FINAL CONF-831047--123

THE MACROSCOPIC BEHAVIOR OF FAST REACTOR FUEL SUBJECTED TO SIMULATED THERMAL TRANSIENTS*

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CONF-831047--123

DE84 004028

June 1983

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To be submitted for presentation at the Winter Meeting of the American Nuclear Society, October 30-November 4, 1983, San Francisco, CA.

*Work supported by the U. S. Department of Energy.

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SUMMARY

The course and severity of hypothetical core disruptive accidents (HCDAs) in fast reactors depend on the location and motion of the coolant, cladding, and in particular, the fuel. Early dispersion of fuel from regions of high-worth to low-worth regions will mitigate the severity of an HCDA and under certain conditions may result in an early termination of the initiating event.[1] It is therefore important to understand the types of fuel dispersion/disruption mechanisms that can occur and how variables such as the fuel history (power/burnup), fuel heating rate, and cladding influence their timing and occurrence.

In this paper, we summarize the types of fuel behavior observed in a recent series of direct electrical heating (DEH) experiments on irradiated fuel (with burnups ranging from 0.6 to 9 at. %) that simulated the initiating phases of a loss-of-flow (LOF) event for the CRBR design. The technique which has been described elsewhere[2] utilizes ohmic heating to simulate the nuclear heating. Prior to initiating an electrical heating ramp, an external heater is used to melt the stainless steel cladding off of the oxide fuel to prevent the current from shorting through the metallic cladding. The occurrence and timing of the types of behavior were identified from high-speed movies and

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*Work supported by the U. S. Department of Energy.

video recordings of the sample, and subsequently correlated with the steady-state pin history and the transient thermal history.

Analysis of the high-speed movies indicated the behavior was dependent on several factors including the quantity of fission gas present in the fuel, the presence of a radial restraint (imposed by the cladding), and the heating rate. The behavior of the fuel during the initial stage (as the cladding melted) was dependent on the presence of the cladding and the fuel burnup/power - or more precisely the retained fission-gas content. Tests on low/medium burnup (or unirradiated fuel) indicated the cladding melted and flowed off the oxide pellets without wetting the surface. In contrast, tests utilizing medium- to high-burnup fuel exhibited fuel spallation after the cladding melted and flowed down the stack. This latter type of behavior was characterized by the energetic ejection of solid particles of fuel from the surface of the fuel pellets. Ejection occurred at relatively low temperatures (~1500°C), and in some instances (depending on the gas retention) resulted in a considerable loss of fuel (up to 60% by mass). The occurrence of spallation as found to be dependent on two factors: (1) the relaxation (upon clad melting) of the radial restraint imposed by the cladding, coupled with (2) a retained fission-gas (Xe + Kr) content in excess of a critical threshold valve. Fuel segments originating from pins with average retained gas contents above ~16 μmoles/gm of fuel exhibited spallation, while segments from pins with gas contents below this threshold failed to spall.

Samples subjected to electrical heating ramps following complete melting of the cladding exhibited fuel dispersive/disruption modes which were dependent on two factors: the heating rate, and whether the fuel was irradiated or unirradiated. For irradiated fuel, the heating rate had a significant impact; at low to medium heating rates (<300 J/g·s) longitudinal cracks formed, gross swelling occurred, and molten fuel was ejected prior to failure, while at high heating rates ($\gtrsim$300-400 J/g·s), the fuel heated up and collapsed without forming longitudinal cracks, gross swelling, or ejecting significant quantities of molten fuel. A minor amount of swelling occurred at the fast rates due to thermal expansion but not of the magnitude observed during the slow transients. Minor quantities of molten fuel were also ejected at the faster rates, but this occurred at the time of failure, not before failure as observed during the slow transients. At failure, samples subjected to fast transients broke into several large pieces with dimensions in the mm range. For unirradiated fuel, the dispersive nature of the fuel was characterized by the ejection of molten fuel from pellet interfaces and cracks, and the drainage of molten fuel from the bottom pellet. Failure of the unirradiated samples occurred when the remaining shell of solid fuel collapsed under the weight of the top electrode.

Figure 1 summarizes the types of behavior observed using the concept of a fuel response diagram developed by Bandyopadhyay et al.[3] The solid data points represent the failure time (measured from the start of the electrical heating ramp) and are plotted vs the average heating rate during the DEH phase. The open symbols denote the termination times for transients stopped prior to failure. [Failure is defined in these tests as a downward motion of the top electrode (slumping or fracture of the sample) of ~0.010 in. which triggers an LVDT to shut off the DEH power supply]. The solid and dashed curves represent the failure times as a function of the average heating rate for irradiated and unirradiated fuel, respectively. The dotted curve shows the time when gross swelling ($\Delta D/D \gtrsim 10\%$) started to occur in tests using Numec-F fuel (~6 at. % burnup).

Two trends are evident in Fig. 1 that arise from the use of irradiated fuel. First, the failure time for unirradiated fuel is 2-3 times larger than that for irradiated fuel. Secondly, irradiated fuel undergoes gross swelling at low-to-medium ($\lesssim$300 J/g·s) heating rates (up to ~200% by volume) prior to failure.

In conclusion, high-speed cinematography has been used to characterize the macroscopic behavior of irradiated and unirradiated fuel subjected to thermal transients prototypical of fast reactor transients. The results demonstrate that as the cladding melts, the fuel can disperse via spallation if the fuel contains in excess of ~16 μmoles/gm of fission gas. Once the cladding has melted, the macroscopic behavior (time to failure and dispersive nature) was strongly influenced by the presence of volatile fission products and the heating rate.

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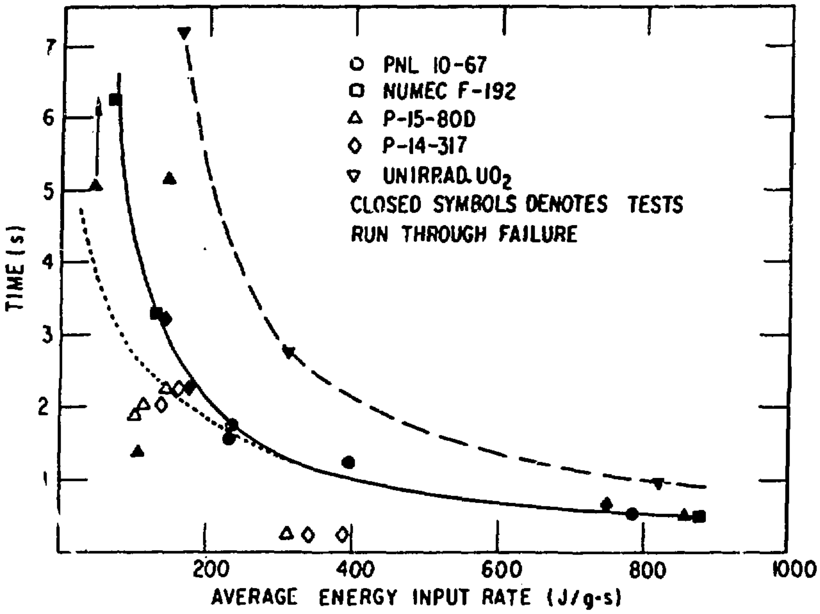

Fig. 1. Fuel Response Diagram of Unirradiated and Irradiated Fuel. Solid and dashed curves show failure times as a function of the average heating rate for irradiated and unirradiated fuel, respectively. The dotted curve shows the onset time for gross radial swelling of irradiated fuel.