HEDL-SA-1658S

Conf-790310--6

MASTER

ANALYSIS OF INTERNAL FUEL MOTION DURING PINEX-2 EXPERIMENT

by

A. Padilla, Jr., R. E. Baars, D. R. Porten, and E. H. Randklev
Hanford Engineering Development Laboratory
Richland, Washington 99352

September 1978

Summary of proposed paper for Specialists Workshop on Predictive Analysis of Material Dynamics in LMFBR Safety Experiments to be held at Los Alamos, New Mexico, on March 13-15, 1979.

DISCLAIMER

Latest version with figures done by Graphics Dept.

ANALYSIS OF INTERNAL FUEL MOTION DURING PINEX-2 EXPERIMENT

by

A. Padilla, Jr., R. E. Baars,
D. R. Porten, and E. H. Randklev

ABSTRACT

This paper describes the analyses performed for the PINEX-2 experiment to calculate the ejection of molten fuel into the reflector and fission gas plenum for an internally-vented fuel pin during a simulated 5$/s transient overpower excursion. The LAFM code was used to predict the transient fuel melting and fission gas release, and the HOTPIM and FUMO-T codes were used to predict the fuel ejection. The analytical results were compared with initial data from both the Pinhole-TV Imaging System and the fast-neutron hodoscope, as well as post-transient examinations of the fuel pin.

I. INTRODUCTION

The PINEX-2 experiment was a joint HEDL-LASL effort with two major objectives:

- To continue development of the Pinhole-TV Imaging (PINEX) System; and in-reactor, realtime system for monitoring fuel motion during experiments to simulate fast reactor accident conditions, and
- To demonstrate the feasibility of internal fuel motion as a shutdown mechanism for mitigating the consequences of hypothetical accidents.

The purpose of this paper is to describe the analyses performed for the PINEX-2 experiment relative to the second objective. A separate paper is planned for presenting the results from the PINEX system.[1] Fuel motion data was also obtained from the TREAT fast-neutron hodoscope and initial results have been presented elsewhere.[2]

The first experiment to indicate the possibility of significant internal fuel motion was the C3C test[3], performed by General Electric, where molten fuel was unexpectedly squirted through an internal stainless steel capillary tube. This extreme mobility of molten fuel was further substantiated by the C5B experiment[4] using an annular blanket. The implication of this behavior was that internal fuel motion during transient overpower conditions might provide sufficient negative reactivity feedback to terminate the nuclear excursion and thus limit the consequences of the accident.

II. PRE-TRANSIENT CONDITIONS

Two special fuel pins (HEDL 59-40 and 59-41) were fabricated and each was encapsulated in a GETR/TREAT MARK-II type capsule, which served as a test vehicle for both steady-state irradiation in the General Electric Test Reactor (GETR) and transient testing in the Transient Reactor Test (TREAT) facility. Figure 1 shows the design of the test fuel pins, which incorporates annular fuel pellets, annular top insulator pellets, and an annular Inconel reflector to provide a passageway for ejection of molten fuel into the fission gas plenum.

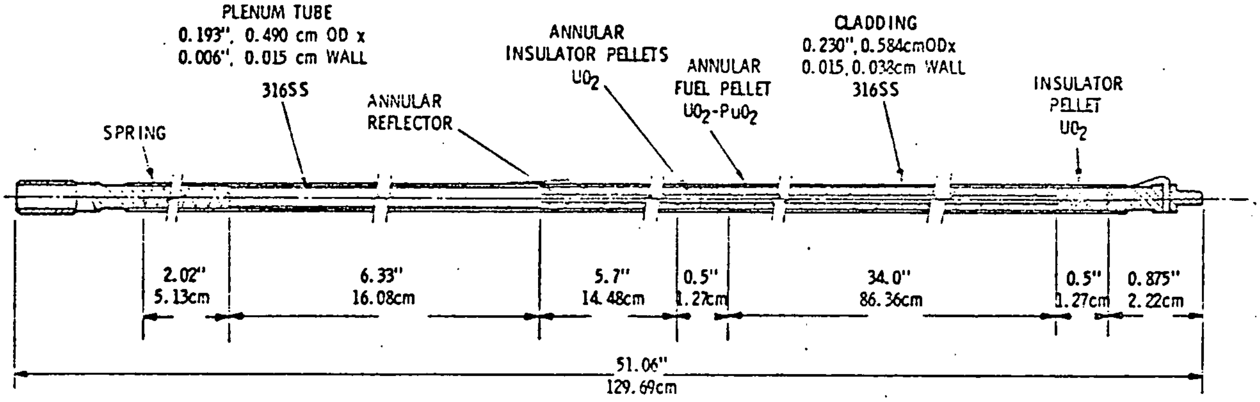


Figure 1.
HEDL-59-40 Mixed Oxide Fuel Pin.

HEDL 7902-222.13

The fuel pins were irradiated in the thermal neutron flux of the GETR at an average peak linear heat rate of 41 kW/m (13.5 kW/ft) to a radially-averaged peak burnup of 19,500 MWd/MTM. Densitometer measurements of post-irradiation neutron radiographs detected what appeared to be an abrupt closure of the central void in an area approximately 10.2 cm (4 in) below the top of the fuel column. However, an abrupt increase in the central void was detected just above this closure, indicating that the closure might be due to some form of solid fuel relocation.

Since the primary driving force for the fuel ejection was postulated to be fission gas, it was important to characterize the radial and axial distribution of fission gas within the fuel microstructure. The sibling fuel pin, HEDL 59-41, was not available for destructive examination because of its own potential as a transient test pin. Therefore, examinations were performed on two sections from other GETR-irradiated mixed oxide fuel pins at axial locations which best corresponded to the axial power and burnup history of the HEDL 59-40 fuel pin.

Electron microprobe measurements of the relative retained xenon content as a function of radius were performed on the ceramographically-prepared specimens of GETR-irradiated fuel. The plateau in the fission gas content, adjacent to the OD of the fuel, was assumed to represent 100% retention of the fission gas generated. The concentration level of this plateau region was calculated using the ORIGEN code.[5] The remainder of the radial distribution was assumed to be in proportion to the profiles determined by the electron microprobe data. The axial variation along the HEDL 59-40 fuel pin was handled by dividing it into 17 axial segments and repeating the ORIGEN calculations and radial apportionment for each axial segment.

III. TRANSIENT ANALYSIS

The TREAT transient design for the PINEX-2 experiment had two objectives:

- To induce extensive fuel melting as rapidly as possible to initiate the internal fuel ejection, and
- To obtain a reactor power level greater than 1000 MW, the realistic value for detecting fuel movement with the imaging system used for the PINEX-2 experiment.

The TREAT transient consisted of an initial flattop portion to achieve quasi-steady state fuel and cladding temperatures, and a power ramp portion which simulated a ∿ 5$/s LMFBR ramp reactivity insertion.

The transient analyses were performed in three sequential stages, with each stage providing the conditions for the next stage. The first stage was the thermal analysis of the static capsule, where experiment conditions were adjusted to give agreement with thermocouple data. The results of the capsule analysis were then used to provide the boundary conditions for a more detailed analysis of transient fuel melting and fission gas release using the LAFM code.[6] Finally, the LAFM results were used to provide the initial conditions for the analysis of the fuel ejection using the HOTPIM[7] and FUMO-T[8] codes. Each of these three stages will now be discussed in more detail.

A. Capsule Analysis

The inner GETR/TREAT capsule was designed to provide an instrumented vehicle for both the GETR steady-state irradiation and the TREAT transient test. Two concentric annular heat sinks (inner-aluminum, outer-type 304 SS) within the capsule encircled the fuel pin and were thermally bonded to it with eutectic NaK. Thermocouples located in the NaK-filled annulus adjacent to the fuel pin cladding, and between the outer heat sink and capsule, monitored the thermal performance of the fuel pin.

One-dimensional radial heat-transfer calculations were performed at locations corresponding to the axial positions of capsule thermocouples. Experiment conditions and irradiation-induced variables such as residual fuel-to-cladding gap were adjusted to give agreement between the calculated and measured capsule temperature.

B. Fuel Pin Analysis

The LAFM code was chosen for the detailed fuel pin analysis because it included a fission gas release model and a "gas bottle" model which could be modified for the PINEX-2 experiment conditions. Although the LAFM code had been used to analyze previous static capsule experiments in TREAT, its capsule geometry was different from the inner GETR/TREAT capsule. Therefore, the results of the capsule analysis described in the previous section had to be used as boundary conditions for the LAFM fuel pin analysis.

Two changes to the LAFM code were required for this analysis. First, the original fission gas release model was modified to reflect the additional information which had become available. Second, the "gas bottle" model was modified to initiate formation of the gas bottle at the first closure of the central void. In addition, the concentrations of retained fission gas at steady-state were specified using data and calculations with the ORIGEN code.

The original transient fission gas release model in the LAFM code was based on the transient gas release rates determined from earlier laboratory thermal transient (FGR) tests. The new transient fission gas release model reflects the interpretation of additional data from post-test examinations of transient overpower and laboratory thermal tests.[9] For the PINEX-2 experiment, one of the principal differences of the new transient fission gas release model is that a substantial fraction of the retained fission gas may still be unreleased from the fuel microstructure upon reaching the solidus temperature. This interpretation is based primarily on the observations of 1) the large radial separation between the solidus and liquidus temperature boundaries that existed in fast-ramp TREAT TOP tests (e.g., 3$/s) and 2) fission gas bubbles within the solid-phase fuel exposed to temperatures above the solidus but below the liquidus.

In the new transient fission gas release model, fission gas in the fuel matrix exists in three categories: 1) unreleased gas within the fuel grains (intragranular gas), 2) gas released from within the fuel grains but held on grain boundaries (intergranular gas), and 3) gas held at the end of the steady-state irradiation within closed intergranular fuel porosity. As the local fuel temperature increases from a predetermined steady-state temperature T_1 (1273°K) to the solidus temperature, a fraction REL1 of the intragranular gas is released to the grain boundaries and then lost to the central void, and a fraction REL2 of the intragranular gas is progressively moved to the grain boundaries and held there. The gas within the closed intergranular porosity at the end of steady-state is also lost to the central void between T_1 and the solidus temperature. The balance of intragranular gas REL3 (i.e., 1-REL1-REL2) remains unreleased up to the solidus temperature.

As the local fuel temperature increases from the solidus to the liquidus, the gas fraction REL2, now held at the grain boundaries, is progressively released. The gas fraction REL3 remains within the fuel grains until midway between the solidus and liquidus temperatures (mid-fusion temperature), and then is progressively released between that temperature and the liquidus temperature. For the PINEX-2 experiment, the gas release fractions REL1, REL2, and REL3 were assumed to be 0.1, 0.2, and 0.7, respectively. Therefore, only 10% of the intragranular retained fission gas is lost to the central void (and then to the plenum) up to the solidus temperature. Another 10%, i.e., one-half of REL2, is released between the solidus temperature and the mid-fusion temperature. The bulk of the retained fission gas, 80%, (i.e., one-half of REL2 and all of REL3), is released between the mid-fusion temperature and the liquidus temperature, according to the model. Ninety percent (REL2 + REL3) of the intragranular retained fission gas is available to pressurize molten fuel during the PINEX-2 experiment.

The original "gas bottle" model in the LAFM code was modified by assuming that the fuel central void and the plenum remained in communication until thermal expansion and/or melting closed the central void at some axial location. The portion of the fuel central void above the "pinch point" remained in communication with the plenum whereas the portion below the pinch point became isolated from the plenum.

An average pressure driving force for molten fuel ejection was determined by considering the fuel region at or below the pinch point. The fission gas inventory in this region consisted of both the gas in the isolated central void and the gas released after the central void was pinched off by thermal expansion and/or melting. The mass-averaged temperature of the molten fuel was used along with the perfect gas law to compute the pressure driving force.

C. Fuel Motion Analysis

The LAFM results for fuel melting, fission gas release, and pressurization were used as the initial conditions for the fuel motion analysis. Two types of analyses were performed. The first type was a "blowdown," where the initial conditions corresponded to about 0.06 s after the start of fuel melting and the pressure in the molten fuel region reached about 10 MPa. The second type of analysis attempted to be more realistic by starting near the time of initial fuel melting and using the transient fuel melting and fission gas release to predict the buildup of pressure and subsequent fuel motion at each axial level. Only the "blowdown" analysis was successful and additional model development is required before the gradual melting and pressurization analysis can be performed.

1. HOTPIM. The HOTPIM (Hydrodynamics of Two-Phase Internal Motion) code solves the Eulerian conservation equations for the one-dimensional flow of a compressible two-phase mixture of molten fuel and fission gas using the method of characteristics. The molten fuel is assumed to be non-volatile and the fission gas is assumed to behave ideally. It was originally developed to predict internal fuel motion and fuel ejection into the coolant channel

immediately after cladding failure during a transient overpower excursion (for a non-vented LMFBR fuel pin). Since the HOTPIM code has been incorporated into the MELT-III accident analysis code,[10] it was hoped that this combination would provide the assessment of internal fuel motion during hypothetical LMFBR accidents.

The HOTPIM results obtained during the pretest analysis are shown in Figure 2. As indicated in Figure 2A, much smaller axial nodes were specified in the region of large abrupt area changes to make the area changes more gradual. The pressure profiles at various times are shown in Figure 2B. A linear variation across the initial molten fuel region was assumed in order to compensate for some movement since the start of fuel melting. Presssure equilization occurs rapidly and the pressures in both the lower fuel region and in the upper (reflector and plenum) region became relatively uniform after 0.02 s. The pressure in the upper region became higher after 0.25 s, and the flow would eventually be expected to reverse. Figure 2C shows the fuel distribution at various times. Molten fuel reached the reflector in a few milliseconds and started to enter the plenum after about 0.01 s. Figure 2D summarizes the ejection of molten fuel into the reflector and plenum.

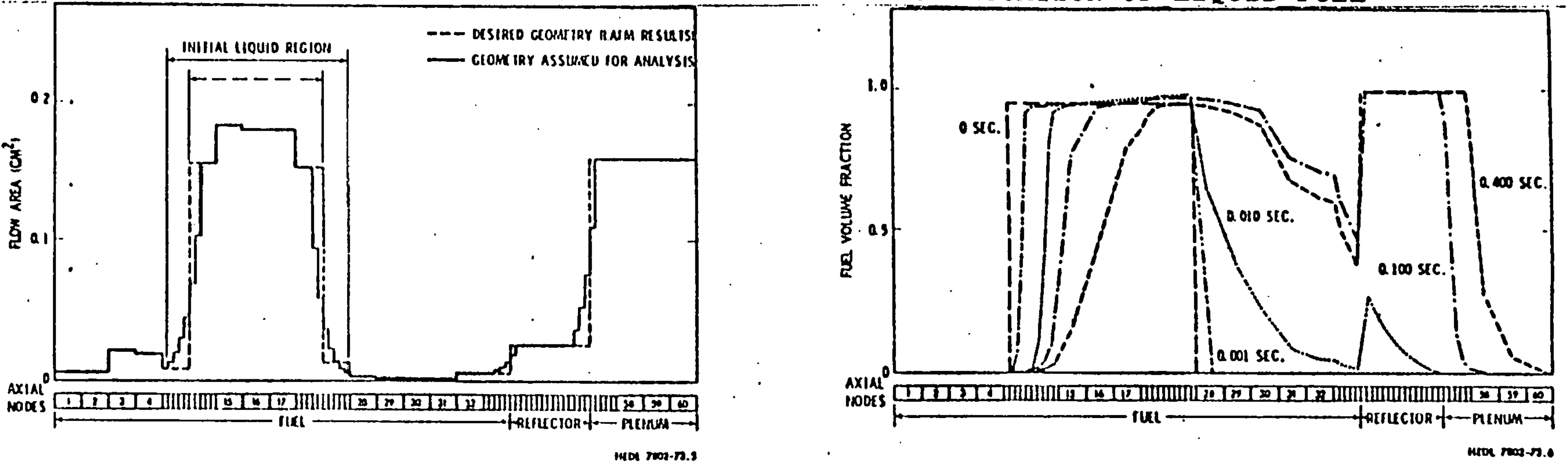
The HOTPIM analysis did not account for fuel freezing and plateout. A separate analysis was performed for fuel plateout in the Inconel reflector to determine whether the central hole would plug up and prevent further fuel ejection. The empirical correlation of Cheung and Baker[11] for the penetration distance of a solidifying material flowing through a tube predicted a penetration distance of about twice the length of the Inconel reflector. However, the conduction-limited model of Epstein[12] predicted the buildup of a fuel crust larger than the radius of the central hole at about 0.5 s, after most of the fuel ejection would have already occurred. Therefore, it was concluded that fuel freezing in the Inconel reflector would not prevent the major part of the fuel ejection into the fission gas plenum.

The post-test analysis using the HOTPIM code was started at the time of initial fuel melting and, using the fuel melting and gas release rates from the LAFM analysis, attempted to predict the process of gradual pressurization and fuel motion. However, mass conservation problems were encountered indicating the need for code modifications.

2. FUMO-T. The FUMO-T code has been used to analyze the fuel/steel boilup during the transition phase of the loss-of-flow accident. It was used for the PINEX-2 analysis to determine its applicability, to assess the need for future model development, and to compare with the HOTPIM blowdown results.

The FUMO-T code solves the Lagrangian conservation equations for a two-phase mixture of fuel, stainless steel, and fission gas using the finite difference approach. The major limitation of FUMO-T for this analysis is that the Lagrangian node formulation assumes a constant flow area. Figure 3A compares the actual variation in flow area with the three constant-area cases chosen for

A. HOTPIM ANALYTICAL MODEL　　　　B. LOCATION OF LIQUID FUEL



C. PRESSURE PROFILES　　　　D. RELOCATION OF LIQUID FUEL

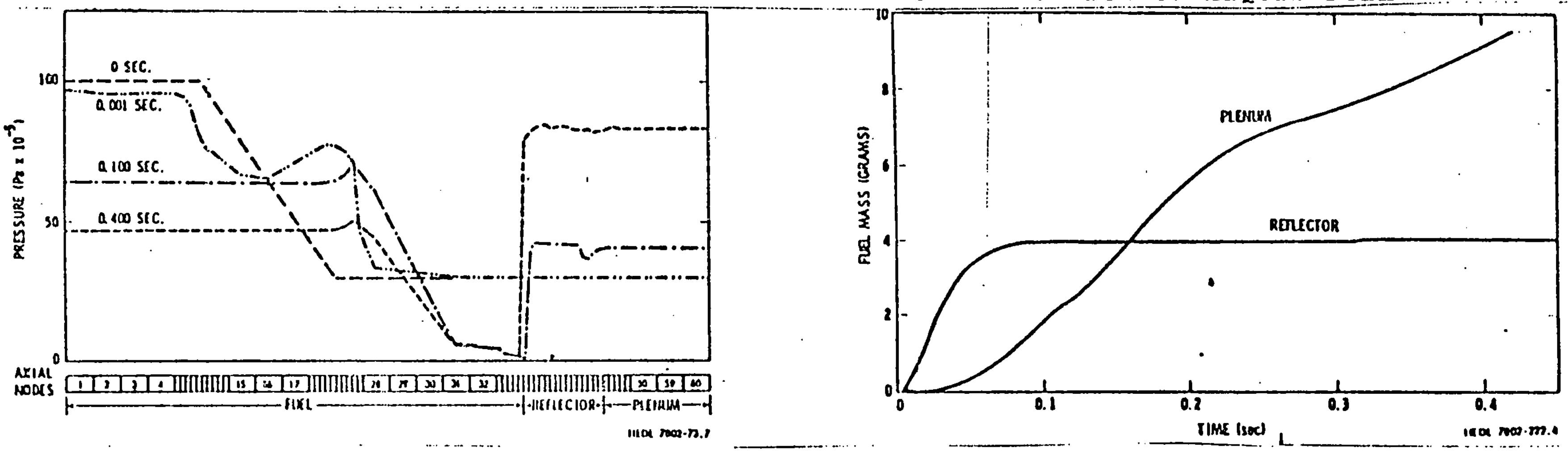


FIGURE 2.
HOTPIM Analysis

analysis. The largest area (Case 1) corresponds to using the average flow area of the molten fuel region. The other two cases correspond to using the Inconel reflector area (Case 2), and the area of the upper fuel central void (Case 3). Since the total volume is held constant, the three cases have total lengths of 1/2, 3, and 15 times the actual length, respectively.

The fuel ejection into the plenum for all three cases is shown in Figure 3B. The peak values are about the same (8.5 g) for all three cases, but the times at which the peaks occur are quite different. The reversal of the fuel ejection indicated in Figure 3B shows another limitation of FUMO-T: homogeneous flow. Actually, the fuel would be expected to disengage from the fission gas and continue its upward ejection even after the plenum is sufficiently pressurized to prevent the entry of additional fuel. The velocity of the upper fuel boundary for all three cases is shown in Figure 3C. Again, the peak values are about the same (18 m/s), but the times at which the peaks occur are quite different. Intuitively, the results for an actual variable-area case might be expected to fall somewhere between the constant reflector area and constant fuel central void area cases.

IV. COMPARISON WITH EXPERIMENTAL DATA

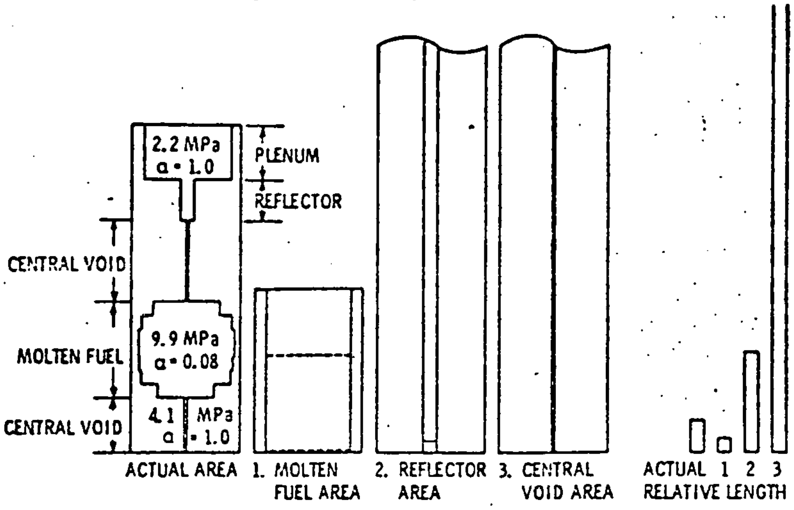
A. Fuel Motion Data

Fuel motion data were obtained from both the PINEX system and the fast-neutron hodoscope. Initial results are available, although these results may change later due to refinements in the analysis. Figure 4 summarizes these results.

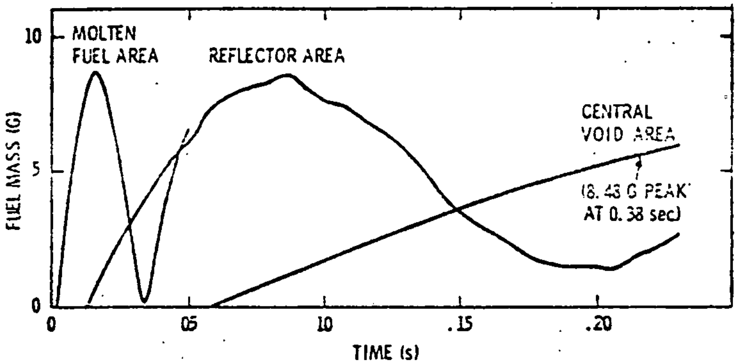
Early fuel motion, i.e., prior to the predicted time of initial fuel melting (solidus), was detected by both the PINEX system and the hodoscope. The PINEX system detected a minor fuel movement at 0.03 s before the solidus, and a "hint" of fuel motion at 0.11 to 0.19 s earlier. The hodoscope detected two minor fuel movements on the order of one gram apiece at 0.01 s before and 0.03 s after the solidus temperature was attained. These early events could have been associated with ejection of solid material lodged in the central void as previously discussed in Section II.

The first major fuel ejection was detected between the solidus and liquidus temperatures. The PINEX system detected a fuel motion which started 0.01 s after the solidus temperature was reached. After initiation of event 3 (10.53 s), and up to the time the liquidus temperature was reached, the apparent end of a column of fuel was observed moving up the reflector with an average velocity of ∿ 0.6 m/s. After the liquidus temperature was reached, the observed signals indicated that the event "strengthened" such that the reflector appeared completely full by at least 10.65 s. About 3.3 cm (1.3 in) of the plenum was also within the field of view, and no significant broadening of the moving fuel as it entered the plenum was detected. Therefore, assuming a volume of fuel having the ID of the reflector and a length including the reflector and the visible portion of the plenum, approximately 4 to 5 g were ejected in this time (10.53 to 10.65 s). This estimated mass

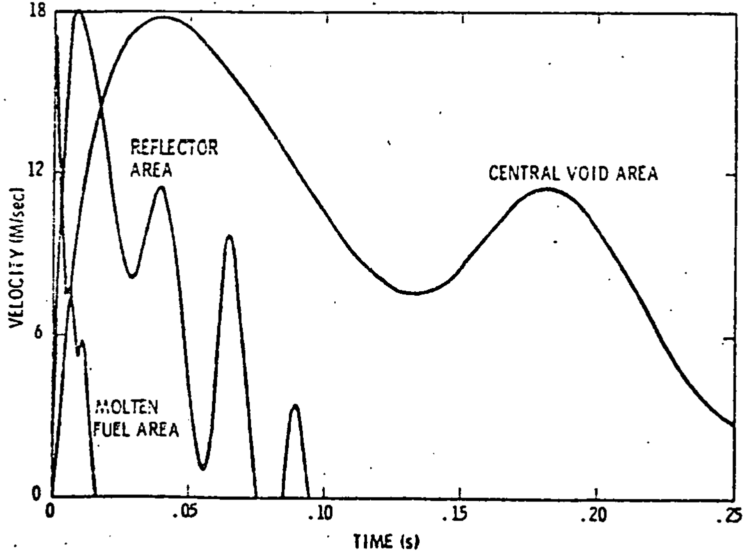
A. FUMO-T MODELS



B. FUEL EJECTION INTO PLENUM

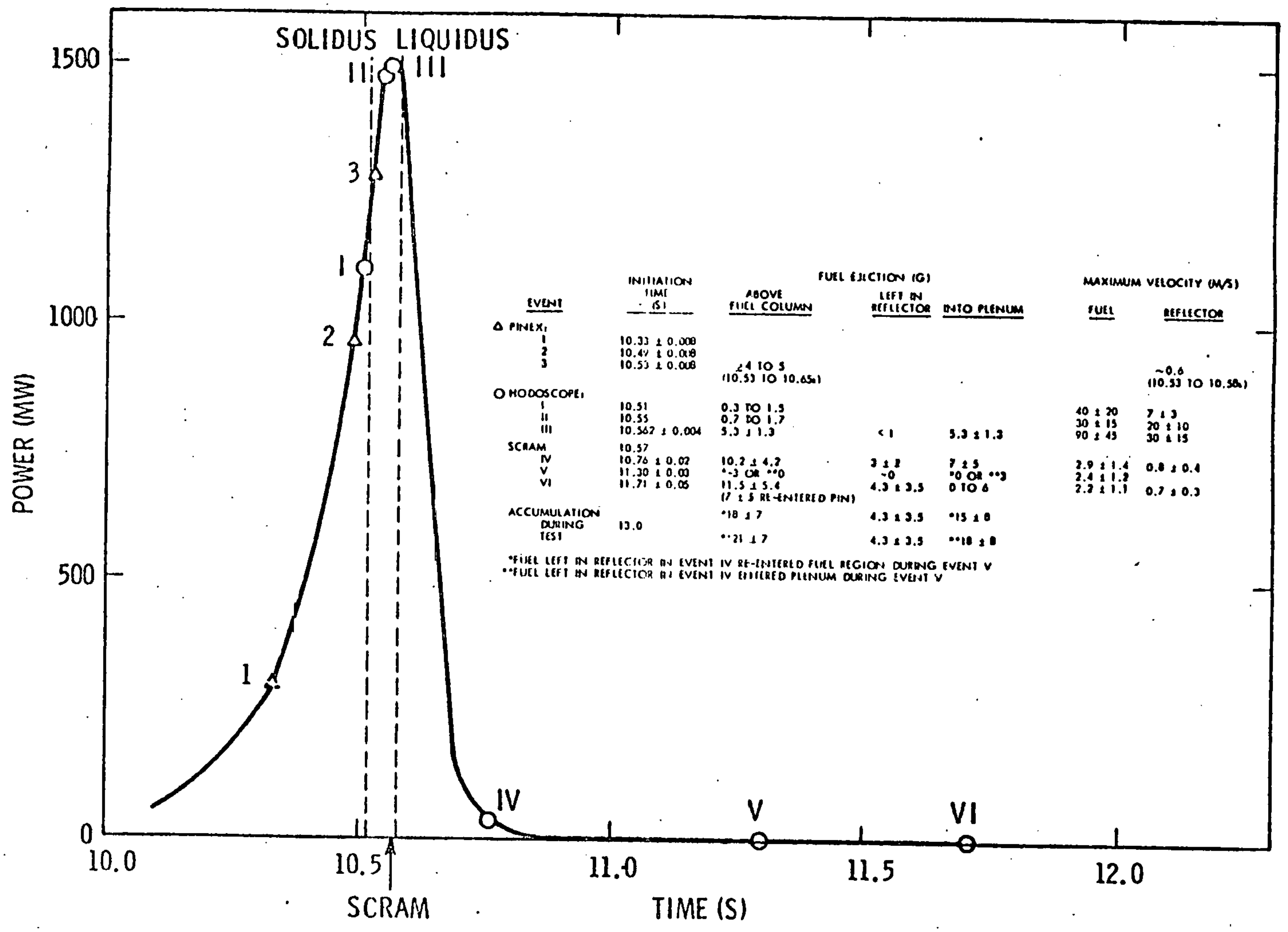


C. VELOCITY OF UPPER FUEL BOUNDARY



HEDL 7902-203.1

FIGURE 3.
FUMO-T Analysis



EVENT	INITIATION TIME (S)	FUEL EJECTION (G) ABOVE FUEL COLUMN	LEFT IN REFLECTOR	INTO PLENUM	MAXIMUM VELOCITY (M/S) FUEL	REFLECTOR
△ PINEX:						
1	10.33 ± 0.008					
2	10.47 ± 0.008					
3	10.53 ± 0.008	≥4 TO 5 (10.53 TO 10.65s)				~0.6 (10.53 TO 10.58s)
○ HODOSCOPE:						
I	10.51	0.3 TO 1.5			40 ± 20	7 ± 3
II	10.55	0.7 TO 1.7			30 ± 15	20 ± 10
III	10.562 ± 0.004	5.3 ± 1.3	< 1	5.3 ± 1.3	90 ± 45	30 ± 15
SCRAM	10.57					
IV	10.76 ± 0.02	10.2 ± 4.2	3 ± 2	7 ± 5	2.9 ± 1.4	0.8 ± 0.4
V	11.30 ± 0.00	*~3 OR **0	~0	*0 OR **3	2.4 ± 1.2	
VI	11.71 ± 0.06	11.5 ± 5.4 (7 ± 5 RE-ENTERED PIN)	4.3 ± 3.5	0 TO 6	2.2 ± 1.1	0.7 ± 0.3
ACCUMULATION DURING TEST	13.0	*18 ± 7	4.3 ± 3.5	*15 ± 8		
		**21 ± 7	4.3 ± 3.5	**18 ± 8		

*FUEL LEFT IN REFLECTOR BY EVENT IV RE-ENTERED FUEL REGION DURING EVENT V
**FUEL LEFT IN REFLECTOR BY EVENT IV ENTERED PLENUM DURING EVENT V

HEDL 7902-203.1

FIGURE 4. Fuel Motion Data

would be a lower limit for total fuel moved since the data show fuel in the reflector at times up to 10.71 s.

The first major fuel movement (event III) detected by the hodoscope started at 10.562 ± 0.004 s and involved the fuel ejection of 5.3 ± 1.3 g into the plenum with a maximum velocity of 90 ± 45 m/s in the upper fuel region and 30 ± 15 m/s in the reflector. The hodoscope was able to detect several post-scram events at very low power levels. The second major fuel movement (event IV) was detected near the end of the TREAT transient and involved the ejection of 10.2 ± 4.2 g of fuel above the fuel column, with 7 ± 5 g entering the plenum and 3 ± 2 g remaining in the reflector. Unlike the first major fuel movement, this event was relatively slow with a maximum velocity of 2.9 ± 1.4 m/s in the upper fuel region and 0.8 ± 0.4 m/s in the reflector. There is an ambiguity regarding the fuel motion above the fuel column in event V, which started at 0.73 ± 0.03 s after TREAT scram. The single asterisk in Figure 4 refers to the case where the fuel left in the reflector in event IV re-entered the fuel region during event V, and the double asterisk refers to the case where this fuel entered the plenum during event V. The last event detected by the hodoscope started at 1.14 ± 0.05 s after TREAT scram and involved the fuel ejection of 11.5 ± 5.4 g above the fuel column, of which 4.3 ± 3.5 g remained in the reflector and 7 ± 5 g re-entered the fuel region. Again, relatively slow velocities of 2.2 ± 1.2 m/s in the upper fuel region, and 0.7 ± 0.3 m/s in the reflector, were detected.

Overall, the hodoscope results indicated that either 18 ± 7 g or 21 ± g of fuel were ejected from the fuel region, depending on whether the fuel left in the reflector in event IV re-entered the fuel region or entered the plenum during event V. For these two cases, the fuel ejected into the plenum was either 15 ± 8 g or 18 ± 8 g, with 4.3 ± 3.5 g remaining in the reflector. The masses of fuel shown in Figure 4 for the hodoscope are probably somewhat high due to a decrease in self shielding of the dispersing fuel which was not corrected for. In comparison, the FUMO-T analysis predicted a maximum fuel ejection of 8.5 g into the plenum with a peak velocity of 18 m/s.

B. Post-Transient Examination

Examination of post-test x-radiographs of the reflector and plenum regions while still in the capsule and neutron radiographs of the entire fuel region and reflector confirmed the observation of fuel ejection into the reflector and plenum. The radiographs also verified that the fuel pin cladding had not failed and showed that solidified fuel completely filled the central hole through the reflector. Fuel traversed the entire length of the plenum and a small quantity of fuel was frozen to the top end cap.

Destructive examination of the HEDL 59-40 fuel pin revealed that extensive fuel melting occurred in a region 30.5 cm (12 in) below to 20.3 cm (8 in) above the fuel axial midplane. Molten fuel moved to fill the central void both above and below the fuel melting region. To measure the quantity of fuel ejected into the reflector and plenum, the fuel pin was cut just below the reflector at its interface with the top insulator pellet. The top section was then weighed and a value of 10 grams over the known component weights was obtained. Of that amount, approximately 4 grams were in the reflector. The bottom section containing the fuel region was also weighed and indicated a loss of about 10 grams.

V. SUMMARY AND CONCLUSIONS

The PINEX-2 experiment has shown that for internally-vented fuel pins and transient overpower excursions on the order of 5$/s, a considerable amount of molten fuel can be permanently ejected from the fuel column.

Although the results of the analysis to predict a "blowdown" process are in general agreement with the total fuel ejection, additional model development is required to realistically track the gradual process of fuel melting, fission gas release, pressurization, and fuel movement. Modifications to the HOTPIM code to eliminate the mass conservation problems encountered, or accounting for variable flow area in the FUMO-T code, would be necessary. In addition, the disengagement between fuel and fission gas in the plenum and an integrated treatment of the fuel freezing and plate-out would also be necessary.

A major question is whether this mechanism would also be effective at more realistic transient overpower excursions on the order of 5¢/s. Experiments at the low end of the transient overpower range are needed to resolve this question. Finally, analysis of this mechanism under LMFBR accident conditions is required to identify differences between experiment conditions and to confirm the expected benefits of this shutdown mechanism.

VI. ACKNOWLEDGMENTS

Initial results from the fast-neutron hodoscope were provided by A. DeVolpi and E. A. Rhodes of Argonne National Laboratory. Initial results from the Pinhole-TV Imaging system were provided by G. J. Berzins and A. H. Lumpkin of Los Alamos Scientific Laboratory. Their assistance is gratefully appreciated.

REFERENCES

1. G. J. Berzins and A. H. Lumpkin, "PINEX-2: Pinhole-TV Imaging of Fuel Ejection from an Internally-Vented Capsule," LA-UR-79-36, Los Alamos Scientific Laboratory, Los Alamos, NM, January 1979; (to be presented at the International Meeting on Fast Reactor Safety Technology in Seattle, WA, August 19-23, 1979).

2. E. Rhodes, A. DeVolpi, C. Fink, R. Pecina, D. Travis, and G. Stanford, "TREAT Fast-Neutron Hodoscope: Improvements in Time and Mass Resolution of Fuel Motion," IEEE 1978 Nuclear Science Symposium, Washington, D.C. (October 18-20, 1978).

3. J. E. Hanson and J. H. Field, "Experimental Studies of Transient Effects in Fast Reactor Fuels, Series III, Pre-Irradiated Mixed Oxide (PuO_2-UO_2) Irradiations Final Report, Transient Irradiations," General Electric Company report GEAP-4469, Sunnyvale, CA (July 1967).

4. T. Hikido and J. H. Field, "Molten Fuel Movement in Transient Overpower Tests of Irradiated Oxide Fuel," General Electric Company report GEAP-13543, Sunnyvale, CA (September 1969).

5. M. J. Bell, "ORIGEN -- The ORNL Isotope Generation and Depletion Code," Oak Ridge National Laboratory report ORNL-4628, Oak Ridge, TN (May 1973).

6. P. K. Mast and J. H. Scott, "Fuel Pin Failure Models and Fuel-Failure Thresholds for Core Disruptive Accident Analysis," Proceedings of the International Meeting on Fast Reactor Safety and Related Physics, CONF-761001, Vol. III, pp. 1015-1024, Chicago, IL (October 5-8, 1976).

7. H. J. Willenberg and A. Padilla, Jr., "Analysis of Transient Compressible Two-Phase Flow with Heat and Mass Sources Using the Method of Characteristics," Proceedings of the Conference on Computational Methods in Nuclear Engineering, CONF-750413, Vol. I, Charleston, SC (April 15-17, 1975).

8. F. J. Martin, "FUSS -- The Integrated FUMO, SAS3A, Neutronics Update System," Trans. Am. Nucl. Soc., 27, p. 539 (1977).

9. E. H. Randklev and C. A. Hinman, "Fission Gas Behavior in Mixed Oxide Fuel During Overpower and Thermal Transient Tests," HEDL-SA-1552, to be presented at the International Conference on Fast Breeder Reactor Fuel Performance in Monterey, CA (March 8-9, 1979).

10. C. H. Lewis and N. P. Wilburn, "MELT-IIIA: An Improved Neutronics Thermal Hydraulics Modeling Code for Fast Reactor Safety Analysis," Hanford Engineering Development Laboratory report HEDL-TME-76-73, Richland, WA (December 1976).

11. F. B. Cheung and L. Baker, Jr., "Transient Freezing of Liquids in Tube Flow," Nucl. Sci, and Eng., 60, pp. 1-9 (1976).

12. M. Epstein, et al., "Analytical and Experimental Studies of Transient Fuel Freezing," Proceedings of the International Meeting on Fast Reactor Safety and Related Physics, CONF-761001, Vol. IV, pp. 1788-1798, Chicago, IL (October 5-8, 1976).