THE BEHAVIOR OF FISSION GAS IN OXIDE FUELS IN A TRANSIENT OVERPOWER

T. WEHNER, D. T. EGGEN
Department of Engineering Sciences and Applied Mathematics,
The Technological Institute, Northwestern University, Evanston, Illinois 60201, U.S.A.

SUMMARY

The purpose of this paper is to describe the effects of fission gas on fuel and fuel motion from the initiation of a transient overpower (TOP) to fuel pin failure. This paper does not deal with fuel motion after fuel pin failure or with the reactivity of the fuel. This paper reports only the thermal response of oxide fuel during a TOP.

A fuel pin can be categorized according to its most advanced fuel microstructure. In low-power irradiated fuel pins the fraction of fission gas in the fuel is greater at the top and bottom than at the midplane of the fuel pin. A high-power irradiated fuel pin has a high-power irradiated fuel microstructure at the axial midplane and a low-power irradiated fuel microstructure near the top and bottom of the fuel pin. The axial distribution of fission gas is peaked at the top and bottom of the fuel pin while the midsection contains a minimum amount of fission gas.

During a TOP three cladding loading mechanisms may operate, fuel thermal expansion, fuel volumetric expansion and transient fission gas release. Fuel volumetric expansion may provide a mechanism for fuel pin failure. Rapid heating rates and/or high gas concentrations tend to produce fuel motion, while lower heating rates and/or lower gas concentrations tend to produce fuel swelling. In transient fission gas release, fission gas becomes free to move in the fuel matrix. Two mechanisms for transient fission gas release are fuel melting and the release of fission gas precipitated at the grain boundaries at temperatures below the fuel melting temperature.

In a low-power irradiated fuel pin failure all three cladding loading mechanisms can operate. Fuel can be dispersed prior to fuel melting, but it has been suggested that failure in irradiated fuel pins occurs when the low-power irradiated fuel microstructure near the axial midplane reaches incipient melting, i.e. when fission gas is released from the unstructured fuel and loads the cladding. After the initial cladding failure a molten fuel and fission gas mixture may be released from the fuel pin.

In a high-power irradiated fuel pin failure, again, all three cladding loading mechanisms can operate. Failure occurs again when a low-power irradiated fuel microstructure portion of the fuel reaches incipient melting, a region away from the axial midplane. Sometimes at failure only fission gas is released through small leaks in the cladding. Other times a mixture of fuel and fission gas is expelled.

During a TOP three cladding loading mechanisms may operate, fuel thermal expansion, fuel volumetric expansion and transient fission gas release. Fuel pin failure in a TOP is dependent upon fuel microstructure and concentrations of retained fission gas. After fuel pin failure fission gas can act as a driving force to eject molten fuel from the fuel pin.
The purpose of this paper is to describe the initial behavior of oxide fuel in a Loss of Flow Accident (LOF). In particular, the time to fuel cracking is compared with the time to fuel melting.

This study examines the LOF in the Gas-Cooled Fast Breeder Reactor (GCFR). However, the study may also be applied to a LOF in the Liquid Metal Fast Breeder Reactor (LMFBR) in which the core has been voided of liquid sodium. In this idealized hypothetical core disruptive accident (HCDA) it is assumed that all coolant flow has stopped while the reactor the reactor remains at full operating power. In this LOF then the fuel pins become effectively insulated and the cladding will begin to melt. Cladding melts and moves to the lower axial blanket where it causes a slight reactivity insertion and consequently a power increase. In order to show that the accident can be terminated it is desirable to show that fuel moves out of the core to yield a subcritical assembly.

In this analysis of the initial fuel behavior in the LOF it is assumed that the fuel has been operating at steady state at full power for a relatively long period of time. The fuel is restructured and has achieved a burnup of approximately $10^3$ MWD/T. It is assumed that cracks in the unstructured and columnar zones make these zones structurally weak. However, the equiaxed zone is assumed structurally sound, so that before molten fuel can exit the center of the fuel pin, the equiaxed zone must either crack or melt. The fuel pellets have sintered together and the central cavity is effectively sealed. (See figure 1 for typical fuel dimensions for the GCFR.) The cladding has melted off of the fuel pins in the center of the core and has moved toward the lower axial blanket causing a net reactivity insertion.

It is assumed that the initial pressure in the central cavity and at the fuel outer surface is 9 MPa (≈ 90 atmospheres), the approximate helium coolant pressure in the GCFR. It is assumed that the temperature distribution is axisymmetric and that axial heat conduction can be neglected. (The time constant for heat transfer for the oxide fuel is about 4 sec, which is longer than the times involved in this study.) It is assumed that the strain rate in the fuel is very large.

Of primary interest is the fuel pin cross section at the axial midplane where the greatest radial temperature gradient is expected. The LOF is modeled by stopping coolant flow and imposing a power transient on the fuel pin as shown in figure 2. Temperatures and pressures are calculated as a function of time to determine the maximum hoop stress in the equiaxed zone. The hoop stress due to pressure forces is given by [1]

$$
\sigma_\theta = \frac{(p_I - p_0)a^2}{b^2 - a^2} \frac{2}{r^2} + \frac{(p_I a^2 - p_0 b^2)}{b^2 - a^2},
$$

where $p_I$ is the pressure at the inner surface of the fuel in the central cavity, $p_0$ is the pressure at the outer surface of the fuel, $a$ is the inner radius of the solid part of the fuel, and $b$ is the outer radius of the fuel.

The hoop stress due to the temperature distribution is given by [2]

$$
\sigma_\theta = \frac{\rho E}{1-\nu} \frac{1}{r^2} \left\{ \int_a^b \frac{x^2 + a^2}{b^2 - a^2} Tr' dr' + \int_a^b Tr' dr' - Tr^2 \right\},
$$
where $\alpha (\approx 2 \times 10^{-5} \text{K}^{-1})$ is the average coefficient of linear thermal expansion, $E (\approx 2 \times 10^5 \text{MPa})$ is an average Young's Modulus, $\nu (\approx 0.35)$ is the average Poisson's ratio over the temperature range, $T$ is the radial temperature distribution, and $a$ and $b$ are as defined above. The fracture strength for the fuel is approximately 100 MPa and when the hoop stress in the equiaxed zone exceeds this value it is assumed that a crack forms through the equiaxed zone.

A typical plot of temperature versus radius for various times is shown in figure 3. For an imposed power transient like that shown in figure 2 with $\Delta t$ between 0.2 and 0.5 seconds the time to initial melting is on the order of 1 second. The time to cracking of the equiaxed zone is on the order of 0.1 second. Therefore, a flow path for the molten fuel and fission gas mixture from the interior of the fuel pin to the surface is established before the onset of fuel melting. The major effect of the fission gas then is to provide a pressure force to expel the molten fuel and fission gas foam out of the fuel pin. Non-violent movement of the molten fuel then is to be expected.

In a loss of flow accident without scram fuel motion from the core outward is a mechanism for shutting the reactor down. Molten fuel motion can be expected to be non-violent if, as indicated in this study, early cracking of the fuel provides a flow path for molten fuel to move out of the interior of the fuel pin.

References


Figure 1. Typical Dimension of the Restructured Zones in Oxide Fuel

Figure 2. Typical Imposed Power Transient ($0.2 \leq \Delta t \leq 0.5$ sec)

Figure 3. Typical Temperature Distribution at Various Times