinetic formulation of equation (1) allows to take the temperature and burnup history correctly into account ; this equation is replaced by

$$\frac{d}{db}\left(\frac{\Delta V}{Vo}\right)_{fgb} = 0 \qquad (4)$$

in case of temperature decrease, to avoid an unrealistic sintering that should happen if the f.g.b. swelling was above its calculated saturation level.

2.3. In-pile sintering

In-pile sintering is only significant in fuels with low (85 % TD) or medium (90 % TD) density. It plays an important role in the kinetics of FBR fuel gap closure and it should be avoided by obtaining, a so-called "stable" porosity distribution as described in /5/ through adequate manufacturing process.

Usually, in FBR conditions, the in-pile temperatures far exceed the fabrication sintering temperatures. In addition to the well-known irradiation induced sintering (see abundant LWR literature), a thermal contribution can appear at high temperature, simultaneously with grain growth. This can be correlated to variations in the mixed oxide diffusion properties as suggested by Marlowe /6/ (Fig. 1). However this high temperature sintering is obviously masked by fission gas bubbles swelling, described in the preceding section ; it can therefore be neglected in a model.

The COMETHE III-J model is therefore simply given by

$$\left(\frac{\Delta V}{Vo}\right)_S = a_2 P_o \left[\exp\left(-\frac{b}{b_2}\right) - 1 \right] \qquad (5)$$

where P_o is the initial pellet porosity, a_2 being the fraction of this porosity which disappears by irradiation induced sintering, and b the local burnup.

Of course, a_2 and b_2 depend on the fuel fabrication process and present wide variations with density and manufacturer. Their value can be deduced from out-of-pile resintering tests in the following manner : when submitting the same pellet to irradiation induced sintering during a time t_{irr} and to an out-of-pile thermal resintering test performed during a time t_{th} at a temperature T, one gets the same final porosities if

$$D_{irr}\ t_{irr} = D_{th}\ t_{th} \qquad (6)$$

where D_{irr} and D_{th} determine respectively the irradiation induced and the thermally induced diffusion coefficients. These two coefficients can be written

$$D_{irr} = K'\dot{F} = K\frac{db}{dt} \quad \text{and} \quad D_{th} = D_o \exp\left(-\frac{Q}{RT}\right)$$

where $\dot{F}$ is the fission rate and b the burn-up. The equivalence between out-of-pile time and in-pile burn-up is then

$$\frac{t_{th}}{b} = \frac{K}{D_{th}} = \frac{K}{D_o} \exp\left(\frac{Q}{RT}\right) \qquad (7)$$

This equivalence allows to determine the constant b_2 from out-of-pile tests, which yield also the a_2 coefficient.

2.4. Equiaxed grain growth

Due to its thermally activated process, grain growth is quite temperature dependent and is therefore a quite useful temperature mark during long term irradiations. The model used in COMETHE III-J is mainly due to Ainscough /7/ and is given by the following relationship :

$$\frac{dG}{dt} = k_o e^{-\frac{Q_o}{RT}} \left(\frac{1}{G} - \frac{1}{G_m}\right) \qquad (8)$$

where k_o and Q are a rate constant
G is the grain size,
G_m is the temperature dependent limiting grain size, given by

$$G_m = G_{mo} \exp\left(-Q_m/RT\right) \qquad (9)$$

Moreover, the grain growth rate is set to zero when a sufficient amount of f.g.b. swelling is reached, its effect being to stop grain boundary movement by accummulation of bubbles on those boundaries.

This kinetic model is essential for understanding grain growth during short term experiments. The effect of stoichiometry on in-pile grain growth has not been modelled by lack of corresponding data, and also by lack of comprehension of the O/M redistribution process.

2.5. Columnar grain growth (c.g.g.)

Columnar grain growth is one of the most important processes occuring at start of irradiation of FBR fuel, as it decreases in two ways the centerline temperature : first, when moving toward the pellet center, the lenticular pores associated to c.g.g. leave after them a very high density material with an improved thermal conductivity ; second, the c.g.g. associated central hole formation reduces through a geometrical effect the temperature drop across the fuel.

This process, which also heals the hottest part of the pellet cracks, leads in fact to the transfer in the central hole of an important part of the volume contained in the fuel porosity, cracks and fabrication gap.

The velocity of migrating lenticular pores has been evaluated by several authors /8, 9, 10/, the common result being :

$$v_p = \frac{C}{pT^{3/2}} \left|\frac{dT}{dr}\right| \exp\left(-\frac{Q}{RT}\right) \qquad (10)$$

where p is the pore inner pressure, i.e. filling gas and fuel vapour partial pressures, T is the absolute temperature, $|dT/dr|$ being the absolute value of its radial gradient and R is the gas constant. Q and C denote an activation energy and a temperature independent quantity which vary with fuel composition (Pu content) and stoichiometry.

The as-fabricated fuel contains much porosities with low total pressure. Following formula (10), their mobility is high and they climb the thermal gradient. Another source of low pressure porosity arises from the fuel cracks. The latter disturb the local temperature field and induce localized high temperature drops across their width. This temperature differences trigger evaporation-condensation processes and lenticular pores are formed which move up the thermal gradient and heal the initial cracks. These effects were investigated by Ronchi & Sari /10/, which showed also that the experimental results were best reproduced by assuming a constant pore volume V and gas content n (in moles), i.e.

$$p = \frac{nRT}{V} \qquad (11)$$

The temperature dependence of the pore radial speed is shown in Fig.2 for five different correlations /8, 9, 10, 17 /. This dependence is particularly strong and shows how much columnar grain growth can vary with linear power. The stoichiometry dependence is also quite strong ; moreover, recent experimental results suggest that oxygen redistribution is strongly perturbed in the columnar grain zone. Therefore, the evaluation of correct pore velocities is a quite difficult task, and more empirical models are believed to provide a satisfying description of the process.

From the pore velocity distribution, a characteristic time for densification t_d can be defined :

$$t_d = -\int_{r_1}^{r_o} \frac{dr}{v_p} \qquad (12)$$

where r_o denotes the final pore position, i.e. the central hole radius and r_1 the starting pore position. Nichols /11/ has integrated expression (12) and has shown that the main parameter influencing t_d is the temperature T_1 corresponding to the radial location r_1.

From comparison between his theoretical expression and experimental results, Nichols has provided the following result :

$$t_d = t_o \exp\frac{Q}{RT} \qquad (13)$$

This formula is used in COMETHE III-J in a damage-like rule, i.e. one calculates at each time step Δt and for each calculation point i the ratio $\Delta t/t_d(i)$. By summation, one gets for each point and at each time t the so-called "c.g.g. fraction"

$$F(i) = \sum_{t=0}^{t=t} \frac{\Delta t}{t_d(i)} \qquad (14)$$

When this fraction reaches unity, it is assumed that almost all the porosity has been drained to the central hole, the remaining one resulting from a compromise between swelling and movement toward the central hole.

Special features are also added to this model to simulate that columnar grain growth can stop or recede toward the pellet centre when temperature is decreasing.

2.6. Fission gas release

Due to the high temperatures characterizing fuel restructuring at start of irradiation, gas release at start of life is usually important and plays an important thermal role : the manufacturing Helium filling gas is progressively diluted by low conducting fission gases Krypton and mainly Xenon. The corresponding gas mixture conductivity change affects the gap conductance, which is fundamental for determining fuel temperatures.

The fission gas release model used in COMETHE predicts the amount of gas which reaches the boundary of a sphere which has the same specific surface as the fuel with respect to the external void. It assumes that the gas which reaches the boundary of that sphere (the so-called Booth equivalent sphere) is free for these voids.

This model, due to Capart, is based on the assumption that the mechanism controlling the release to the plenum, in the temperature range below equiaxed grains growth, is the diffusion of single gas atoms to the Booth sphere boundary. It is very similar in this respect to the original model of Booth /12/. However, the number of atoms which effectively participate to diffusion results from a balance between the trapping of gas atoms by defects and resolution from these defects by radiation damage. Basically, this latter effect is due to the fact that small cluster of gas atoms which tend to form by nucleation are continuously dispersed by the passage of fission fragments. Because of this process, a significant fraction of gas is maintained in solution, even above the kinematic solubility limit.

The model is based on the following fundamental assumptions :

- as in the original model of Booth /12/, the fuel is considered as made from effective grains having approximately the same sizes and no preferred orientation as regards their shapes. Under such conditions, it is best to approximate the grains by spheres, termed Booth spheres, with given equal radii ;
- in describing the diffusion to the Booth sphere boundary, it is assumed that the latter behaves as a perfect sink for gas atoms. In other words, atoms reaching the Booth sphere boundary have zero probability of returning to the matrix ;
- the atoms trapped in defects or precipitated in bubbles are considered immobile, that is the model does not consider bubble migration ;
- the probability of trapping of gas atoms by defects and bubbles is assumed independent of time, either directly or through the concentration of gas in the grains ;
- the rate or probability of resolution is similarly assumed independent of concentration and time.

Assuming for the moment that these assumptions hold true without further justification, the concentration of gas in each sphere obeys the following coupled differential equations :

$$\left[\begin{array}{l} \dfrac{\partial c}{\partial \theta} = \beta + D\,\nabla^2 c - gc + bm \\[2ex] \dfrac{\partial m}{\partial \theta} = gc - bm \end{array}\right. \qquad (15)$$

where $c = c(r, \theta)$, is the concentration of gas in solution and allowed to diffuse ;

$m = m(r, \theta)$, is the concentration of gas trapped at defects or precipitated in bubbles ;

$\beta = Y_f R_f$, is the number of inert atoms created by fission per unit time and unit volume. It is defined as the product of the fission rate density R_f and the fission yield Y_f ;

D is the diffusion coefficient for single gas atoms ;

g is the capture rate (s^{-1}) by defects and bubbles ;

b is the resolution rate (s^{-1}). It expressed by : $b = n.R_f$ where n is a resolution coefficient (cm^3).

The differential equations (15) have an obvious physical meaning. They express the changes in the concentrations of the two sorts of atoms as the difference between the rates of production and disappearance. The influence of the sphere boundary is considered by assuming the boundary condition of zero concentration on the Booth sphere surface at all times :

$$c(a,\theta) = m(a,\theta) = 0 \,, \tag{16}$$

where a is the Booth sphere radius.

This set of equations and initial conditions can be analytically integrated. A main conclusion is that the influence of trapping, resolution and Booth sphere size, can all be accounted for in a diffusion model by the definition of an effective diffusion rate :

$$D' = \frac{D\,b}{a^2(b+g)} \tag{17}$$

The diffusion coefficient D in (17) refers to unimposed diffusion of inert gas atoms in the perfect monocrystalline material during irradiation. It can be written as the sum of two terms :

$$D = D_g + D'_g = D_o \exp\left(-\frac{A}{RT}\right) + \delta R_f \tag{18}$$

where D_g is the usual thermodynamic diffusion coefficient and D'_g is a radiation enhanced diffusion coefficient proportional to the fission rate R_f (number of fissions per unit volume and unit time).

The main problem in the actual application of this model is the definition of the equivalent sphere radius a. This radius depends in fact on the connection between the spatially distributed porosities. If all porosities are open, one can reasonably assume that this radius is equal to the fuel grain radius : the gas reaching any grain boundary is released from the pellet. Oppositely, if all porosities are closed, gas reaching the grain boundary has still to diffuse till the pellet free surface (including cracks) before being released.

The leading parameter is therefore the ratio between the specific surface S of the pellet cracked sector and the corresponding volume V, i.e. the Booth sphere radius a is defined by :

$$\frac{1}{a} = \frac{1}{3}\,S/V \tag{19}$$

This ratio can be measured by gas adsorption techniques on the as-fabricated pellet, and then corrected in order to take the cracking pattern into account.

This equivalent sphere radius depends strongly on the porosity connection which is influenced by f.g.b. swelling. With the notations of section 2.2, it is possible to define a "bubble ratio" b_r

$$b_r = \frac{P - P'_o}{P_L - P'_o} \tag{20}$$

which expresses the ratio between actual porosity increase due to fission gas bubbles swelling and the actual porosity limit under given conditions of temperature and hydrostatic stress. In COMETHE III-J, once this bubble ratio reaches a treshold value, the equivalent sphere radius is put to half the grain size : fission gas release is so enhanced, simulating the so-called "tunnelling" effect experienced in LWR conditions /13/ and always present in FBR conditions.

2.7. Conclusion

The presented models share some important features as :

- their kinetic character ;
- the semi-empirical approach of processes which are too difficult to model completely theoretically ;
- their low computing requirements.

Such models must be calibrated, in order to assess their capability, and this has been realized in a wide range of operating conditions (see e.g. /14/).

3. IMPACT ON POWER-TO-MELT

3.1. Introduction

The FBR fuel pin peak linear rating must be chosen so that, taking all uncertainties into account together with a given reactor overpower margin, power-to-melt is never exceeded. One important problem is that this power-to-melt is burnup dependent : in fact it increases steeply at very low burnup through restructuring of the fuel pellet and gap closure, and it decreases later slowly, till end of irradiation, depending mainly on the long term behaviour of gap conductance.

Well characterized data related to short term experiments are rather rare in the literature. Very interesting results related to power to melt and its variation at low burnup were however presented by HEDL at the recent Monterey conference /15/. The experimental points are presented in Fig. 3 ; they evince the following phenomena :

- power to melt at zero burnup depends strongly on as-fabricated fuel-to-cladding gap ;

- once the fuel clad has closed (i.e. at burnups as low as 0.4 at %), the gap dependence is much weaker, and power-to-melt increases significantly.

Ref. /15/, based on fuel ceramography samples, showed also that a greater as-built gap leads to a higher power to incipient melting once gap has closed, due to more intense restructuring of the fuel pellet.

3.2. COMETHE III-J results

COMETHE calculations were performed with FFTF driver fuel pin characteristics and irradiation conditions as given in /15/. The corresponding results are given in Fig. 4 , together with the HEDL correlations based on PIE P-19 and P-20 results.

Some remarks are to be done :

- the standard set of models parameters of COMETHE III-J was used, and no parameter was therefore chosen according to PIE results ;
- the fuel thermal conductivity correlation was taken from GEAP-5591 (January 1968) ; this UO_2 correlation is usually used in COMETHE even for mixed oxide because the effect of Pu content is not clearly understood ; the porosity dependence is based on the results of Biancheria /16/ ;
- the COMETHE results were normalized to a cladding inner temperature of 571°C.

When comparing the HEDL correlation with COMETHE III-J results, one can see that a fair agreement is obtained when comparing the relative effects of as-built gap. The discrepancy between absolute values of about 50 W/cm, i.e. about 7-8 % can be attributed to unaccuracies in fuel thermal conductivity, which vary easily from ± 15 % within one experiment (see e.g. /17/ p. 127).

As can be seen from Fig. 4 , the effect of as-built gap on fresh fuel and at low burn-up is well predicted by COMETHE. This is to be correlated with the predicted gap closure kinetics.

It is therefore felt that the set of restructuring and gap closure models implemented in COMETHE III-J give a good quantitative approach to the deterministic BOL behaviour of mixed-oxide fuel. Some parameters (e.g. thermal conductivity of the fuel) remain however subject to wide statistical variations (due e.g. to manufacturing process, pores shape and distribution) and can be improved by means of a "a posteriori" calibration in very specific conditions.

3.3. COMETHE predictions during start-up

The fuel-clad gap and centerline temperature evolutions have been calculated by COMETHE, during steady-state irradiation, for FFTF driver fuel. The clad inner temperature was adjusted at 571°C for 450 W/cm peak power. The calculation results are given in Fig. 5 and Fig. 6 . The calculated gap closure is continuous , resulting mainly from f.g.b. swelling, which is overriding in-pile sintering. At 450 W/cm, gap closure is expected after about 12 days irradiation. Due to higher temperatures, thermal expansion decreases the initial gap size at high power, but the gap closure rate remains essentially the same.

One remark here : coming back to the results of section 3.2, it has to be noted that correct gap closure is achieved without any spontaneous relocation ; this relocation suggested by some LWR fuel rod specialists (see e.g. /18/) is not required within the frame of COMETHE models.

The central temperature evolution is more complex than gap closure, due mainly to the central hole formation by columnar grain growth, which acts faster when temperatures are higher. This central hole grows in about one day at 450 W/cm, leading to a 80°C temperature drop. This process has to be accounted for when interpreting power-to-melt on fresh fuel ; for instance, at 550 W/cm, a 50°C temperature drop is achieved in about one hour, improving thereby the power-to-melt by about 20-30 W/cm.

Once columnar grain growth has slowed down, after a very small temperature increase due to in-pile sintering, fission gas bubble swelling has time to act, and the temperatures fall, due to gap closure.

Once gap is closed, the temperatures increase again due to fission gas release, with a slope (log scale !) depending on fission gas release rate, but also on clad strain evolution, which was neglected in this contribution.

With the curves of Fig. 6 , it is possible to select a start-up procedure corresponding to a fixed centerline temperature level : it suffices to follow the corresponding isotherm. The start-up corresponding to 2500°C is given in Fig. 7 .

4. CONCLUSIONS

The restructuring and gap closure models implemented in the COMETHE III-J code have been described, and their validity to predict the BOL behaviour of mixed oxide was assessed by comparison with well characterized power to melt experimental data.

Calibrated against experimental LWR and FBR /19/ data, the COMETHE code can be applied to a very wide range of fuel pin calculations, including uranium or mixed oxide fuel. Such calculations have been presented in the case of the start-up of fresh FBR fuel pins.

5. REFERENCES

/1/ Study of the Thermal Behaviour of LMFBR Fuel.
M. CONTE et al.
ANS Breeder Conference, Monterey, March 5-8, 1979

/2/ Short Term Experiments in BR2 Towards a Better Fast Fuel Performance.
J. VAN VLIET, A. PAY
BR2 Review Meeting, Mol, June 1, 1978

/3/ Some Observations of Density and Porosity Changes in UO_2 Fuel Irradiated in Water-Cooled Reactors.
D.A. BANKS
J. of Nucl. Mat., 54 (1974)

/4/ Fission Gas Behavior in Oxide Fuel Elements of Fast Breeder Reactors.
H. ZIMMERMANN
Nucl. Tech., 28 (1976)

/5/ Densification in Mixed Oxide Fuel During Fast Reactor Irradiation.
M.C.J. CARLSON
Nucl. Tech., 22 (1974)

/6/ M.O. MARLOWE
NEDO-12440, July 1973

/7/ Isothermal Grain Growth Kinetics in Sintered UO_2 Pellets.
J.B. AINSCOUGH et al.
J. of Nucl. Mat., 49 (1973/4)

/8/ C.F. CLEMENT
J. of Nucl. Mat., 68 (1977)

/9/ P.F. SENS
J. of Nucl. Mat., 43 (1972)

/10/ C. RONCHI and C. SARI
J. of Nucl. Mat., 50 (1974)

/11/ Theory of Columnar Grain Growth and Central Void Formation in Oxide Fuel Rods.
F.A. NICHOLS
J. of Nucl. Mat., 22 (1967)

/12/ A Method of Calculating Fission Gas Diffusion from UO_2 Fuel.
A.H. BOOTH
AECL-496 (1957)

/13/ COMETHE Fission Gas Release Model.
N. HOPPE and P. BOUFFIOUX
ACS Meeting, Detroit, May 8-10, 1978

/14/ Benchmarking Results of the COMETHE Code.
P. BOUFFIOUX and E. DE MEULEMEESTER
IAEA Meeting, Blackpool, March 13-17, 1978

LWR Fuel Rod Modeling Code Evaluation.
EPRI, NP-369, March 1977

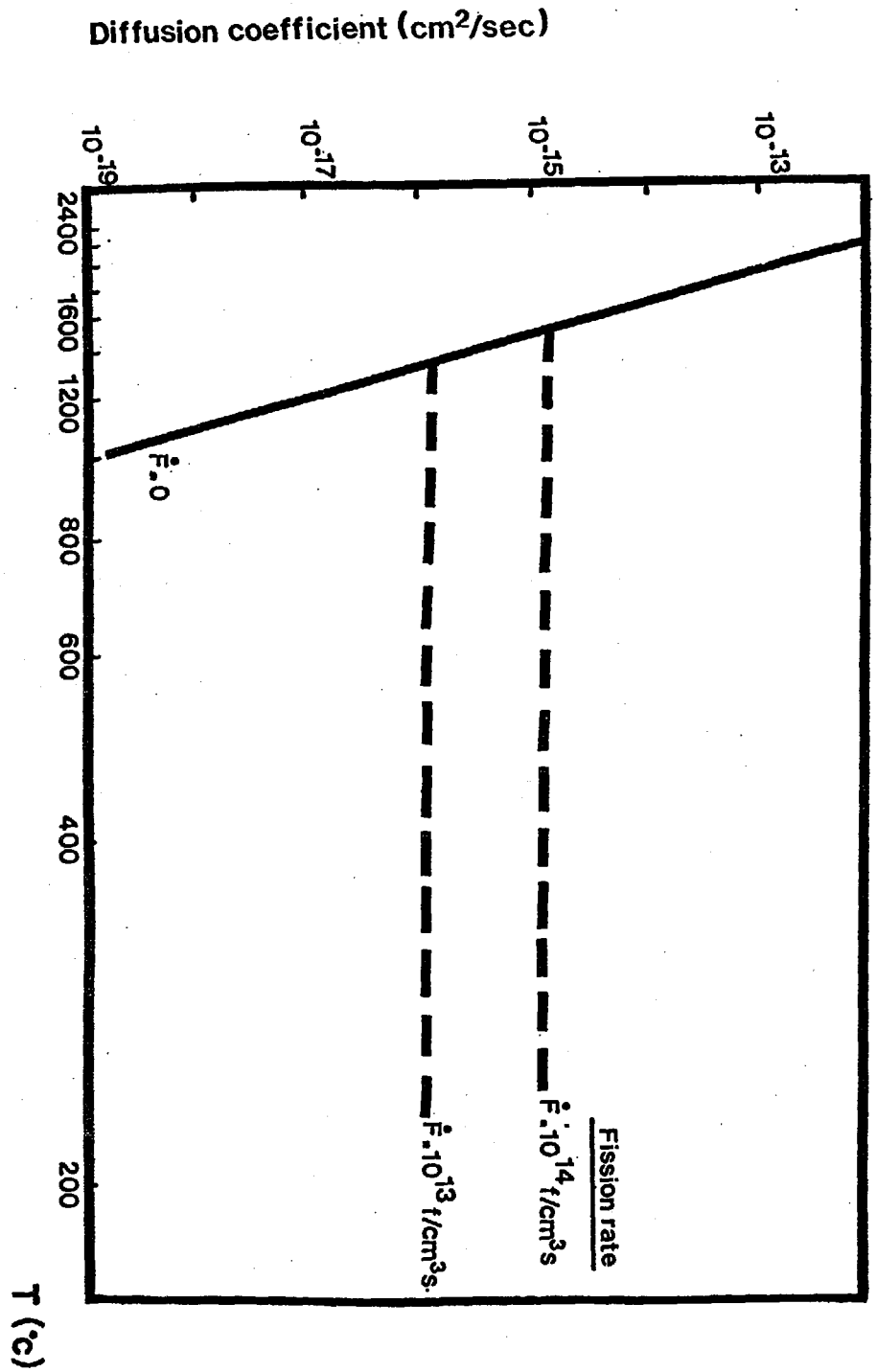
/15/ Early in Life Thermal Performance of UO_2-PuO_2 Fast Reactor Fuel.
R.B. BAKER and R.D. LEGGETT
ANS Breeder Conference, Monterey, March 5-8, 1979

/16/ Effect of Porosity on Thermal Conductivity of Ceramic Bodies.
A. BIANCHERIA
Trans. ANS, Vol. 9, mr 1, 15 (1966)

/17/ Fundamental Aspects of Nuclear Reactor Fuel Elements.
D.R. OLANDER
TID-26711-P1

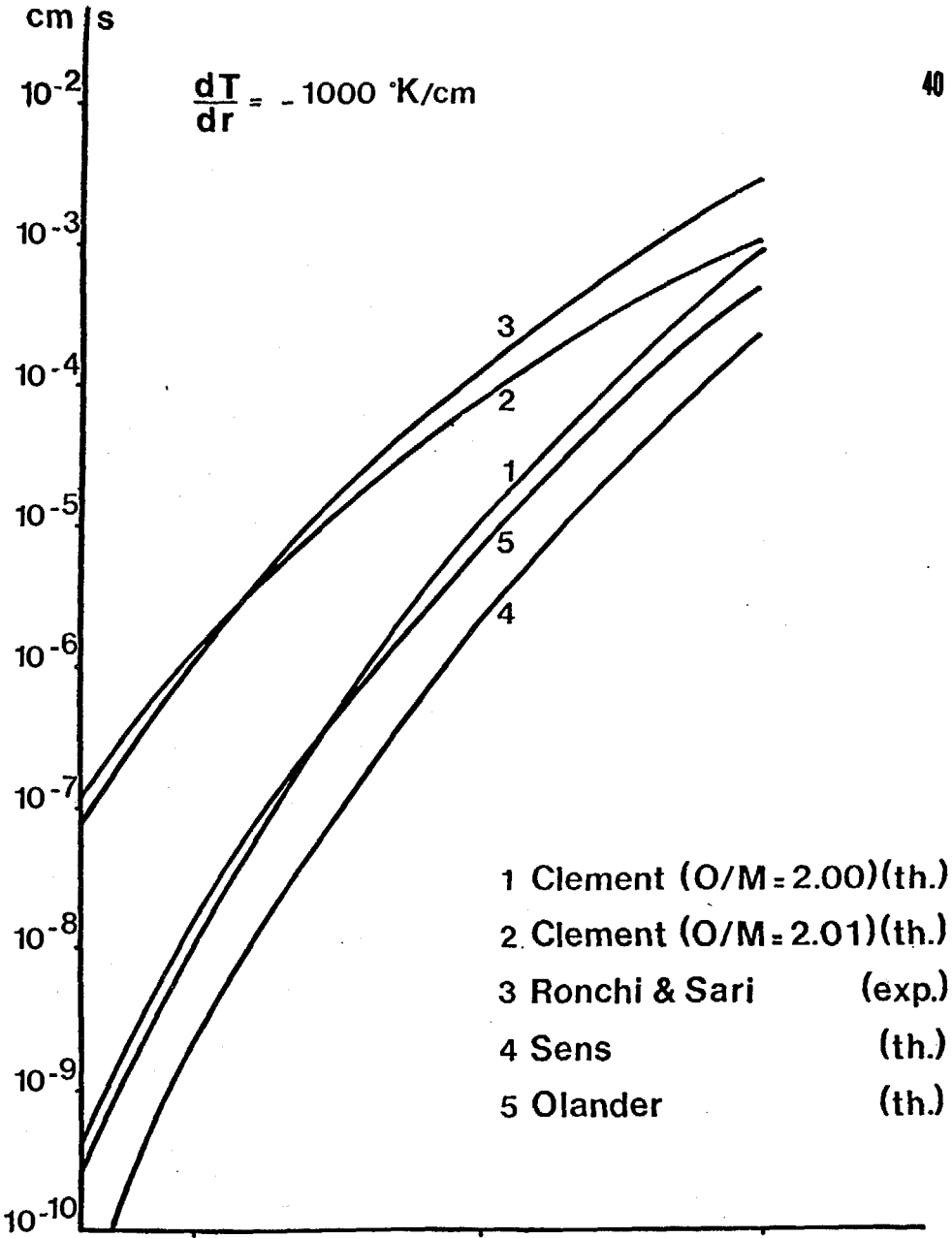
/18/ Analytical Verification and its Limitations.
N. KJAER-PEDERSEN
Post SMIRT Seminar, San Francisco, August 1977

/19/ LMFBR Fuel Rod Performance and Modelling at High Burnup.
P. VERBEEK et al.
Nucl. Tech., 39 (1978)



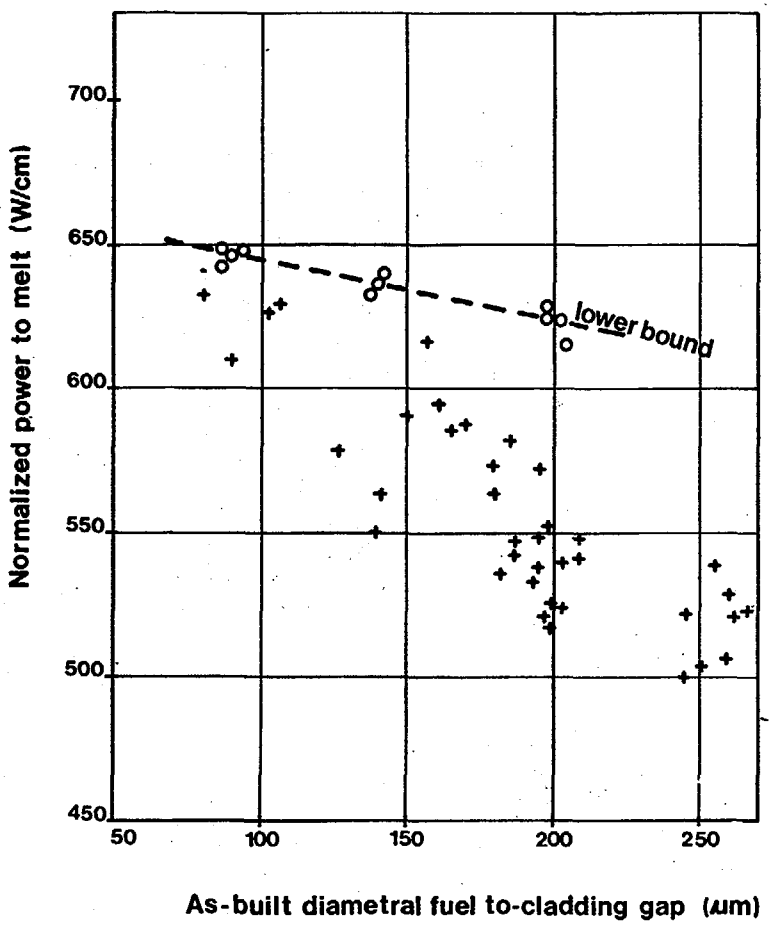
Comparison of thermally activated and irradiation induced diffusivity in UO_2

FIG. 1



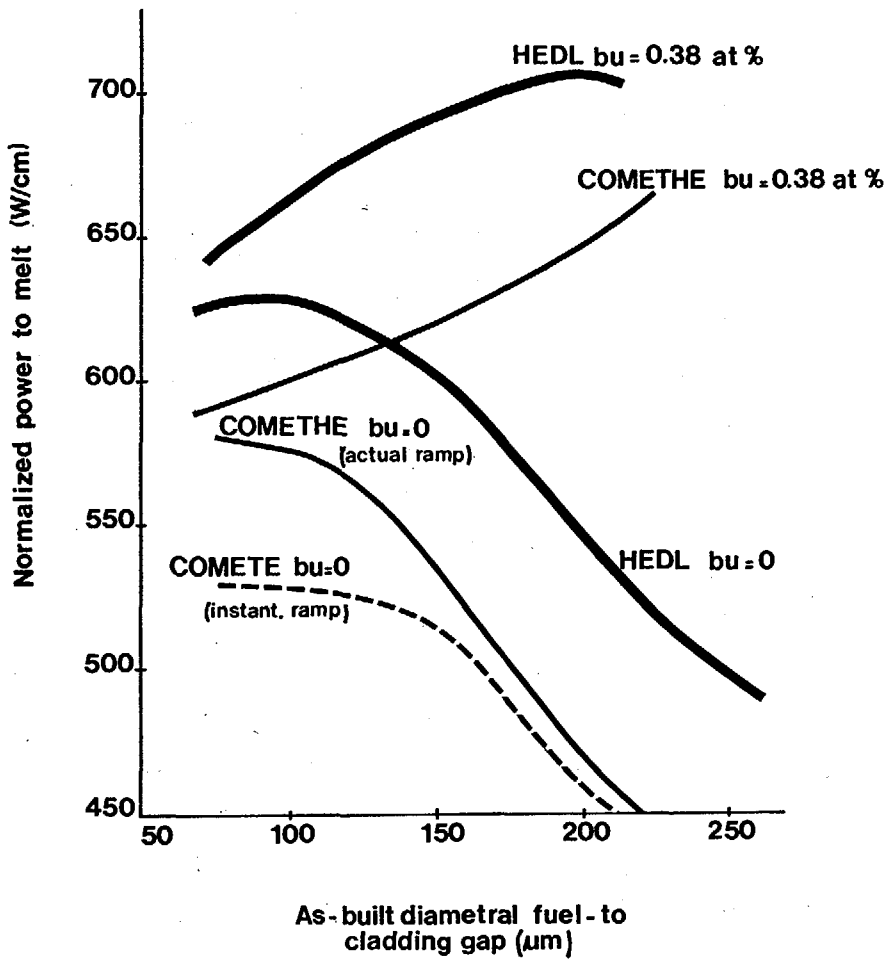
Lenticular pore velocity - Correlations

FIG. 2



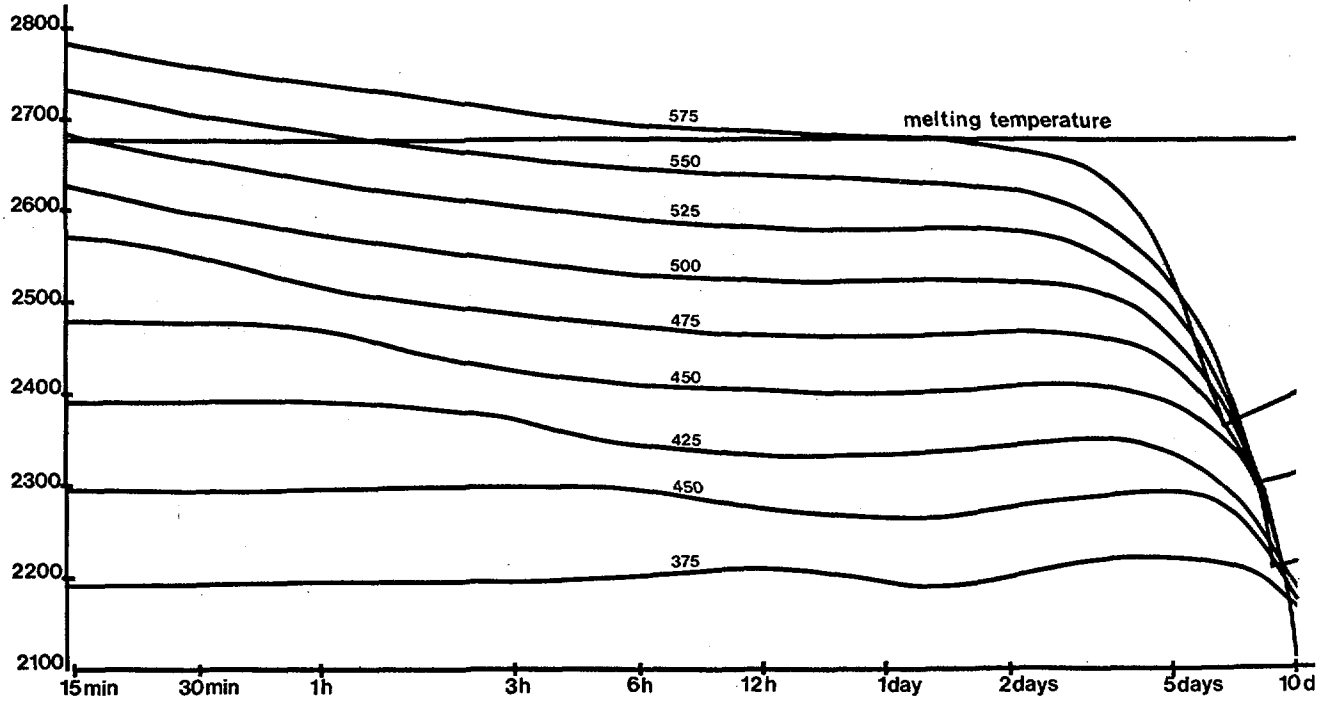
HEDL experimental results

FIG. 3



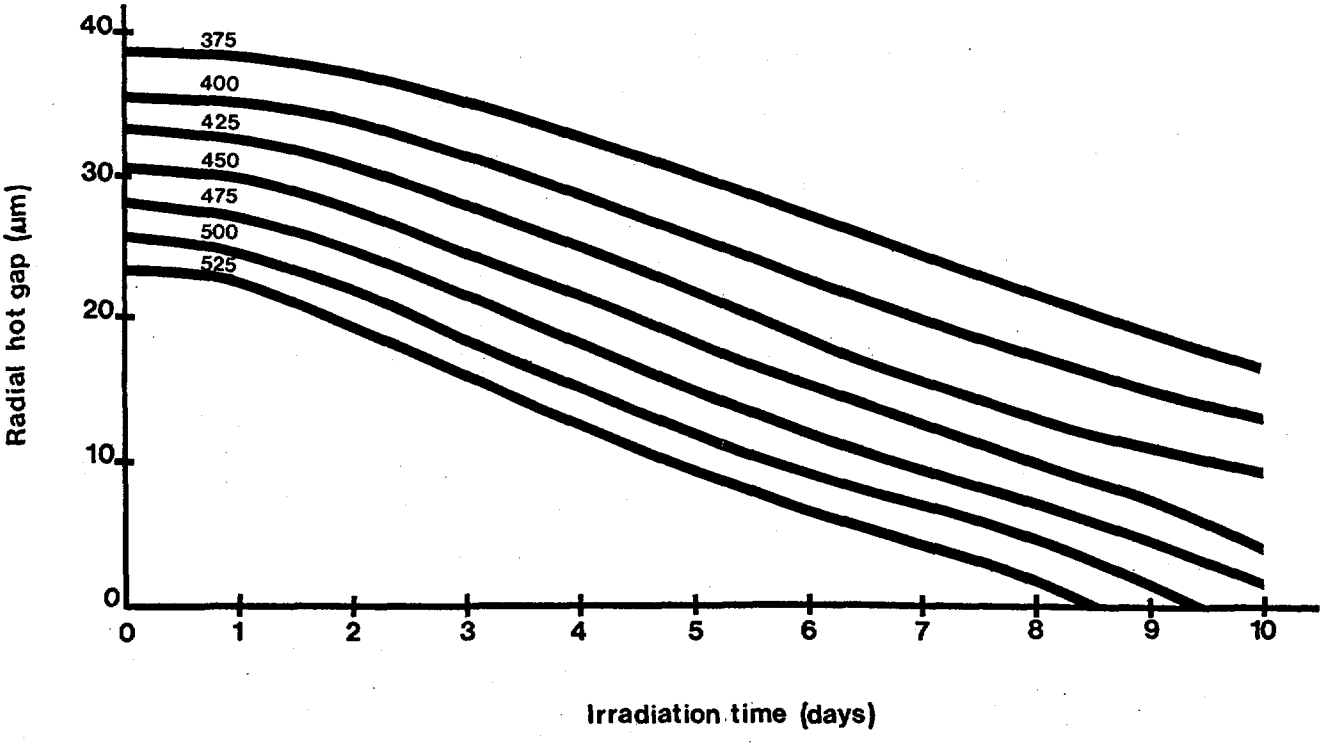
COMETHE III-J predictions of power to melt

FIG. 4



Central temperature evolution during start-up

FIG.6



Gap closure during start-up

FIG.5

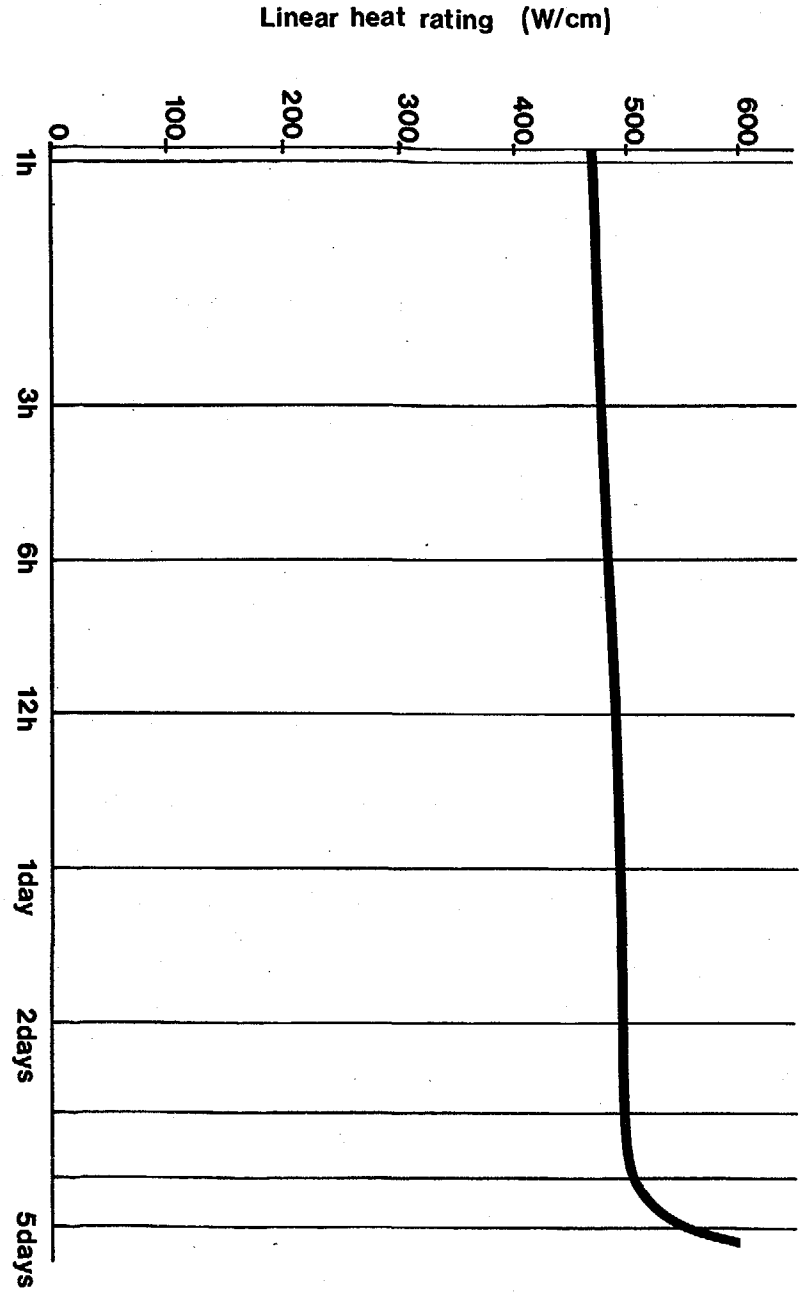


FIG.7 Start-up procedure corresponding to 2500 °C centerline temperature

ACTIVITIES AT THE INSTITUTE OF MATERIALS AND SOLID STATE RESEARCH OF THE KARLSRUHE NUCLEAR RESEARCH CENTRE IN THE FIELD OF FUEL PIN MODELLING

H. ELBEL
Kernforschungszentrum Karlsruhe,
Karlsruhe,
Federal Republic of Germany

1. Objectives

Fuel pin modelling has been pursued at the Institute of Materials and Solid State Research (IMF) of the Karlsruhe Nuclear Research Centre (KfK) with the main objective to provide a detailed quantitative analysis of the fuel pin behaviour in a LMFBR under normal and off-normal operation conditions. The computer programs and models developed at the IMF serve the purpose to aid effectively in the development of an optimized fuel pin concept for a LMFBR.

In the design of fuel pins and in the evaluation of their in-pile behaviour the answers to some important questions have to be found. These questions are:

- How large are the temperatures in the fuel ? This question concerns particularly the behaviour at BOL. But also the development of the temperatures with increasing burnup is of interest.
- When will the gap between fuel pellets and clad be exhausted ? What are the mechanisms which influence gap closure ?
- When has mechanical interaction between fuel and clad to be expected ? How large is the load onto the clad and what are the phenomena which influence it ?