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EUTECTIC-PENETRATION-INDUCED CLADDING RUPTURE IN EBR-II DRIVER FUEL ELEMENTS*

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One facet of the Operational Reliability Testing Program at the Experimental Breeder Reactor II (EBR-II) has been an interest in the behavior of the standard EBR-II metallic-fuel driver element, the Mark-II (Mk-II), during off-normal operating conditions. In the event of an off-normal transient when the fuel-cladding temperature exceeds the eutectic formation temperature, the time to cladding rupture is of great importance. Cladding rupture, even though initiated by eutectic formation, is not in itself a safety concern, but the resulting release of fission gas and products can interfere with ongoing experiments and operational tests. Previous researchers have concentrated on either the steady-state eutectic diffusion rates[1-4] or the eutectic penetration rates resulting from a hypothetical accident in which molten fuel reacts with the cladding.[5-7] However, data are lacking in the off-normal intermediate region between normal steady-state operation and low-probability hypothetical accident operation. The purpose of this study was to determine the time to rupture of both irradiated and unirradiated Mk-II fuel elements operating above the eutectic temperature of 715°C. The eutectic alloy that forms between the annealed Type 316 stainless steel cladding and the uranium-5

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wt % fissium* fuel is U-34 wt % Fe. Details of the Mk-II element design are given in Ref. 8 with the nominal radial dimensions being: cladding OD, 4.42 mm, cladding ID, 3.81 mm, and fuel OD, 3.30 mm. The fuel bond material is sodium.

The experimental test procedure employed a high-temperature furnace which heated the Mk-II elements to above the eutectic temperature and maintained the environment until the element-cladding ruptured. The elements were encapsulated in a close-fitting sealed tube instrumented with a pressure transducer and a thermocouple to detect element rupture. The three-zone, vertical, fast-recovery furnace established an axial temperature profile similar to that in the EBR-II core. The encapsulated element was then quickly inserted into the furnace and remained there until cladding rupture occurred. Once rupture occurred the element was then quickly removed. Seven elements were tested, and three test temperatures were used: 750°C, 800°C, and 850°C.

A summary of the test temperatures, element burnups, and times to rupture are listed in Table 1. The time-to-rupture data listed under the heading of "equivalent total steady-state time at temperature" have been correlated with a correlation coefficient of 0.958 by the following equation based on a 0.305 mm wall thickness:

$$t_r = 91420 \left(\frac{T}{715}\right)^{-28.495} (1 + b)^{-0.54469} \qquad (1)$$

over the range of $750°C \le T \le 850°C$, and

$0 \le b \le 7.8$ at. %,

where t_r is the time to element rupture in seconds, T is the temperature in °C, and b is the burnup in at. %. The average error in the t_r predicted by

*Fissium (Fs) is an equilibrium concentration of fission-product elements left by the pryometallurgical reprocessing cycle for EBR-II. The major constituents of fissium are zirconium, molybdenum, palladium, ruthenium, and rhodium.

this correlation is ±24%. For comparison, the time to rupture based solely on eutectic penetration of the full cladding thickness, as determined from Ref. 6, is also shown in Table 1. The "total time above eutectic temperature" in Table 1 represents the actual time the element was above the eutectic temperature until rupture. The "equivalent total steady-state time at temperature" represents the total time at the specified furnace temperature until rupture, and includes a time equivalent at the steady-state furnace temperature for the short period in which the element was above the eutectic temperature but below the final steady-state temperature.

Several factors appear to contribute to early cladding rupture in fuel elements operating above the eutectic temperature. The major factor seems to be the cladding hoop stress caused by fission-gas loading. A possible contributing factor is stress enhancement of the eutectic penetration rate. Element burnup also appears to influence the time to cladding rupture via two contributing factors: (1) the increase in contact area as the fuel swells to the cladding, and (2) some diffusion of the eutectic species into the cladding wall during normal operation. The effects of burnup become clear when these data are compared to the corresponding calculated times for eutectic penetration based on the data from molten-uranium dip tests in Ref. 6. Also, the time to rupture for this study are much less than predicted by solely eutectic penetration through the entire cladding wall. Thus, two important conclusions were reached in this study. The first is that the time to achieve cladding rupture in Mk-II fuel elements, at temperatures above the eutectic temperature, is shorter than predicted from basic eutectic-penetration data. The second is that the time to cladding rupture at a given temperature is dependent upon burnup.

Summary of Data for the Mark-II Element Eutectic-Penetration Rupture Tests

			Rupture Times		
Element Number	Burnup (at. %)	Furnace Temperature[a] (°C)	Total Time Above Eutectic Temp. (s)	Equiv. Total Steady-state Time at Temp. (s)	Calc. Time for Full Eutectic Penetration[b] (s)
EU35	1.4	750	17 658	17 592	45 750
XM771	7.66	750	5 820	5 754	45 750
HL45[c]	0.0	800	2 772	2 592	7 320
U5502	1.8	800	3 954	3 864	7 320
XM857	7.8	800	1 062	972	7 320
U5440	1.8	850	437	334	954
XM841	7.8	850	323	220	954

[a]The eutectic alloy formation temperature is 715 ± 5°C, and the uranium-5 wt % Fs melting point is 1081 ± 5°C.

[b]Based on the molten-uranium dip tests of Ref. 6.

[c]This element was heated up twice, with the first heat up lasting about three minutes.

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