EFFECT OF MATERIAL PROPERTIES ON PELLET-CLAD INTERACTION PRESSURE

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ABSTRACT

Pellet-Clad Interaction Pressure, after the fuel clad contact is made, is determined by establishing continuity equation at fuel clad interface. Exact balance of clad strain determined by its swelling and creep behaviour and pellet strain determined by its swelling and creep behaviour at all points of time gives interaction pressure evolution history. It is found that once the free swelling phase is over and Pellet-Clad contact is established within a short time interaction pressure goes to its equilibrium value so as to counter balance swelling strain rate by creep strain rate exactly. This equilibrium interaction pressure is purely a function of above mentioned material properties and does not change with time or BU. Sensitivity analysis is done to evaluate the effect of creep behaviour of clad and fuel on the Interaction pressure and attainable burn-ups.

1.0 Introduction

Analysis of published information [1,2,3,4] indicates that fuel pin integrity and performance behaviour of advanced fuels like mixed carbides for fast reactors depend mainly on fuel clad interaction pressure which controls the clad stress and creep rate. While fission gas pressure is of little significance because of low gas release, interaction pressure is expected to be much more in carbides than in oxides on account of their higher swelling rates and low creep rates. An attempt has been made to determine the interaction pressure as function of irradiation time and fuel and clad creep properties.

2.0 Computation Model

After certain duration depending on free swelling rate of fuel, fuel clad gap closes and pellet starts interacting with clad as there is no free space available for pellet to swell. This fuel-clad interaction pressure is determined by establishing continuity condition at fuel clad interface. At any instant, increase in pellet diameter (given by swelling strain ϵ_{FS} — creep strain ϵ_{FC} — Elastic strain ϵ_{FE}) will be equal to the increase in clad diameter (given by swelling strain ϵ_{CS} + creep strain ϵ_{CC} + elastic strain ϵ_{CE}).

Rearrangement of this balance of strains gives

$$\epsilon_{FE} + \epsilon_{CE} = \left(\epsilon_{FS} - \epsilon_{CS}\right) - \left(\epsilon_{FC} + \epsilon_{CC}\right) \qquad (1)$$

Left hand side of this equation gives sum of elastic strains for fuel and clad which can be written as

$$\epsilon_{FE} + \epsilon_{CE} = \frac{P(1-\nu)}{E_F} + \frac{Pd}{2tE_c}$$

$$= KP \qquad (2)$$

where P is interaction pressure and K is a constant depending on fuel elastic modulous E_F, clad elastic modulous E_C, fuel poisons ratio ν , and clad diameter d and thickness t.

From (1) and (2), continuity equation becomes

$$KP = (\epsilon_{FS} - \epsilon_{CS}) - (\epsilon_{FC} + \epsilon_{CC}) \quad (3)$$

Solution of this equation gives fuel clad iteration pressure as function of time.

As creep strain (Term in 2nd paranthesis on right hand side of Eqn.3) and interaction pressure are interdependant, above Eqn. is solved in repetitive small time intervals. Net swelling strain (given by 1st paranthesis on right hand side of Eqn.3) is known for any point of time once fuel and clad swelling behaviour is known. Net creep strain at any point of time is given by the creep strain at the start of the time interval + creep strain obtained during the interval while keeping P as constant during the interval. At the end of each interval new interaction pressure P is obtained based on the net swelling and creep strain at that moment.

3.0 Reference Data

Based on the above model fuel clad interaction problem has been analysed for fuel pin having 5.1 mm OD, 0.37 mm thick, 20% CW SS-316 clad. Based on large irradiation data for advanced fuels reported in the literature, fuel swelling rate has been taken as 1.5% per a/o BU. This value is a little conservative considering the low operating temperature of fuel after the pellet-clad contact is made.

Fuel irradiation creep rate is taken as 10^{-6} per hour when normalised to 1 Kg/mm^2 stress and 10^{14} fiss/cc. This is based on correlations suggested by Clough [5] . Nominal clad creep rate is based on the measurement of Yoshida [6] for similar clad tube at 600°C and is given by

$$\dot{\epsilon}\ (hr^{-1}) = 6 \times 10^{-13}\ \sigma^{5} (Kg/mm^2) \qquad (4)$$

4.0 Interaction Pressure Vs Irradiation Time

Using the model and reference data as described earlier, fuel-clad interaction pressure was computed as a function of time. Results are given in Fig.1 which shows interaction pressure, net swelling strain and net creep strain as function of time. It is found that the moment fuel-clad gap closes, interaction pressure starts building up until it reaches its equilibrium value at which swelling strain rate is counter balanced by creep strain rate. It is to be noted that this equilibrium interaction pressure is purely a function of material properties and does not change with time.

5.0 Interaction Pressure Vs Creep Behaviour

With present state of knowledge, fuel creep rate is the most uncertain parameter which can vary over orders of magnitude with a slight change in composition and fabrication routes. Calculations have been made to determine the effect of fuel creep rates varying from one order less to one order higher than the reference creep rate as suggested by Clough. Similarly, to account for uncertainty in clad creep behaviour, interaction pressure has been evaluated for clad creep rates varying from one order less to one order higher than the reference creep rate given by Eqn.4.

Results, as given in Fig.2, indicate that reference creep rates for fuel and clad (after Clough and Yoshida) will lead to a strong interaction pressure around 5 Kg/mm^2 which will result in an early clad failure. To avoid ratcheting and excessive strain of the clad, interaction pressure should be limited to 1 Kg/mm^2 or below. From Fig.2 it can be seen that to keep the interaction within permissible limits fuel should creep atleast 8 times the reference value. It can also be noted that uncertainty on clad creep rate is of no consequence as far as realisation of a weak fuel-clad interaction is concerned.

6.0 Conclusions

Once the free swelling phase is over and fuel clad contact is made, interaction pressure starts building up until it reaches its equilibrium value where swelling rate is counter balanced by creep rate. This equilibrium interaction pressure is purely a function of material properties and does not change with time.

Present analysis shows that reference creep rates will give rise to a very high interaction pressure and will result in an early clad failure. It is necessary to have a fuel which can creep around 10^{-5} per hour under 1 Kg/mm^2 stress and 10^{14} f/cc. This will ensure a weak fuel-clad interaction resulting in a longer clad life without excessive stress and strain.

References

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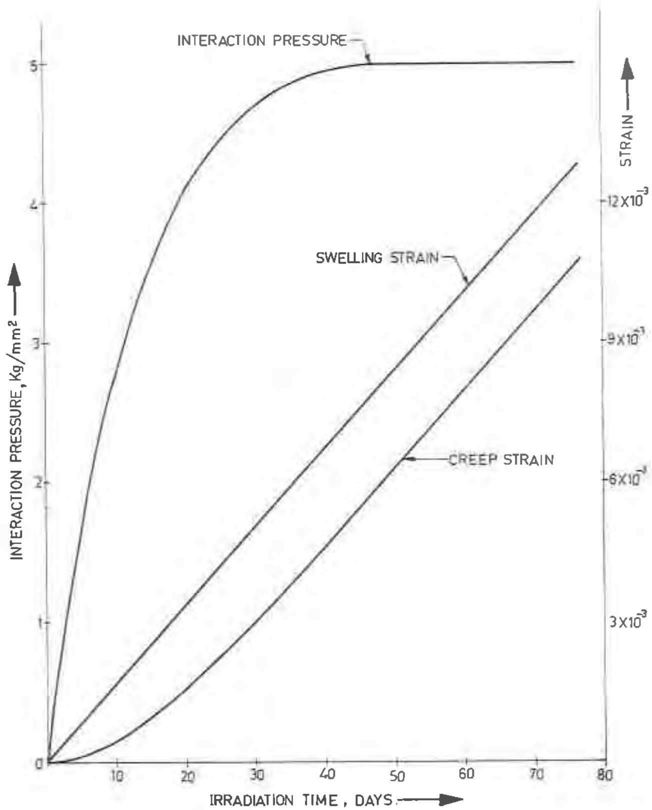

Fig. 1 Fuel-Clad Interaction Pressure and Effective Swelling and Creep Strains Vs Time After Gap Closure.

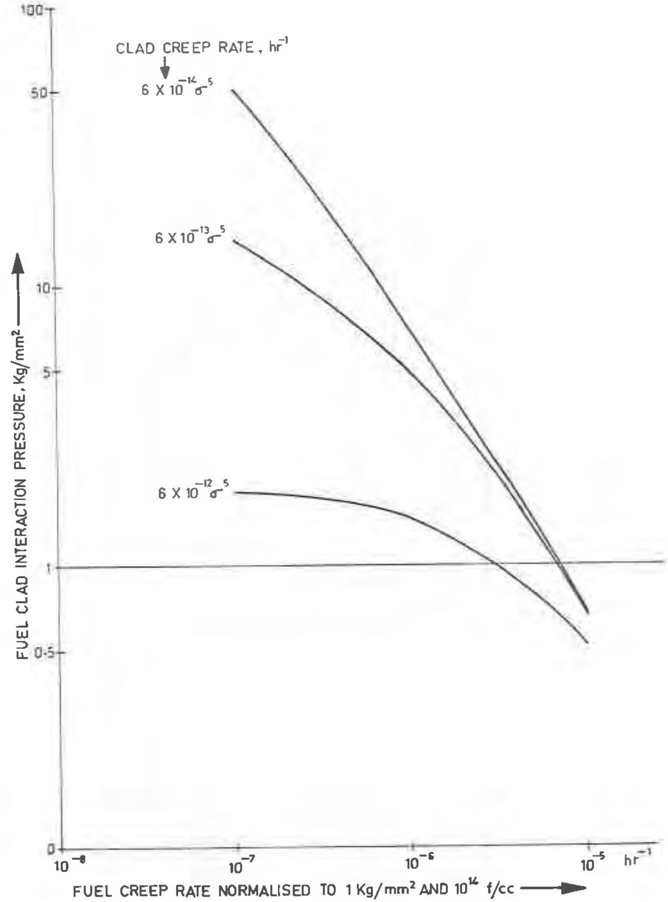

Fig.2 Fuel-Clad Interaction Pressure As Function of Fuel and Clad Creep Behaviour.