DUCTILE-BRITTLE BEHAVIOR OF ZIRCALLOY FUEL CLADDING*

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This paper describes the results of two sets of experiments designed to characterize the ductile-brittle behavior of Zircaloy fuel element cladding in terms of amount of oxidation, degree of penetration of brittle phases into the tube wall, and type of deformation used in the tests.

Ring specimens were cut from 0.422-in. OD $\times$ 0.027-in.-wall thickness Zircaloy-4 tubes previously steam-oxidized on both inner and outer surfaces at temperatures ranging from 1700 to 2400°F for various times. Two types of deformation tests were employed: high-strain-rate compression (flattening) tests in an argon atmosphere at temperatures from room temperature to 1900°F and slow-strain-rate compression tests from room temperature to 300°F.

The high (near impact)-strain-rate test results¹ showed that a correlation exists between deformation temperature and amount of oxidation. The ductile-brittle transition is defined by a zero-ductility temperature (ZDT) and the amount of oxidation by the parameter F_w , which is the fraction of the as-oxidized wall thickness that reverted to α -phase from the β -phase on quenching from the steam exposure temperature. The empirical correlation derived from the high-strain-rate tests is given by

*Research sponsored by the U.S. Atomic Energy Commission under contract with Union Carbide Corporation.

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$$\text{ZDT } (^{\circ}\text{F}) = 2727 - 3636 \left[1 - \frac{2 \xi}{w_0 + 0.252 \xi} \right], \quad (1)$$

where ξ = the thickness of oxide and oxygen-stabilized α phase on one surface (cm), and w_0 = original wall thickness = 0.0675 cm. The quantity within parentheses represents F_w based on original wall thickness.

The slow (0.01 in./min crosshead speed)-strain-rate tests indicate that the ductile-brittle strain behavior of specimens exposed to steam at temperatures from 1700 to 2200°F and tested at room temperature, 200 and 300°F could be correlated with F_w . The empirical relationship derived from the slow-compression tests and bounded by the temperature conditions given above is

$$\text{ZDT } (^{\circ}\text{F}) = 2410 - 3660 \left[1 - \frac{2 \xi}{w_0 + 0.252 \xi} \right]. \quad (2)$$

Specimens oxidized at 2400°F did not fit the correlation described in Eq. (2). The behavior of those specimens coincidentally was more closely defined by Eq. (1), the impact correlation. At the deformation temperatures used, the 2400°F-exposed specimens all tended to be more brittle than their F_w values indicate they should be, based on the lower temperature data. The basic inference to be drawn from this observation is that embrittlement is not only a function of F_w or ξ penetration, but is related to the exposure temperature. The most obvious rationale for this behavior is that the oxygen content of the β phase tends to be much higher in the 2400°F specimens due to increased oxygen solubility and to more rapid diffusion. The rate of oxygen diffusion into the β phase continuously increases with temperature, as does the solubility of oxygen, and for the slow-compression

test conditions, the effect of the increased oxygen concentration becomes critical in specimens tested after exposure at some temperature between 2200 and 2400°F.

In addition to the ductility results, a correlation was found between midwall hardness and F_w , which indicates a linear increase in hardness with decreasing F_w , for each exposure temperature, between $F_w = 0.8$ and $F_w = 0.4$.

The following conclusions are drawn from these studies:

1. There are correlations between amount of oxidation (F_w) and the ductile-brittle, or zero-ductility temperature (ZDT), behavior of Zircaloy-4 fuel element cladding exposed to steam at various temperatures and subsequently tested in either high- or low-strain-rate compression (flattening).

2. At some steam exposure temperature between 2200 and 2400°F the F_w -ZDT correlation developed from the low-strain-rate tests becomes inapplicable. This is believed to be caused by faster overall diffusion increased solubility of oxygen in the β phase.

REFERENCE

1. D. O. Hobson and P. L. Rittenhouse, *Embrittlement of Zircaloy-Clad Fuel Rods by Steam During LOCA Transients*, ORNL-4758 (January 1972).