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TREAT F-SERIES LMFBR LOSS-OF-FLOW EXPERIMENTS

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ABSTRACT

The F-series tests are done to study fuel behavior in an LMFBR LOF accident. These tests are performed in dry (no sodium) capsules to separate out effects of sodium on fuel behavior and, in F3 and subsequent tests, to permit visual observation. Justification for a dry capsule is that the fuel behavior of interest such as fuel pin breakup and extensive axial motion are assumed to occur after sodium voiding in a LOF accident. Two distinct F-series designs have been subject to TREAT tests. The design used for tests F1 and F2 permitted a study of extensive axial fuel motion and used the fast neutron hodoscope as the principal instrumentation. The second design, used for tests F3 and F4 and to be used for tests F5 and F6, permits a study of fuel pin break-up with high speed photography as the principal instrumentation.

F1 AND F2 TESTS

F1 and F2 General Description

The purpose of the F1 and F2 tests was to determine axial fuel motion during an LOF in an LMFBR with near-zero sodium reactivity such as FTR[1]. Such a reactor passes through the initial sodium voiding phase of a LOF at power levels near nominal. Both tests were conducted using EBR-II pre-irradiated pins with 34.3 cm (13.5 in) fuel columns. A unique feature of the F1, F2 design is that the pin in the fuel column region is surrounded by an annular refractory nuclear heated wall. Axial and horizontal views of the F1, F2 tests are shown in Figs. 1 and 2 respectively. Two thermocouples and a capsule pressure transducer that comprise the test capsule instrumentation are shown in Fig. 1. The radial area inside the nuclear heated wall shown in the horizontal view was selected to represent the area inside the perimeter of an LMFBR coolant channel. Both the radial rigidity and the reduction of pin heat loss provided by the nuclear heated wall simulate how the channel boundary conditions are modeled in accident codes such as SAS[2]. In SAS, a single pin and channel boundary are modeled as being representative of several subassemblies of pins. The principal instrumentation for these tests is the fast neutron hodoscope. Fig. 3 shows how the test and hodoscope are oriented relative to the TREAT reactor core in the horizontal plane. The neutron hodoscope measures fuel motion by detecting changes in the number of fission neutrons produced in test fuel located at the center of the TREAT reactor. At the test fuel, the image plane of the hodoscope is divided into 345 rectangular regions

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that are usually referred to as channels. Each channel has associated with it a collimator slot, a neutron detector, and the necessary electronics to amplify and to count pulses produced by fission neutrons. The design of the collimator slot allows only those neutrons originating in a specific rectangular region to be detected by the neutron detector placed in back of the slot. The neutron detector consists of a Hornyak button mounted on a photomultiplier tube. Digital scalers record the number of counts from each channel. The scaler contents are read out at regular intervals and the data are stored for analysis. Fig. 4 shows the relationship between the hodoscope axial and radial viewing area relative to the pre-test fuel column position. The pretest location of the test fuel in Fig. 4 shows that it is radially centered in column 11 and ranges axially from rows 4 to 18. Each rectangle in Fig. 4 represents a single channel. The dimension of the rectangles are 3.6 mm horizontally and 22.4 mm vertically and thus the scale in Fig. 4 is considerably compressed in the vertical direction. Figs. 5 and 6 show pretest axial and radial relative power distributions respectively in the test fuel as determined by radiochemistry in power calibration tests. This axial power distribution insured fuel melting occured first near the axial center of the 34.3 cm. fuel column in each test. In spite of thermal neutron filters located external to the capsule, Fig. 6 shows a fuel self-shielding effect due to fission by TREAT thermal neutrons.

Test F1 Description

Test F1[3] was performed at a constant nominal power level to evaluate the effect of fission products on the lead power-to-flow subassemblies in a reactor with near zero sodium void reactivity. The purpose of the experiment was to determine the effect of fission products on the initial axial fuel motion. F1 used EBR-II pre-irradiated fuel with 394 w/cm peak power and 2.35 at. % burnup. Neither the pressure transducer nor the thermocouples reported any abrupt events. Rather, the capsule pressure transducer and thermocouples showed a monotonic increase reflecting heatup of the capsule fill gas. The hodoscope showed a sequence of events described as bending of the fuel column, axial expansion, and fuel slumping. Fuel slumping was the most dramatic event, began at 12.7 s of TREAT time, and continued to reactor scram at 14.3 s. Figure 7 shows the hodoscope determined mass change as a function of test time for both the lower 14.0 cm and the upper 20.4 cm of test fuel assembly. The downward fuel acceleration during the slumping phase is approximately 1.4% of the acceleration of gravity. Figure 8 shows an artist's conception of the posttest materials distribution as determined by posttest metallographic examination. Note that the F1 heated wall survived the transient intact and fulfilled its test fuel containment purpose. Figure 8 shows that only one fuel pellet at the top of the fuel column moved out of the pretest axial fuel column confinement. Below that pellet were remains of the second and part of the third pellet from the fuel column top. These pellets were partially molten and swelled due to fission products. The swelling was so extreme that these pellets swelled out to the inside of the heated wall. Below the swelled pellets is an extensive axial region where only molten fuel is frozen as an even layer on the heated wall. This fuel was in the process of draining down the

heated wall to feed a liquid fuel pool region. This pool region was substantially devoid of fission products at the top. The pool was supported, sealed from leakage, and fed from below by swelled fuel that had expanded out to the inside of the heated wall. Lower portions of the pool region contained some fission product voids as the released fission products from the swelled fuel below percolated upward into the fuel pool. At the very bottom of the fuel region were some partially swelled and unmelted fuel pellets surrounded by liquid clad that had drained down to that level.

A model of the F1 fuel motion should reproduce the axial zones reported in Fig. 8 and correlate with the slumping initiation test time of 12.7 $\pm$ .1 s reported by the hodoscope. Such a model can be devised by a one-dimensional radial heat transfer model that uses a simple melt fraction criteria to determine both the formation time and axial extent of each zone. The highly swelled fuel near the fuel column top is shown in a photomicrograph with a solidus line estimate imposed in Fig. 9. Agreement with the melting transition at test scram time in Fig.9 was made by lowering the axial power level 12% from the radiochemical power calibration. Furthermore, these pellets were determined to touch the heated wall at a melt fraction of 7.0% and to start draining along the heated wall at a melt fraction of 13.6%. When the heat transfer analysis is done for every axial level lowering the power by 12% these melt fraction criteria from Fig. 9 can be used to define how the axial zones change with time. Figure 10 shows the result of the model in a time sequence of fuel motion prediction. Figure 10 shows why the upper half of the fuel column did not fall downward en masse after the clad melted. Evidently, the fission product induced swelling tightly gripped the inside of the heated wall, so the upper half of the fuel column was supported by a gripping mechanism. Note also that Fig. 10 d, which is the prediction of the model at test power termination, qualitatively shows the same axial fuel zones shown in Fig. 8 from posttest examination. Furthermore, both the model and the hodoscope data agree on the inception of fuel collapse to be at a test time of 12.7 s. Figure 11 shows a comparison of the model and the hodoscope data at a test time of 13.86 s. Axial zones of fuel depletion and fuel accumulation are in general agreement. However, the model predicts more mass movement than the hodoscope reported. One explanation for this lack of agreement is that the hodoscope data are not corrected for changes in fuel self-shielding evident by examining Figs. 6 and 8. An important conclusion to be drawn from the F1 results is that post-test, semi-intact fuel microstructures can provide invaluable clues to fuel motion prediction.

Test F2 Description

Test F2[4] was conducted with a power burst at the end of the TREAT transient. The original F2 test purpose was to demonstrate the effectiveness of fuel vapor as a disperser in case fuel in the lead power-to-flow subassemblies slumped. The test fuel was pre-irradiated in EBR-II at 381 w/cm. A low burnup (0.35 a/o), restructured pin was selected for F2 because fuel restructuring was considered necessary to prevent premature collapse of the fuel column as individual pellets following clad melting. Figure 12 shows the behavior of the capsule thermocouples and pressure transducer on the same time scale as the

TREAT reactor power. Both thermocouples burned out during the F2 test. The lower thermocouple located in the tantalum cup below the fuel column burned out at the end of the power flattop (~ 10.5 s). Posttest disassembly of the capsule indicated that molten clad filled the tantalum cup, so contact with molten clad burned out the lower thermocouple. The upper thermocouple burned out while the power was increasing during the power spike. Posttest disassembly of the capsule, the posttest neutron radiograph, and the hodoscope all confirm that the upper thermocouple burned out from contact with molten fuel at ~ 11.04 s. Before each thermocouple burned out, their small rises in temperature reflect heatup of the capsule fill gas. The pressure transducer reflected a capsule pressure rise due to heatup of the capsule fill gas before peak TREAT power was reached at 11.56 s. After peak power some radiation response is reflected in the pressure transducer data. The largest event reported by the hodoscope took place at ~ 11.04 s when fuel was ejected above the top of the original fuel column into rows 2 and 3. Hodoscope data in Fig. 13 indicates that starting at ~ 11.00 s, a slug of fuel moved upward from row 4 to row 2. The speed of movement can be estimated from the data in Fig. 13 by the difference in arrival time in each row to be ~ 45 cm/s. Posttest examination revealed the material ejected above the fuel column top to be mainly liquid test fuel, and it constituted ~ 15% of the weight of the test fuel column.

Analysis of the F2 results was performed to determine which of three possible vapor species was responsible for the ejected liquid fuel found above the pretest fuel column. Candidate vapor species are fuel, clad or fission products.

Table I presents peak F2 axial fuel radial temperatures calculated by a one-dimensional heat transfer model. Intact (pretest) geometry is assumed except the heat sink effect of the clad is removed after the clad has absorbed its entire heat of fusion. Fuel is calculated to be in transition from solid to liquid at the time of the major fuel ejection. If the heat transfer calculation is reliable, then fuel vapor is eliminated as the dispersive species for the initial ejection event at 11.04 s. Benchmark heat transfer calculations could not be performed directly for the F2 fuel remains since the large energy deposition following fuel ejection erased microstructural temperature markers. Benchmark F1 heat transfer calculations on a geometry similar to F2 indicated agreement with fuel microstructures when the test power was lowered by 12%. Table I also gives the sensitivity of the F2 heat transfer calculations to variations in the test power. Lowering the test power by 12% in F2 would still result in a liquid fuel phase according to the calculation at the time of the ejection which is consistent with observation. In order to obtain significant fuel vapor pressure, the fuel temperature would have to slightly exceed 3500°K in the heat transfer calculation; this would require an increase in the test power used in the calculation of approximately 20%. Therefore, if all the error in the heat transfer calculation was ascribed to the power, the power in F2 would have to be increased by approximately 32% to produce significant fuel vapor over a power level known to give agreement between heat transfer calculations, and fuel microstructures in test F1.

TABLE I

Sensitivity of Heat Transfer Calculations to Fuel Power

	Power Multipliers 1.10	1.00	0.90	Event Description
F2	7.35	7.65	8.00	Begin Clad Melting
TEST	8.0	8.30	8.70	End Clad Melting
TIME	9.65	10.15	10.95	Attain 2500°C Fuel Temp (Fuel radius = 15.2 mm)
(SEC)	10.45	10.80	10.95	Begin Fuel Melting (Solidus)
	10.95	11.05	-----	End Fuel Melting (Liquidus) Near Outermost Node

Clad vapor can not be absolutely ruled out as the F2 fuel dispersive species since the fuel was ejected in the liquid state, but a comparison with F1 results indicate clad vapor was not the source of the F2 fuel ejection. That is, F2 thermal conditions at fuel ejection would imply a significant amount of clad vapor pressure if liquid clad was in intimate contact with liquid fuel. However, the F1 fuel slumped, and yet clad drainage out of the liquid fuel axial region was much less significant for F1 than it was for F2. Therefore, if clad vapor was the dispersive agent in F2, F1 fuel would be expected to be much more dispersive than F2 which is contradictory to the actual fuel motion results. Fig. 8 of the F1 remains shows that clad did not drain into the bottom tantalum cup, but F2 posttest examination shows the bottom tantalum cup to be filled with drained clad. Other support for increased clad drainage in F2 is the burnout of the lower thermocouple in F2 due to contact with molten clad ~0.5 s before the fuel ejection. Burnout of the lower thermocouple in test F1 did not occur. No fuel ejection occurred in F1 even though the total test fuel energy (assumes intact fuel geometry) in F1 exceeded the energy in F2 at the fuel ejection time by 13%, and clad drainage out of the fuel was much less pronounced for F1.

Since both clad and fuel vapor have been eliminated as the cause of the principal F2 fuel ejection, only fission product vapor pressure remains. The problem with fission product vapor pressure is that the F2 fuel had such a low burnup (0.35%) that it is not intuitively obvious that this small a fission product inventory could cause the observed fuel ejection. However, it can be shown that the absolute pressure that can account for the ejection is less than the pressure that could have been generated by the fission products. The absolute pressure at the pretest fuel column midplane necessary to drive the observed ejection is the sum of three components:

(1) The static pressure head necessary to support a 40 cm liquid fuel height. This is the maximum height of the ejected fuel above the fuel column center. This pressure is readily

calculable using 100% of the theoretical liquid fuel density. This results in a static pressure head of 0.034 MPa. Note this is conservative in the sense that if the ejected fuel was frothy over any part of the 40 cm then a lower pressure would be indicated.

(2) The pressure drop across the moving fuel slug in the narrow constricted annular region above the fuel column. Ref. 5 provides a method to calculate the inertial and viscous pressure components taking into account the continuously decreasing liquid fuel flow area due to fuel freezing on the cooler surroundings. Every attempt was made to interpret the F2 results to calculate an upper bound for this pressure. The calculated pressure drop was 0.016 MPa.

(3) The absolute pressure above the liquid slug. Fig. 12 reports the absolute pressure above the slug as the sum of the differential capsule pressure transducer reading and the absolute pressure outside the capsule. At 11.04 s the absolute pressure was 0.150 MPa.

The sum of the three pressure components is 0.200 MPa. This value should scope the absolute pressure at mid-fuel column necessary to account for the observed ejection, since the experimentally measured component is the largest component.

Calculation of the fission product pressure for the F2 burnup of 0.35 at. % was performed next using the method of Ref. 6. If 100% of the fission products were retained prior to the fuel ejection, 1.00 MPa pressure was calculated to have been generated by all the fission products just prior to the fuel ejection. This exceeds the necessary ejection pressure by a factor of five. Therefore, considerable fission product release from the fuel prior to the fuel ejection could occur, but the retained fission products can still account for the necessary fuel ejection pressure. Even the fission product noble gas contribution alone would exceed the necessary fuel ejection pressure, if only half of the noble gas known to be present in the fuel at the start of the F2 transient were available to disperse the fuel at the ejection time.

A brief summary of the F2 results is that fuel vapor and clad vapor were not likely to have caused the fuel ejection. Fission product vapor pressure from the low burnup fuel was found to be sufficient to account for the observed fuel ejection. The reason for focusing the analysis on a determination of which vapor species drove the initial fuel dispersal is that there is currently some uncertainty as to the timing and extent of early fuel motion in a hypothetical LOF for a LMFBR with a moderately positive sodium void reactivity. Specifically, the postulate that the highest power-to-flow ratio subassemblies are to experience an early fission product driven axial fuel dispersal after the fuel region is voided of sodium and at power levels about ten times nominal, is crucial to the resultant accident energetics of such a reactor. The F2 fuel was being heated at a power level of approximately eight times nominal at the fuel dispersal time. Note also that the F2 fuel ejection[8] results in a high rate of LMFBR reactivity removal.

General Conclusions Drawn From the F1 and F2 Test Matrix

Two important general conclusions can be drawn from the F1 and F2 test matrix.

The first conclusion is that fission product driven molten fuel dispersal is strongly favored by higher than nominal heating rates during the fuel melting phase of a LOF. Recall that the higher than nominal power F2 fuel dispersed while the nominal power F1 fuel mildly slumped at fuel melting. The heating rate effect on the efficiency of fission product driven molten fuel dispersal must be a very strong effect, since the higher burnup F-1 test fuel had a much higher pretest fission product inventory than the F2 fuel. For instance, the experimentally determined noble gas inventory of the F1 fuel was six times the F2 fuel before the tests. On the basis of a high fission product inventory by itself promoting fuel dispersion, exactly the opposite fuel motion in each test what was observed would have been recorded.

The second conclusion is that a simple geometry of a single pin surrounded by a ridgid heated wall made these tests simple to analyze relative to multipin tests with weaker radial surroundings. The F1, F2 analysis was not complicated by azimuthal power generation asymetries or time varying radial fuel restraint present on other TREAT LOF tests.

F3 AND F4 TEST RESULTS

Tests F3 and F4 were performed to determine the timing and disruption mode of fuel pins in the lead power-to-flow subassemblies of a LMFBR with a moderately positive sodium void reactivity such as CRBR.[7] Consequently, the transient power levels reflected power levels greater than nominal. The fuel pins in each test were at ambient temperature at the start of the TREAT transient. Sample power was increased on a 200-ms period until constant powers of 820 and 2165 w/cm were achieved in F3 and F4, respectively. Typical lead power-to-flow CRBR subassemblies operate at ~300 w/cm nominal power. Nominal power and burnup for the F3 and F4 fuel were 295 w/cm and 9 at. %. Sample failure was achieved during the constant-power portion of the transient for each test. The design for these tests is shown in Figs. 14 and 15. Fig. 14 shows the axial region around the modified pin with a 5.08 cm (2.0 in.) fuel column. A mirror next to the fuel column reflects the pin image upward. The overall axial view in Fig. 15 shows how the pin image is eventually captured by a high speed 16 mm motion picture camera positioned on top of TREAT.

The results of the photographic and hodoscope fuel observations from F3 and F4 can be summarized as follows:

Interpretation of the pin image after pin disruption is difficult because the degradation of the mirror next to the pin occurs very quickly. In test F3 at 2000 frames per second, pin failure was well underway in less than 1.5 ms. A visible clad intact pin edge on one side of the pin with ejection of fuel and clad on the opposite side of the pin was observed in F3. The time scale for mirror degradation (~1.5 ms) and the initial pin-mirror distance (25.4 mm) imply accelerations of ~2300 G from

the pin to the mirror. Therefore the pin disruption was very violent.

Both the photography and the hodoscope independently agree on the time and direction of fuel ejection from the pin following failure.

Heat transfer calculations based upon the experimentally determined pin disruption times indicate the fuel was not molten at failure for both F3 and F4 and indicate the clad may not have been molten at failure in test F4.

The most important conclusion from the F3 and F4 results is that camera framing rates must be greatly increased to observe the pin disruption process. A tentative additional conclusion is that initial pin disruption may occur in the absence of molten clad or fuel. This conclusion is tentative because F3 and F4 fuel had a very high fission product inventory compared to lower burnup fuel that is more prototypical of CRBR design burnup. However, it is interesting to note that direct electrical heating tests[8] at Argonne, also show that high fission product inventory can favor pin disruption before molten fuel or clad develop. Previous SAS analysis[7] has assumed both fuel and clad were molten at disruption.

TEST F5 AND F6 PLANNING

Future tests F5 and F6 are planned with increased camera framing rates since pin disruption was observed on a very short time scale in tests F3 and F4. Both tests F5 and F6 will repeat the F3 TREAT power transient with the same in-core hardware as used in tests F3 and F4. Test F6 will use fuel from the same subassembly as used in F3 and F4. Camera framing rates will be increased to as high as 32,000 frames/s in test F6 with an improved photographic system. The increased framing rate will be achieved by a laser illumination system, since the pin's self-luminescence at disruption is not sufficient to permit framing rates higher than ~ 4000 frames/s. Fig. 16 illustrates how both the laser illumination beam and the pin image will pass through the narrow aperture test windows.

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