CONF-880506--14

BEHAVIOR OF METALLIC FUEL IN TREAT TRANSIENT OVERPOWER TESTS

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TI88 010042

MAY 17 1988

ABSTRACT

Results and analyses are reported for TREAT in-pile transient overpower tests of margin to cladding failure and pre-failure axial expansion of metallic fuel. In all cases the power rise was exponential on an 8 s period until either incipient or actual cladding failure was achieved. Test fuel included EBR-II driver fuel and ternary alloy, the reference fuel of the Integral Fast Reactor concept. Test pin burnup spanned the widest range available. The nature of the observed cladding failure and resultant fuel dispersals is described. Simple models are presented which describe observed cladding failures and pre-failure axial expansions yet are general enough to apply to all metal fuel types.

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Transient Reactor Test Facility (TREAT) tests M2 through M6 were the first transient overpower (TOP) tests of the margin to cladding breach and prefailure elongation of metallic fuel of recent design. Models and concepts of these effects have been needed early in the safety assessment of the metal-fueled Integral Fast Reactor (IFR) to verify both wide failure margins and to quantify axial expansion, a potentially significant pre-failure reactivity removal mechanism. Understanding the nature of pin failure, itself, and obtaining preliminary assessments of post-failure fuel dispersal is also desireable. Because of its early availability and because it had been well-characterized, initial tests in the series used EBR-II driver (U-Fs) fuel. Later tests used ternary (U-Pu-Zr) fuel as it became available. Ternary fuel is the reference fuel for IFR concept. Test fuel spanned as wide a range of available burnups as possible. Although the various metal-fuel types are similar in many respects, the IFR ternary alloy exhibits a much more complex physical structure, has lower thermal conductivity, and is typically irradiated at much higher temperatures than the U-Fs used in EBR-II. Thus, as

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* Work performed under the auspices of the U.S. Department of Energy.

Work supported by the U.S. Department of Energy "Technology Support Program" under Contract W-31-109-Eng-38.

the database of test pins accumulate, comparison of safety-related fuel performance characteristics among metal fuel types is of great interest.

All test fuel in this series was subjected to similar overpower conditions: full coolant flow and an exponential power rise on an 8 s period. Baseline thermal conditions in the test fuel were referenced to nominal conditions in a fast reactor including a peak linear power rating of 40 kW/m (12 kW/ft), an inlet temperature of 630 K and a 150 K coolant temperature rise. The power rise was rapidly terminated upon detection of cladding breach or, by using previously measured failure thresholds, just prior to failure. thirteen pins have already been tested; four were overheated to a cladding breach, which in every case occurred near the fuel top. Overpower levels achieved in each case were in the neighborhood of four times nominal. The experimental techniques and the instrumentation used are described in Ref. 1. It is the purpose of this paper to summarize results and analyses pertaining to safety issues.

A comprehensive summary of results and peak overpower conditions achieved in the test series is given in Table I. Peak power level achieved for each test pin is shown (with an uncertainty of roughly 5% [Ref. 1]). Pin failures, when they occurred, are noted. Estimates of peak internal pressure given in Table I are based on sibling pin measurements and thermal calculations. Finally, Table I indicates measurements of peak pre-failure elongation made by the fast neutron hodoscope [Ref. 1] for each test pin.

Cladding failure threshold in metal fuel has been modeled on the basis of both overpressure and penetration by a low temperature iron-uranium eutectic. In contrast to ceramic fuels, the lower mechanical strength of metal fuel leads to pin plenum pressure as the primary pressure loading of the cladding. Cladding stresses, however, reflect not only the pin plenum pressure but also thinning by eutectic. Cladding deformation and strain-to-failure are computed on the basis of stress history and correlations derived from transient tube burst tests [Ref. 2].

These concepts may be applied rather simply to the present overpower test series. The high thermal conductivity of metal fuel assures peak cladding temperatures, hence likely failure sites, near the fuel top. Temperatures key to the failure threshold analysis (pin plenum, peak cladding midwall and cladding inner-surface temperatures) are close to or easily derived from the measured whole-pin coolant temperature rise. The rise rate is sufficiently rapid that, except at the highest possible burnups, failure would not be expected until the temperature of the fuel cladding interface exceeds a "threshold" value of 1350 K, the temperature at which eutectic penetration into the cladding becomes very rapid (associated with the melting of a protective solid iron-uranium compound). From thermal calculations, this temperature is reached at overpower levels of about four times nominal. Detailed model calculations predict that nearly total eutectic penetration would be required to fail cladding at low burnup, partial penetration would be required at midrange burnups, and almost no penetration would be required at high burnup. At these heating rates, the margin to failure is not expected to depend strongly on the particular metal fuel or cladding type. In general, observed timing, location and form of cladding failure are in good agreement with these concepts.

Turning attention to pre-failure fuel axial expansion there is a good deal of evidence to support the notion that significant elongation beyond thermal expansion, i.e., greater than about 1%, occurs when gas bearing fuel melts. Calculations and destructive post-test examination (PTE) indicate about half of the fuel had been melted in each test pin. Quantitatively, axial expansion is estimated by a model in which the fission gas present in molten fuel expands in volume until its pressure equals that of the pin plenum. Measured expansions of irradiated EBR-II driver fuel, which were especially pronounced at low burnup, are well predicted in both timing and magnitude under the assumption that, upon melting, a concentration of fission gas equal to that generated in about 0.5 at.% of burnup suddenly becomes available. By contrast, expansion of the IFR ternary fuel was typically less than EBR-II driver fuel and did not show large burnup dependence. In fact, only gas trapped within the fuel porosity (rather than dissolved in the fuel) is sufficient to explain observed expansion of IFR ternary fuel.

Typically, measured whole-pin fission gas retention is much greater than what seems to be "available" for producing axial expansion. One possible explanation is that local concentrations of dissolved gas decrease rapidly with irradiation temperature, and it is the fuel with the least dissolved gas that melts first. In EBR-II driver fuel the minimum measured local gas concentration is consistent with that assumed successfully in the expansion model. The IFR ternary fuel was irradiated at significantly higher linear power and temperature than the EBR-II driver fuel, and the ternary fuel which melts might contain little, if any, dissolved gas.

When cladding failed, post-failure events were characterized by rapid fuel dispersal, rapid coolant voiding, and partial flow blockage. Different fuel types tested behaved similarly. Pressure spikes were minor (less than 1 MPa) and were correlated to the plenum pressure of the failed pin. In each case about half of the fuel inventory was ejected through a small breach at the fuel top. The amount of disruption observed seems correlated to the amount of pin depressurization following failure. Under these circumstances, disruption could be driven either by expansion of trapped fission gas or sudden boiling of the liquid sodium bond within the fuel. (Pre-failure sodium bond vaporization was probably responsible for the elongation observed in the unirradiated test pin- Table I.)

In conclusion, test results have helped generate and validate simple models of cladding failure and pre-failure expansion. Failure threshold under the rapid overpower conditions tested is about 4 times nominal and not strongly dependent upon fuel type. Pre-failure axial expansion in metal fuel is significant beyond thermal expansion with strong dependence on fuel type, especially at low burnup. Finally, on a qualitative basis, post-failure material motion was benignly dispersive in all metal fuel types tested.

In the near future the current test database will be broadened to explore more features of metallic IFR fuel. These will include a wider range of burnups, options such as binary (U-Zr) fuel, and comparisons of advanced cladding types. M7 in particular, planned for late 1987, will test a 10 at.% burnup D9 clad ternary and a 3 at.% burnup HT-9 clad binary pin.

REFERENCES:

1. A. E. Wright T. H. Bauer, W. R. Robinson, and A. E. Klickman, "Techniques of Metal Fuel Transient Testing in TREAT", Paper submitted to this conference.

2. T. H. Bauer, G. R. Fenske, and J. M. Kramer, "Cladding Failure Margins for Metallic Fuel in the Integral Fast Reactor", Invited lecture in the SMiRT-9 conference, August 1987.

Table I Peak Overpower Conditions in Test Pins

Fuel	Burnup (at.%)	Peak Overpower (rel. to nominal)	Peak Pressure (MPa) *	Max. Axial Expansion (%)
U-5% Fs (EBR-II Driver)	fresh	3.8	0.6	4 **
	0.3	4.1	0.6- 0.8	16
	0.3	4.1	0.6- 0.8	18
	2.4	4.1 (failed)	2- 6	7
	4.4	4.2 (failed)	7- 9	***
	4.4	4.0	7- 9	4
	4.4	3.8	7- 9	4
	7.9	4.1 (failed)	17- 20	3
	7.9	3.4	17- 23	4
U-Pu-Zr (IFR-Ternary)	0.8	4.2	0.9- 1.0	2
	1.9	4.4	1- 3	3
	1.9	4.2	1- 3	3
	5.3	4.1 (failed)	7- 9	4

* Indicated uncertainty due to uncertainty in gas release fraction

** Expansion may have been caused by localized sodium bond boiling

*** Data ambiguous