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EFFECT OF THERMAL STRESS ON OXIDE CRUSTS

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R. W. Ostensen
Sandia Laboratories
Albuquerque, New Mexico

In the transition phase in LMFBR hypothetical accidents, the existence of an insulating crust of frozen fuel between molten fuel and cold structure is of key importance. The disruption of such a crust for fuel flowing through the axial blanket regions can lead to rapid freezing and subsequent blockage formation[1,2]. In a boiling pool of molten fuel and steel, the presence of the crust may be necessary in order to reduce the convective heat transfer rate and allow a subcritical boilup.[3,4] This paper describes the effect of thermal stress on such a crust and points out that such crusts may be far weaker than previously believed.

The thermal stress, σ, in a thin crust which is infinite in the transverse direction may be found from

$$\sigma = \alpha E(T - T_o)/(1 - \mu) \quad , \qquad (1)$$

where α is the coefficient of thermal expansion, E is Young's modulus, μ is Poisson's ratio, and T and T_o are the fuel temperature and a reference temperature respectively. The constants α and μ are assumed to be temperature independent. If the temperature profile is assumed to be linear and E is a linear function of temperature, going to zero at the melting point, then the unknown reference temperature may be eliminated and the stress distribution found.

With the hot crust boundary at the melting point, the maximum tensile stress occurs at the cold crust boundary. If this stress is equated to the failure stress, σ_u, of mixed oxide, a maximum temperature drop, δT, is found for which cracks will not propagate:

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$$\delta T = \left[3(1 - \mu)\ \sigma_u / (\alpha \frac{dE}{dT})\right]^{1/2} \qquad (2)$$

For a coefficient of expansion of 2×10^{-5} K^{-1}, an ultimate strength of 206 MPa and a temperature derivative of Young's modulus for mixed oxide fuel[5] of 150 MPa/K, the maximum uncracked crust thickness has a temperature drop of only 230 K. Crusts can exist with a larger temperature drop, but fracture of the crust should occur on the cold side with cracks propagating part of the way through the crust. The cracks should end in the region where the temperature is 330 K below the fuel melting point. Clearly, the strength of the crust will be determined by the thickness of the uncracked region.

Consider a crust which forms when molten fuel contacts cold steel. If the steel temperature is above about 1100 K, the steel surface will instantly melt,[6] and the temperature drop across the crust will be the difference between the fuel and steel melting points (about 1350 K). Cracks from the cold side will penetrate about 76 percent of the crust thickness, leaving only 24 percent of the crust to withstand mechanical stress.

Consider a crust on the steel walls surrounding a pool of boiling fuel and steel. The thickness of this crust, L, is given by

$$L = \left(\sqrt{1 + 2k\delta TQ/q^2} - 1\right) q/Q \quad , \qquad (3)$$

where k is the thermal conductivity (about 300 W/m^2 K), Q is the volumetric power in the crust, and q is the total heat flux to the steel. At full power in an FFTF subassembly, Q is about 1500 MW/m^3 and q is about 15 MW/m^2. This leads to a crust thickness of 0.26 mm. However, 76 percent of this crust thickness will be cracked, so for mechanical strength considerations the effective crust thickness is only 63 μm. The survival of such a crust in a highly turbulent environment seems unlikely. If the reactor power were only 10 percent of nominal (6 percent decay heat plus some fission heating), which is a more likely power-level for a subcritical system, the full crust thickness is 2.3 mm and the uncracked thickness is 0.6 mm. Further study is needed to determine whether such a crust could maintain its integrity. For a larger pool, the smaller surface to volume ratio would lead to higher heat fluxes at the wall, and therefore thinner crusts. For a 100 subassembly pool at 10 percent power, the crust thicknesses are about the same as for a single subassembly pool at full power, and, as discussed previously, such a crust is not likely to be stable. Without a stable crust to provide insulation, a full core pool would probably lose too much heat by convection to remain boiled up at low power levels.[4] This may lead to a recriticality as the pool subsides.

Because of the large temperature gradients across a fuel crust, which is insulating molten fuel from cold steel, thermal stress will induce a partial failure of the crust. Cracks will penetrate most of the way through such a crust, greatly reducing its strength. Stability of a crust for a full core pool is unlikely and, as a consequence, pool subsidence and recriticality may occur.
For a single subassembly pool, oxide crusts may be stable at low power.

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