STRESS AND STRAIN CALCULATIONS ON COATED PARTICLE FUEL AND COMPARISON WITH IRRADIATION RESULTS

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ABSTRACT

The use of a computer code, written for a spherical geometry and based on the mechanical and physical properties of the materials used for the coated particle fuel, enables to predict and explain the mechanical behaviour of the H T R fuel concept.

1. INTRODUCTION.

At the time of the H T R fuel development, an analytical study of the stress evolution in the fuel particle coating enables :

- to show the effect of the layer thickness distribution on the coated particle mechanical behaviour ;
- to indicate the physical and mechanical properties which possible variations influence significantly the coated particle lifetime ; this can then serve as a guide to determine the data that should be known with a better accuracy and to influence the basic and fundamental research programmes accordingly ;
- to advise the experimenters about irradiation conditions and coated particle designs to be tested.

2. COMPUTATION CODE.

Since 1967, BELGONUCLEAIRE has developed COCONUT*, a computer code, which calculates the stresses and strains in the coating layers considered as a pressure vessel [1] .

This mathematical model proceeds through successive time steps and has been written for any fuel, coating material, number of layers, temperature and irradiation evolution.

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*COating COmputation for NUclear Technology.

The stresses and strains in the layers are based on the fission gas and carbon monoxide build-up, fuel swelling and the dimensional changes induced in the coating layers by the thermal history and the irradiation damage. At each time step, the stresses and strains are corrected for creep effect induced by irradiation and temperature.

3. PHYSICAL AND MECHANICAL PROPERTIES OF THE COATING MATERIALS.

The physical and mechanical properties of the coating materials at 1200°C are assembled in Table I [3][4].

4. INFLUENCE OF THE THICKNESS DISTRIBUTION BETWEEN THE BUFFER AND THE OUTER PyC LAYER ON THE COATED PARTICLE MECHANICAL BEHAVIOUR.

The study which has been carried out consists to determine the stress level evolutions in the layers, as a pressure vessel, for several thickness distributions between the buffer and the outer PyC and for a constant heavy metal loading.

The coated particle is designed as follows in Table II.

The stress evolutions are presented at Fig. 1 for several thickness distributions between the buffer and the outer PyC.

From these evolutions, it appears that we have two effects which play in opposite directions.

On one hand, the buffer thickness increase attempts to reduce the decompression rate of the SiC layer, the internal gas pressure build up being reduced.

On the other hand, the decrease of the outer PyC thickness reduces the compression of the SiC layer.

It results of it that small tensile hoop stresses in the SiC, for the end of life conditions, are obtained for a thick buffer ($\simeq$ 75 μ), and a relatively thin outer PyC ($\simeq$20μ).

This fact is principally due to the PyC irradiation creep which moderates the compression induced on the SiC by the PyC dimensional change.

5. EFFECT OF THE PHYSICAL AND MECHANICAL PROPERTIES SCATTERING ON THE STRESS EVOLUTION.

The aim of this work was to determine the effect which certain PyC mechanical properties and UO_2 physical properties have on the lifetime of the coated particle.

To determine which properties are most important for the design of a particle, we have calculated the evolution of stresses for various designs, identical with the <u>Basic Case</u> in geometry (Table II) but possessing different mechanical and physical properties.

The cases we have pointed out after several calculations were the following at 1200°C :

- a lower irradiation creep, 1.54×10^{-27}/psi.EDN ;
- a constant initial value of Young's modulus, 2.0×10^{6} psi ;
- an overstoichiometric fuel.

The most important of the mechanical properties is the irradiation creep coefficient. The stresses in the PyC and the SiC layers are raised of 40 % with the lower irradiation creep coefficient which has been chosen in comparison with the Basic Case.

Another important mechanical property of PyC is its Young's modulus. With the constant initial value of the PyC Young's modulus, the SiC layer gets sooner in tension in comparison with the Basic Case, at 7.4 % instead of 8.5 % fima. For the end of life conditions, the SiC hoop stresses are raised of 40 % and the PyC hoop stresses are reduced of 60 % versus the stress level for the Basic Case.

The last property we have investigated, is a physical one, an overstoichiometry of the fuel. In the Basic Case, for a good stoichiometry at 1200°C, the CO pressure is growing up to 10 at. for the end of life conditions, while for a bad one, the CO pressure could reach 100 at. as an extrapolated value.

Due to the bad stoichiometry, the gas pressure is raised of 23 % and the SiC layer becomes in tension sooner in comparison with the Basic Case, at 6.0 % instead of 8.5 % fima.

For the end of life conditions, the SiC hoop stresses are raised of 110 %.

6. EFFECT OF THE BACON ANISOTROPY FACTOR EVOLUTION ON THE MECHANICAL BEHAVIOUR OF THE COATED PARTICLE.

The pyrolytic carbon currently preferred for coatings on fuel particles is initially isotropic and under irradiation apparently behaves anisotropically, having a shape change with a volume increase.

Thus, we get for the creep strain

$$2\,\mu_c \eta_{c\theta} + (1 - \mu_c)\,\eta_{cr} = 0. \qquad (1)$$

Referring eq.(1), the parameter μ_c described as a "Poisson's ratio in creep" has a value below 0.5.

This parameter is equally connected with the BAF and the R_i parameter by the following suggested relation :

$$\frac{2\,\mu_c}{1 - \mu_c} = \frac{R_i}{1 - R_i} = \frac{2}{BAF}$$

Besides, the dimensional change under irradiation increases with the anisotropy.

To predict the influence of the anisotropy build-up on the mechanical behaviour of the coated particle, we have done several calculations with different BAF values reached during the lifetime.

The geometry of the particle was the one chosen for the Basic Case (Table II).

Fig. 2 shows the effect of the anisotropy build-up versus the Basic Case whose layers, as a pressure vessel, remain nearly isotropic.

The different anisotropies reached in the calculations are presented at Table III.

This anisotropy build-up could have a determining effect on the coated particle behaviour. For the end of life conditions, the outer PyC hoop stresses are raised of 34.0 and 77.0 % respectively for a BAF of 1.5 and 2.0 : for the SiC hoop stresses, the increase is of 83.0, 126.0 and 300.0 % respectively for a BAF of 1.2, 1.5 and 2.0.

From these calculation results, one may conclude that measurements of the anisotropy obtained on irradiated coated particles will be quite useful to predict the coated particle mechanical behaviour with a good accuracy.

7. SHUT-DOWN STRESSES.

For the shut-down stress calculations, one has determined, for the Basic Case (Table II), the stresses obtained at 1 - 2 - 3 and 4×10^{21} EDN when the temperature is decreasing to 20°C and the coolant gas pressure is reaching the atmospheric pressure.

Fig. 3 shows that the shut-down stresses present an important increase of the tensile stresses in the PyC layers versus the stress evolution without shut-down.

In fact, the PyC hoop stress is increased of 6×10^3 psi (420 kg/cm^2) due to the differential effect of the PyC and SiC thermal elongations.

8. COMPARISON WITH IRRADIATION RESULTS.

8.1. PuO_2 coated particle [5] [6] [7] [8] .

This coated particle, designed for a feed and breed HTR concept, is constituted by a PuO_2/Pu_2O_3 kernel dispersed in a carbon matrix surrounded by a PyC/SiC/PyC coating.

This Pu fuelled coated particle, required for irradiation in the DRAGON Reactor Experiment, has reached a burn-up of 60 % fima and a fast neutron dose of 10^{21} EDN at an average temperature of 1200°C.

The characteristics of this Pu coated particle, fabricated by BELGONUCLEAIRE at Mol, are presented in Table IV.

Fig. 4 shows the stress and gas pressure evolution in this Pu fuelled coated particle. The mechanical behaviour predictions are in good agreement with the in-pile fission gas release measured, to wit $R/B = 7 \times 10^{-6}$, for xenon and krypton (maximum value).

8.2. UO_2 coated particle [9].

This coated particle is also a PyC/SiC/PyC one with a low enriched UO_2 fuel.

This fuel which has been irradiated in the BR3 at Mol, has reached in a first approximation an average burn-up of 5.0 % fima for a dose of 1.25×10^{21} EDN and for an average temperature of 900°C.

The characteristics of this low enriched coated particle, fabricated by BELGONUCLEAIRE at Mol, are presented in Table V.

Fig. 5 shows the coated particle mechanical behaviour predicted by the mathematical model.

At the moment of the typewriting of this paper, the postirradiation examinations are in progress.

9. CONCLUSIONS.

In conclusion, for the coated particle fuel design, one may emphasize the following points :

- the mechanical behaviour is improved ; providing in the total coating thickness, a thick buffer and a reduced outer PyC layer, still able to support the shut-down stresses ;
- the mechanical and physical properties which have the greatest effect on the computation results are :

  a. the anisotropy build-up in the PyC layer ;
  b. the PyC irradiation creep coefficient ;
  c. the PyC Young's modulus value ;
  d. the stoichiometry of the fuel.

SYMBOLS.

BAF Bacon Anisotropy Factor ($\alpha_{\perp}/\alpha_{//}$ at 400°C)
R_1 orientation parameter
μ_c Poisson's ratio in creep
η_{cr} radial elongation induced by creep
$\eta_{c\theta}$ tangential elongation induced by creep

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- TABLE I -

PHYSICAL AND MECHANICAL PROPERTIES
OF THE COATING MATERIALS AT 1200°C

Coating material	PyC	SiC
Rupture strength (psi)	40,000	20,000-30,000
Young's modulus (psi)	$2.0\text{-}4.0 \times 10^{6}$	47.0×10^{6}
Poisson's ratio	0.24	0.33
Thermal expansion ($°C^{-1}$)	5.45×10^{-6}	5.64×10^{-6}
Irradiation dimensional change	[4]	[2]
Irradiation creep ($psi^{-1} EDN^{-1}$)	4.6×10^{-27}	3.0×10^{-29}

- TABLE II -

COATED PARTICLE

		Characteristics	Remarks
Kernel UO_2	ø % TD	760 μ 90 %	Constant diameter
Buffer	ρ thickness	1.0 g/cm^3 from 45 up to 85 μ	75 μ for the Basic Case
Transition	ρ thickness	from 1.0 up to 1.8 g/cm^3 30 μ	5 μ included in the buffer 20 μ transition layer 5 μ included in the inner PyC
Inner PyC	ρ thickness	1.8 g/cm^3 15 μ	Constant thickness
SiC	ρ thickness	3.2 g/cm^3 30 μ	Constant thickness
Outer PyC	ρ thickness	1.8 g/cm^3 from 50 down to 10 μ	20 μ for the Basic Case
Total coating thickness		170 μ	Constant thickness
Heavy metal density		1.0 g_U/cm^3	for 35 v/o

- TABLE III -

DIFFERENT ANISOTROPIES REACHED IN THE CALCULATIONS

BAF	μ_c	$\eta_\perp^*$	$\eta_{//}^*$	Remarks
≃ 1.0	0.500	+ .232	- .160	Basic Case
1.2	0.455	+ .300	- .160	
1.5	0.400	+ .393	- .220	
2.0	0.330	+ .520	- .320	

* at 1200°C and 4×10^{21} EDN for 1.8 g/cm^3

- T A B L E IV -

Pu COATED PARTICLE

Kernel	ϕ % TD C/Pu	297 - 300 μ 70 % 20
Buffer	ρ thickness	1.1 g/cm^3 10 μ
PyC HDI	ρ thickness	1.8 g/cm^3 30 - 40 μ
PyC porous	ρ thickness	1.2 g/cm^3 ≃ 5 μ
SiC	ρ thickness	3.20 g/cm^3 40 - 60 μ
PyC porous	ρ thickness	1.2 g/cm^3 ≃ 5 μ
PyC HDI	ρ thickness	1.8 g/cm^3 60 - 80 μ

- T A B L E V -

LOW ENRICHED COATED PARTICLE

Kernel	ϕ % TD	850 μ 90 %
Buffer	ρ thickness	1.05 g/cm^3 30 μ
Transition	ρ thickness	1.05 - 1.75 g/cm^3 40 μ
Inner PyC	ρ thickness	1.75 g/cm^3 30 μ
SiC	ρ thickness	3.20 g/cm^3 40 μ
Outer PyC	ρ thickness	1.8 g/cm^3 40 μ

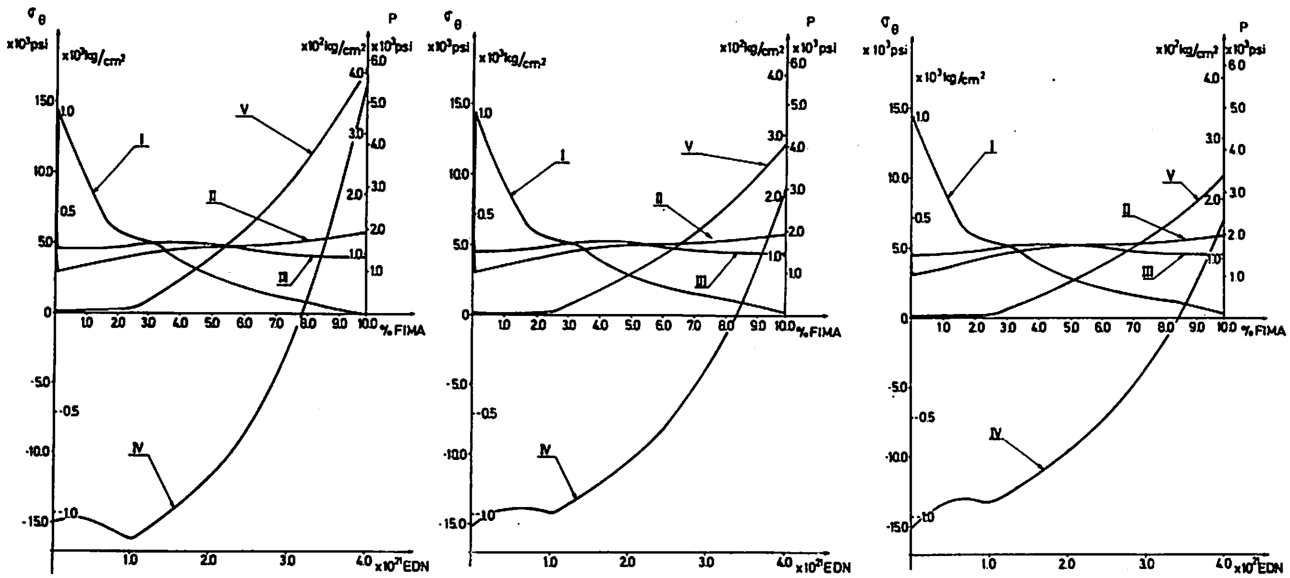

FIG. 1 - Hoop Stress and Gas Pressure Evolution in a PyC/SiC/PyC Coated Particle at 1200°C.

Buffer	45 μ	65 μ	75 μ
Outer PyC	50 μ	30 μ	20 μ

I transition ; II outer PyC ; III inner PyC ; IV SiC ; V gas pressure.

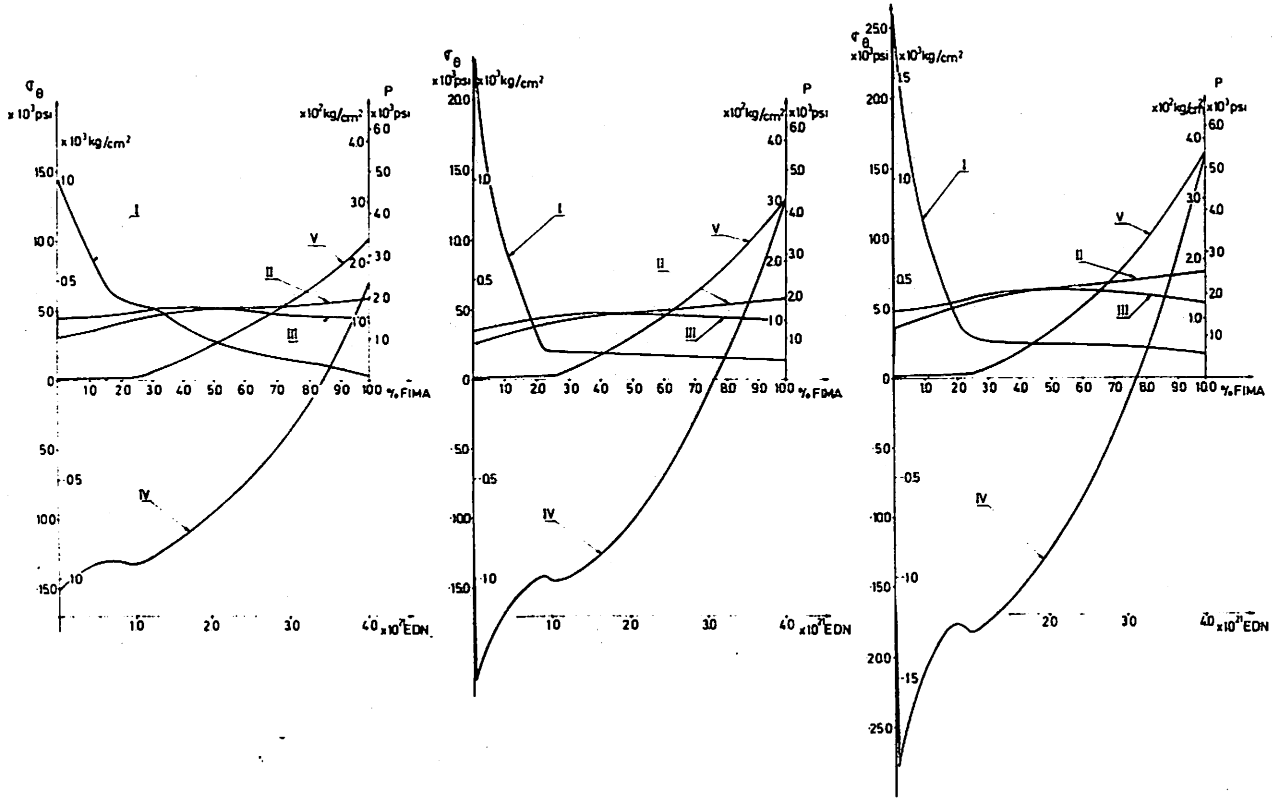

FIG. 2 - Hoop Stress and Gas Pressure Evolution in a PyC/SiC/PyC Coated Particle at 1200°C.

BAF 1.05 1.2 1.5

I transition ; II outer PyC ; III inner PyC ; IV SiC ; V gas pressure.

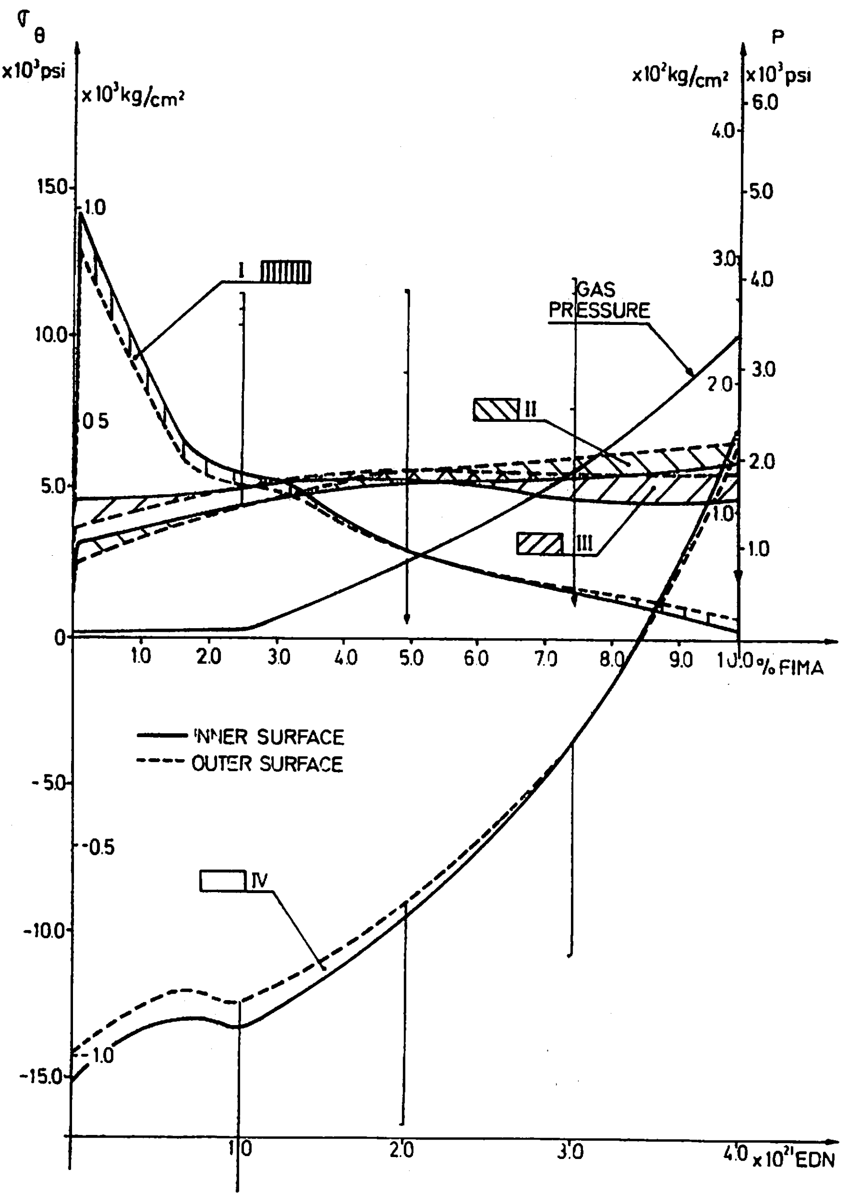

FIG. 3 - Hoop Stress and Gas Pressure Evolution in a PyC/SiC/PyC Coated Particle at 1200°C with Shut-Down Stresses.

I transition ; II outer PyC ; III inner PyC ; IV SiC ; V gas pressure

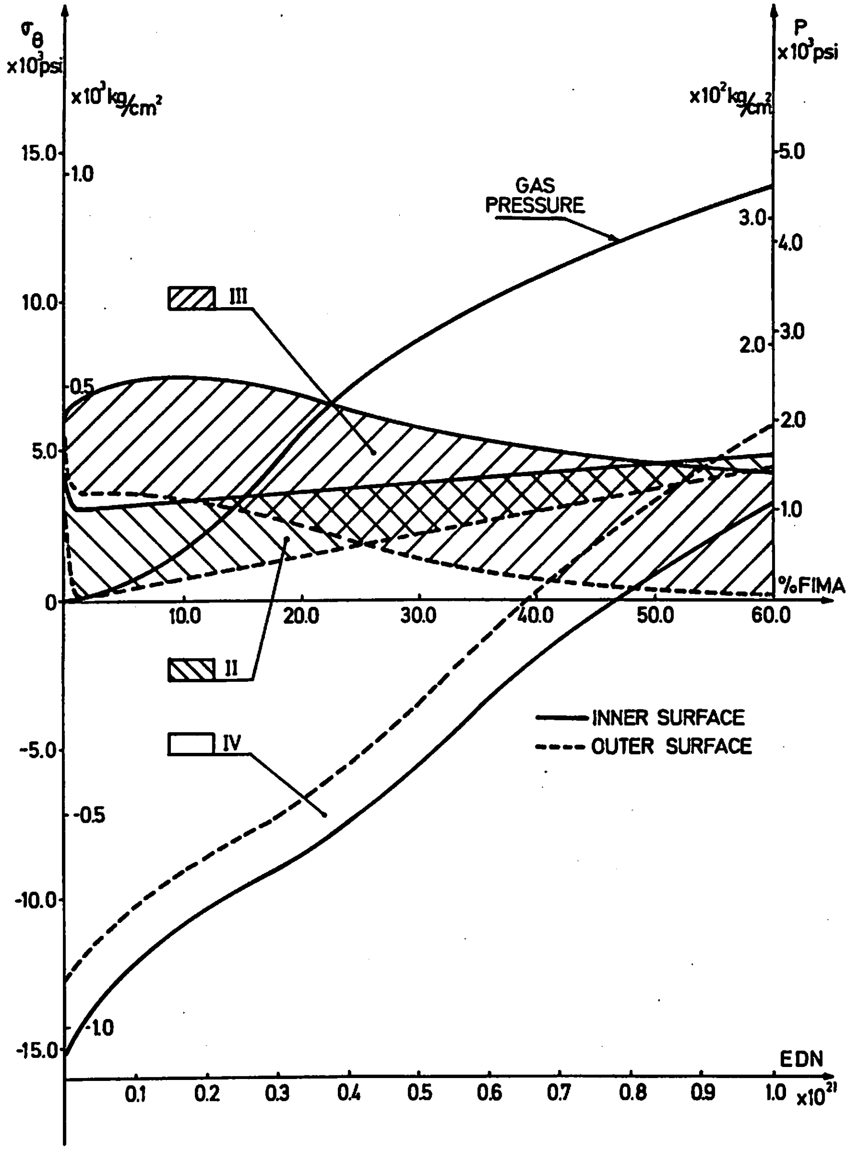

FIG. 4 - Hoop Stress and Gas Pressure Evolution in a Pu Coated Particle at 1200°C for a Feed-and-Breed H T R Concept.

I transition ; II outer PyC ; III inner PyC ; IV SiC ; V gas pressure

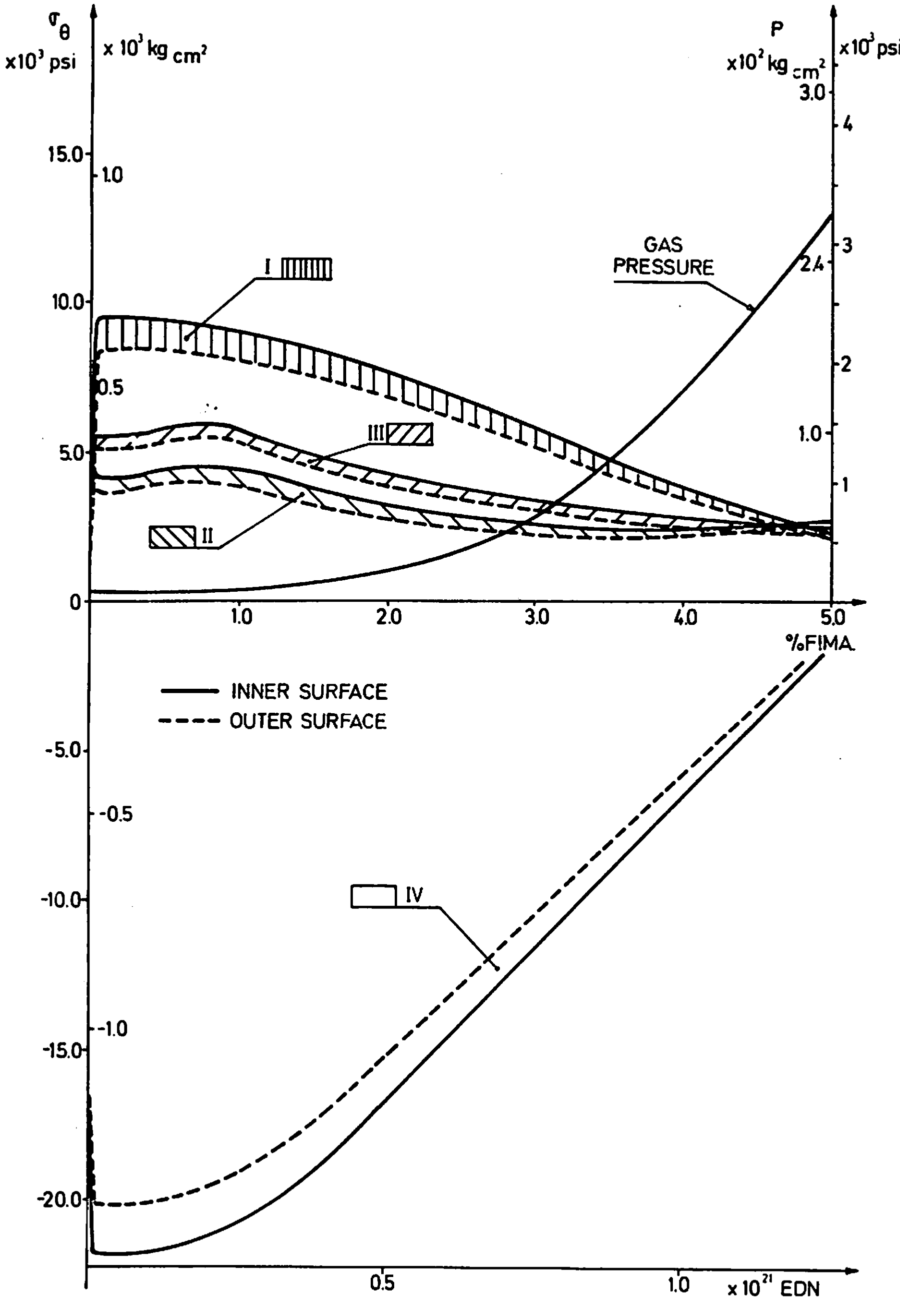

FIG. 5 - Hoop Stress and Gas Pressure Evolution in a PyC/SiC/PyC Coated Particle around 900°C in the BR3/2 bis Experiment.

I transition ; II outer PyC ; III inner PyC ;
IV SiC : V gas pressure

DISCUSSION

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I have not understood the way in which you explore the creep anisotropy. Your equation (1) is valid only under two conditions, namely for isotropic creep behaviour and for a creep Poisson's ratio of 0. 5 which means no volume change by creep. A value lower than 0. 5 means a volume increase, always for the isotropic case. According to your relation between the orientation parameter and the creep Poisson's ratio it seems that you have not explored the anisotropy but the possible influence of volume increase by creep. For exploring anisotropy the principal deformation components in at least two directions should be related.

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$\sigma = \sigma_\eta - \sigma_\theta$

Von Mises Criterium (Energy of deformation)

$2\mu_c \eta_{c\theta} + (1-\mu_c)\eta_{cr} = 0$

$\eta_{c\theta}$ creep elongation in the tangential direction

η_{cr} in the radial direction

The pyrolytic carbon currently preferred for coatings on fuel particles is initially isotropic and under irradiation apparently behaves anisotropically, having a shape change with a volume increase. This effect is induced by the preferential direction of the stresses and the neutron dose. A Gulf General Atomic's study has determined this effect expressed by the μ_c value, the "Poisson's ratio in creep".
Assuming there is a volume change of the layer one gets: $2\mu_c\eta_{c\theta} + (1-\mu_c)\eta_{cr} = 0.$

Calculating the dimensional change in the tangential and the radial direction with the Soderberg's relation one obtains:

$$\eta_{c\theta} = -(1-\mu_c)\,\eta_{ce}$$
$$\eta_{cr} = +\,2\mu_c\,\eta_{ce}$$

η_{ce} = equivalent creep strain