MASTER

ANALYSIS OF TREAT TESTS L7 AND L8 WITH SAS3D, LEVITATE AND PLUTO2

by

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WITH SAS3D, LEVITATE AND PLUTO2

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ABSTRACT

Fuel motion in TREAT Tests L7 and L8 is analyzed with the SAS3D, LEVITATE, and PLUTO2 computer codes. These results are compared with fuel motion data obtained from the fast neutron hodoscope. It is concluded that fission gas acts to disperse fuel during the early stages of fuel motion.

I. INTRODUCTION

TREAT tests L7 and L8 were designed to investigate sodium voiding and fuel motion phenomena in subassemblies which are partially voided (L7) or just beginning to boil (L8) when subjected to a sub-prompt-critical power burst in a positive-void-worth LMFBR under loss-of-flow (LOF) accident conditions. The conditions in L7 are typical of those predicted by SAS3D for medium or high-power and the ones in L8 for low-power CRBR subassemblies experiencing the voiding-driven power burst in the LOF accident (referred to as an LOF-driven transient overpower or LOF "d" TOP event).

For an LMFBR with a homogeneous core of sufficient size to have β or more of positive reactivity worth associated with voiding the core and upper axial blanket, it is currently believed to be possible to avoid the occurrence of LOF "d" TOP phenomena in a LOF accident only if the fuel in the highest power/flow (P/F) subassemblies begins to relocate early in a monotonically dispersive fashion.¹ At some void worth level not far above β , even rapid early fuel dispersal is predicted to be inadequate to prevent the occurrence of LOF "d" TOP events. These events have the potential to substantially dominate the LOF

accident scenario in the latter stages of the initiating phase and could lead to a substantial increase in accident energetics. The tests L7 and L8 and the analysis of them with available fuel pin disruption models from the SAS3D² and SAS4A³ codes are viewed as a significant first step in attempting to assess the true energetics-augmenting potential of these LOF "d" TOP events in a LOF accident.

Section II of this paper contains a brief overview of the designs for tests L7 and L8 and a discussion of the specific part of the LOF scenario each was intended to simulate. In Section III, brief descriptions of the SLUMPY fuel motion model in SAS3D and the LEVITATE fuel motion model for SAS4A are provided. Following each model description, the manner in which the model was used to simulate the test and a comparison of model predictions and test results are given. Section IV is organized in the same fashion to describe the analysis of L8 with PLUTO2. Section V summarizes the key information gained from the two tests and the analysis of them.

II. OVERVIEW OF TESTS L7 AND L8

TREAT tests L7 and L8 were part of a series of tests (L5, L6, L7 and L8) designed to bracket conditions in LOF accident scenarios predicted for larger LMFBRs with moderately positive sodium void worths. Each test utilized three full-length GETR-irradiated fuel pins in a TREAT MARK-II loop. In larger LMFBRs, the SAS3D reactivity feedback calculations of the effects of sodium voiding, fuel temperature increases and cladding relocation lead to a variety of power variations within the uncertainty of the principal variables in a loss-of-flow accident.¹ Fuel could therefore experience a wide range of conditions depending on its location within the core and on the actual sequence of events. The key objective for the L5 and L6 experiments was to determine the nature and extent of early fuel motion in the first subassemblies to void under these conditions for the case in which competing effects are offset so that initial sodium voiding in the hypothetical reactor core covered the lower range of power increase before fuel dispersal. Based upon this planning strategy, the range of parameters would be covered if fuel motion in L6 occurred at a power level about 10 times nominal. Alternately, the objective was established for dispersal to occur in test L7 at or above 20 times nominal in order to cover the upper range of uncertainties.

The L8 test examined fuel motion behavior with low-power-structure fuel, also preirradiated in GETR, characteristic of fuel in an assembly which experienced a power increase caused by voiding in the higher power subassemblies. The objective for test L8 was that initial failure would occur at a power level 30 times nominal or greater but into sodium. The sodium conditions corresponding to the accident scenario were for its temperature to be close to the saturation temperature. The accident issues addressed in part by test L8 represent a contingent scenario for tests L6 and L7, since, if fuel dispersals in lead subassemblies

do not terminate the accident, then fuel motion in unvoided subassemblies could become a source of extensive feedback reactivity.

The focus on this paper is on the results and analysis of tests L7 and L8. The TREAT time-dependent power levels required to achieve the design conditions for the two tests are shown in Fig. 1. The actual peak power achieved in L7 was about 22 times nominal with a half width of the burst of 0.4 s, whereas the maximum power in L8 was about 43 times nominal and a half width of the burst of 0.25 s.

III. ANALYSIS OF TEST L7

Two separate analyses of test L7 were conducted. The first reported here utilized the integrated fuel motion modeling capability in the SAS3D code, the SLUMPY model.⁴ The second used the LEVITATE fuel pin disruption model⁵ which is to be integrated into the SAS4A code. Since this integration is not yet complete, the SAS3D code was used to analyze the pre-pin disruption part of the test and the appropriate transient conditions were then transferred to LEVITATE at pin disruption.

A. SLUMPY Fuel Motion Model Summary

SLUMPY operates as a module in the multichannel SAS3D accident analysis code. The SLUMPY fuel motion modeling is initiated in a given channel provided that a) sodium has voided past the axial node(s) where b) any one of several user-specified criteria are met in the fuel, such as reaching a specified temperature or melt fraction condition. Pressure due to retained fission or fill gas in the fuel and any fission gas in a central void is assumed to cause radial expansion to fill the voided channel volume of the initial axial node(s) which satisfy the slumping criteria. The subsequent fuel motion is determined by considering fuel in three distinct regions: 1) a central "slumped" region, 2) an upper falling segment, and 3) a lower stationary segment. The middle slumped region is assumed to move according to area-dependent one-dimensional (axial) compressible hydrodynamics in Lagrangian geometry. The formulation includes gravity, fission gas, fuel vapor pressures, friction, and mixing of cladding steel and fuel when the presence of cladding steel cannot be neglected. The force of gravity, pressure forces exerted by the slumped region, and any forces postulated by the user are summed to provide the equation of motion of the upper segment.

The SAS3D transient heat-transfer module continues to calculate temperatures in both the upper moving segment and the lower stationary segment. When the slumping-initiation criteria are satisfied for a new axial node, the Lagrangian calculation includes the new node by rezoning, using conservation of mass, momentum, and energy.

Of key importance in the SLUMPY application for L7 is the effect of fission gas on the fuel. The modeling is in terms of overall continuity, energy, and momentum equations for fission gas plus fuel, and continuity and momentum equations for fission gas. The gas can slip around suspended particles of fuel with the gas momentum equation being reduced to a steady state equation relating the pressure gradient to the drag term which contains a drag coefficient⁷ based on the user-specified fuel particle diameter, and the Reynold's number of the fuel particles (assuming a particle in an infinite gas continuum). The combination of this drag coefficient and the pressure gradients predicted by SLUMPY result in fuel motion being strongly affected by fission gas. On the other hand, fuel motion is not strongly effected by either fuel wall friction, which is based on a continuum fuel flow, or freezing of once-molten fuel on the structure and cladding and subsequent plugging at each end of the heated zone.

B. SAS3D/SLUMPY Modeling of L7

The SAS3D code, modified to include the PRIMAR-3 primary loop model,⁸ was used for the L7 analysis. The PRIMAR-3 model permitted a detailed description of the TREAT Mark-II loop to be included in the calculation. Of major importance to this test was the fission gas content of the fuel; assumptions consistent with those used in Ref. 1 for release of gas during the initial fuel melting and motion were used. The test fuel elements were irradiated at about 41 KW/m in GETR to a burnup of 3 a/o. Based on the Dutt correlation,⁹ it was estimated that the average gas content in the unrestructured region of the fuel was 2.02 mg of gas per g of fuel. This has been verified by laser gas sampling measurements which yield 1.73 mg of gas per g of fuel.¹⁰ Of this retained steady-state gas concentration it was assumed that 70% would escape from the fuel matrix to the fuel element fission gas plenum before fuel melting and/or breakup (failure) and could not affect fuel motion. In the SLUMPY modeling of fission gas, the remaining fission product gas was split between gas atoms within the grains (intragranular) which is released slowly following failure, and gas atoms on grain boundaries (intergranular) which is released instantaneously at failure. For the L7 calculation, 5% of the remaining 30% was assumed to be on grain boundaries and available instantaneously, while the remaining 95% was retained within grains. The intragranular gas was assumed to be released from the fuel with a time constant of 0.1 s and the intragranular gas from solid fuel with time constant of 3 s.

As stated above, SLUMPY models fuel motion as a suspension of particles in a flowing gas/vapor mixture. While this is no longer thought to be a correct description of the flow regimes(s) likely to be found in a disrupting fuel subassembly during a LOF accident, it is possible to simulate various modes of fuel relocation in SLUMPY with a proper choice of input parameters. Given the fission gas release assumptions described above the SLUMPY flow regime, and a user-specified small particle diameter,

relatively rapid fuel dispersal will be predicted in an L7-like transient. A particle diameter of .2 mm was used for L7; this is about ten times the fuel grain size. Fuel motion was initiated based on attainment of a 60% melt fraction (liquidus) at any axial level. This value was chosen because it resulted in fuel motion being initiated in SLUMPY coincident with the time motion was detected in the test by the fast neutron hodoscope.

TABLE I.

COMPARISON OF L7 TEST EVENTS WITH SAS3D CALCULATIONS

Actual Time (s)	SAS3D Time (s)	Actual Energy (MJ)	SAS3D Energy (MJ)	Event
0	0	0	0	Program Initiation
4.6	4.6	13	13	Start of constant power of 187.3 w/g
8.66	8.57	164	164	Start of flow coastdown
13.4	13.43	346	348	Time of probable boiling from flowmeter data
13.74	13.74	357	360	Burst initiation
14.05	xx	446	xx	Time of rapid slug ejection in test section based on flowmeters
~14.1	14.101	xx	481	Fuel motion initiation (60% melt fraction in SAS3D) (motion first observed in Hodoscope)
14.19	14.19	550	551	Peak power

xx not observable or predicted

C. Comparison of SAS3D (SLUMPY) Predictions with Test Results

Table I above contains a summary of the timing of key events observed in the L7 test and predicted by SAS3D. The time-dependent power trace input to SAS3D represented a fit to the actual integrator data taken during the test. The actual flow coastdown proceeded at a rate of $20 \text{ cm}^3/\text{s}^2$. The flow rates measured by the inlet flowmeter and predicted by SAS3D are shown on Fig. 2. For the period between boiling initiation and 14.05 s, the predicted and measured inlet flow rates agree well. However, a very rapid lower slug ejection was observed in the test at

14.05 s which was not predicted in SAS3D. Subsequent inlet flow oscillations occurred in the test with a frequency of about 5 HZ. In seeking an explanation for the rapid ejection, it was observed in the SAS3D calculation that fuel had melted sufficiently to satisfy the fuel motion initiation criterion at an elevation below the top of the lower slug by about 14.1 s. Since SLUMPY does not permit fuel failure to occur in a node which is even partially covered by liquid sodium, it did not respond to this substantial fuel melting in any way. However, it is quite possible that the cladding failed in the test at this point of high melt fraction, thus permitting direct molten fuel-liquid sodium interaction. Such a fuel-coolant interaction could have then caused the rapid lower slug ejection. This issue is discussed further in the LEVITATE analysis.

Using the 60% melt fraction criterion, SLUMPY fuel motion was initiated at 14.1 s, coincident with the first indication of motion in the hodoscope data. The subsequent predicted and observed axial linear fuel density distributions at time points spread over the next 190 ms are shown in Figs. 3-4. Over this time frame, no appreciable quantities of either fuel or steel vapor were predicted to be present by SAS3D; the dispersal calculated with SLUMPY was due almost entirely to fission gas pressures, with some small assist from the streaming sodium vapor. Figure 3 compares predicted and measured linear densities 60 ms following motion initiation. As suggested earlier, SLUMPY predicted a pronounced slug-like dispersal in both directions in contrast to the rather mild upward dispersal shown in the hodoscope data. After 190 ms of motion, the observed and predicted distributions are in better agreement (see Fig. 4), with both evidencing a strong dispersal away from the axial midplane. At later times, the predicted and observed distributions continue to converge. Fuel and steel vapor were predicted by SAS3D to have played a role in the later motion.

D. LEVITATE Fuel Pin Disruption Model Summary

The LEVITATE fuel pin disruption model⁵ has been developed to provide an integrated treatment of post-failure fuel, steel, sodium and fission gas dynamics in voided or nearly voided regions of channels for the new SAS4A code. LEVITATE models the motion of molten fuel within the pins, the out-of-pin or disrupted region motion, and the behavior of stationary upper and lower pin stubs. It also incorporates the treatment of various pin-disruption modes. The molten fuel inside the pins may be injected in the channel through rips in the fuel pin. If a significant fraction of the fuel pin is molten and the mechanical resistance of steel cladding has decreased considerably (due to temperature increase and ablation) the fuel pin can be completely disrupted. The fuel and steel in the disrupted region then becomes part of the moving components in the channel. A typical LEVITATE configuration is shown in Fig. 5.

Fig. 1.
Comparison of Power Histories
for TREAT Tests L7 and L8

Fig. 2.
Comparison of Inlet Flow Rates
Measured in the Test, Calculated by
SAS3D, and Calculated by LEVITATE.
The Nominal Sodium Flowrate of 1 is
173 cc/s which corresponds to 263
cm/s in the Test Section

Figs. 3 - 4.

L7 Test Measured and SAS3D Calculated Fuel Distributions at Different Times Compared with the Initial Fuel Distribution. Initial Fuel Motion Occurred at 14.101 s.

The moving components in the channel are solid fuel chunks in one field, liquid fuel and liquid steel in a second field, and fission gas and vapors of fuel, steel and sodium in a third field. Liquid sodium in limited amounts can also be present. The modeling of channel motion is based on a one-dimensional, Eulerian, compressible, multiphase hydrodynamic formulation with a sophisticated treatment of abrupt area changes.¹¹ As opposed to SLUMPY, there is a tight coupling in LEVITATE between the fuel motion and the sodium slug hydrodynamics. It calculates both the slug motion and fuel motion simultaneously and also takes into account the possibility of slug penetration by the fuel.

Of key importance in LEVITATE are the flow regimes and the freezing model.¹² Depending on the fuel flow regimes, annular or bubbly, the slip between the fission gas and vapors on one side and moving fuel on the other side can be either large (for the annular regime) or very small (for the bubbly regime). Other phenomena modeled in LEVITATE which have been shown to play a significant role in the fuel dynamics are cladding and structure ablation and fuel-steel mixing.

E. LEVITATE Modeling of L7

A calculation was made with the LIFE-III code¹³ to generate the initial radial and axial fission gas density distribution in the fuel pin. The average radial fission gas distribution at the location of peak axial power was 0.7×10^{-3} g of gas per g of fuel. The SAS3D code was used to calculate the transient up to the point of predicted fuel failure. At this point, the appropriate transient information was translated to LEVITATE. It was assumed that a considerably larger amount of liquid sodium than that calculated by SAS3D was left on the structure and clad. This assumption was made in order to simulate roughly the extensive downward voiding in this test. The justification for this is that radially noncoherent boiling effects, which are not treated at all in the SAS3D voiding model, could be important in such a few-pin test. This remaining liquid sodium is vaporized in LEVITATE through heat transfer from hot fuel.

F. Comparison of LEVITATE Predictions with Test Results

The inlet flow rate predicted by LEVITATE is compared with that measured by the inlet flowmeter in Fig. 2. The sodium vapor and released fission gas lead to extensive voiding in LEVITATE. Although the slowing of the lower slug ejection predicted by LEVITATE to occur from about 14.15 s to 14.2 s was not observed in the test, both the initial downward flow rate and the maximum downward flowrate from LEVITATE are in generally good agreement with the test results.

The limited rate of fuel dispersal predicted by the fuel motion calculation generally agrees with the one observed in L7. Fuel does not seem to disperse rapidly under L7 conditions. The LEVITATE calculation indicates that this was due to a slow disintegration of the fuel pins, friction effects in the continuous

flow regimes and fuel and steel plateout. Figure 6 shows a comparison of LEVITATE-calculated and hodoscope-measured fuel distributions 120 msec after the first sign of pin failure. Also shown is the initial fuel density configuration. It can be seen that LEVITATE somewhat overpredicts the fuel density peak at .8 m, although the general fuel distribution is in good agreement with the observed data. It is interesting to note that much fuel had already moved out of the pins and into the channels, but axial fuel motion was limited. This was due to frictional effects and fuel freezing, which in turn were enhanced by the cladding ablation and fuel-steel mixing. It was assumed that 0.7 mg of gas per g of fuel acted to effect fuel motion, which was about 40% of the steady state gas content according to laser sampling measurements.¹⁰

Fig. 5.
Typical LEVITATE Configuration

Fig. 6.
Comparison between LEVITATE
calculated fuel distribution
and HODOSCOPE data from the L7
experiment, at $t=120$ ms since
pin failure

IV. ANALYSIS OF TEST L8

In the L8 TREAT test a power burst peaking out 43 times nominal (see Fig. 1) was initiated during a simulated flow coastdown, leading to pin failures at the time of incipient sodium boiling.

The three fuel pins used in this test were irradiated in the GETR reactor to a burnup of 2.74 a/o at a linear power of 23 kW/m (7 kW/ft). The SAS3D and PLUTO2 codes were used in combination to analyze it much as SAS3D and LEVITATE were used in the L7 analysis.

A. PLUTO2 Fuel Pin Disruption Model Summary

The PLUTO2 fuel pin disruption model⁶ has been developed to provide an integrated treatment of postfailure fuel, fission gas and sodium dynamics in region of channels in SAS4A where a) liquid sodium still remains or b) where cladding still provides a reasonable radial restraint to fuel motion. The LEVITATE model was derived as an extension of PLUTO2, and the two are sufficiently consistent and compatible that they can be operating in different axial portions of a single channel in SAS4A at the same time. The PLUTO2 model describes the fuel motion within a fuel pin whose cladding has failed at some axial location. It also describes the fuel ejection into the channel and the sodium voiding and channel fuel motion. A pictorial of the mechanisms simulated by PLUTO2 is shown in Fig. 7.

The important new features in PLUTO2 relative to PLUTO1 are: a) the modeling of the growth of the fuel pin cavity due to fuel melt-in; b) two types of fission gas are treated in the pin cavity and the channel -- released gas and dissolved gas that is released only after a user-specified coalescence time; c) the treatment of a stagnant sodium film; d) cladding and structure temperature calculation; e) the treatment of arbitrarily long or propagating cladding ruptures; f) the modeling of particulate, partially- or fully-annular and bubbly fuel flow regimes; and g) the treatment of freezing fuel plateout. Steel motion and complete pin disintegration are not considered; any region of the channel where these begin to occur will be treated by the LEVITATE model in SAS4A.

B. PLUTO2 Modeling of L8

As with the LEVITATE analysis of L7, the fission gas distribution in the L8 fuel pins, which is very important for the PLUTO2 calculation, was determined with the LIFE-III code.¹³ For the transient analysis, SAS3D was used to analyze conditions up to cladding failure, and PLUTO2 was used to treat the post cladding-failure sequence of events.

The SAS3D model of the test pins was identical to the model used for the L7 post-test analysis except that the flow and power histories appropriate for L8 were inserted and the standard PRIMAR primary loop model in SAS3D was used. The SAS3D model was used to simulate the pre-failure coolant channel conditions external to the pin and the pin internal molten-cavity boundaries throughout the transient. These boundaries are based on the radii of any fuel within the pin that has gone through 70% of the melting range. These radii are input to the PLUTO2 code to define the boundary for in-pin fuel motion.

In the PLUTO2 simulations of L8, half of the fission-gas in the molten cavity existing at failure time was assumed to be released. Only 10% of the fission gas entering the cavity via fuel melt-in was assumed to be released instantaneously; the dissolved gas was released according to a coalescence constant (60 msec in the base case). The void fraction in the pin at the failure time was chosen such that a gas pressure of 15 MPa was achieved. This is the pressure necessary to fail the clad at

around 1000°C. Since the clad temperature was around 1000°C in the three nodes above the midplane (6.5 cm node length), these nodes were assumed to fail simultaneously in the base case. Additional nodes were assumed to fail if the cladding had melted in a node or if 90% areal fuel melting was reached and the clad had exceeded 1200°C. The sticking of freezing fuel on the clad was only allowed if the temperature of the outer clad node (comprising 30% of the clad) was below 1000°C. This corresponds roughly to a clad interface temperature of the steel melting point.

C. Comparison of PLUTO2 Predictions with Test Results

The early sodium voiding measured in L8 (see Fig. 8) can be simulated reasonably well with PLUTO2 with a mild fuel-coolant interaction (FCI) using a particle diameter of 0.17 mm and a dependency of the fuel-to-sodium heat transfer coefficient as a quadratic function of the liquid sodium fraction. The later downward motion of the lower slug in Fig. 8 was underpredicted by PLUTO2. Since the fuel and sodium in the channel had mostly separated by this time and because the lower pin structure was quite cold, a better agreement could not be achieved by initiating a stronger FCI. Assuming a more rapid coalescence of dissolved fission gas, however, gave a better agreement with the lower flow. However, this also led to an overprediction of the fuel dispersal. This may be an indication that large amounts of fission gas can escape from failed pins without ejecting corresponding amounts of fuel as currently modeled in PLUTO2. Fuel vapor pressure should not have played a role before 7.10 s according to the SAS3D calculation, and thus, cannot explain the rapid voiding between 7.06 and 7.10 s.

Figures 9, 10, and 11 show PLUTO2-calculated and hodoscope-measured fuel distributions along with the initial fuel distribution for comparison. At 35 ms after pin failure PLUTO2 predicted fuel losses due to in-pin fuel motion from the molten region below the midplane which moved toward the cladding rupture. The hodoscope indicated considerably smaller losses at this location. This may be in part due to the strong self-shielding effects in this unfiltered test. Fuel moving inside a pin was well-shielded from the thermal neutrons (the power in L8 pins was about 2.5 times higher at the outside than in the center) and thus experienced fewer fissions and emits fewer fast neutrons which are detected by the hodoscope. It is important to note that by this time considerable fuel sweepout from the active fuel region had already taken place.

By 65 ms the fuel pin was largely molten from a height of 0.06 to 0.68 m and the cladding has ruptured from 0.25 to 0.68 m. The main disagreement at this time was the magnitude of fuel sweepout above the active fuel. The hodoscope-measured fuel peak is uncertain because the high flux above the shaping collars has not yet been taken into account. Moreover, the post-test radiograph does not show a dense fuel region at this location. By starting the PLUTO2 calculation with only one failure node at .57 m (this is the location where SAS3D predicted incipient boiling) a more

Fig. 7.
Basic Modeling in PLUTO2

Fig. 8.
Comparison of Measured and PLUTO2
Calculated Inlet and Outlet Flow-
rates

Figs. 9, 10, and 11.
Comparison of Initial, Measured, and PLUTO2-Calculation Linear
Fuel Densities (Time = 0, ms Corresponds to the Fuel Pin Failure
Time 7.015 s)

rapid axial upward dispersal can be achieved. However, such a calculation leads to an exaggerated upward bias of the fuel distribution at 125 ms and to a worse agreement between calculated and measured lower flow.

By 125 ms the fuel pin was largely molten from 0.0 to 0.8 m and the cladding failure extended from 0.06 to 0.8 m. The slight fuel compaction at .3 m, which has disappeared in the PLUTO calculation at 125 ms, was small compared to the calculated and measured fuel dispersal. The fuel dispersal in this PLUTO2 post-test simulation is considerably stronger than in the pre-test calculation.⁶ In the latter fuel-plateout criteria were used which overestimated the fuel sticking on cladding.

V. CONCLUSIONS

The conclusions which can be drawn from these analyses of the L7 and L8 tests fall into three general areas. These are a) the importance of fission gas in relocating fuel early in the pin disruption sequence in a LOF accident; b) the difficulties encountered in trying to realistically model this fuel relocation with SLUMPY; and c) the improved modeling capabilities represented by the LEVITATE and PLUTO2 models. Relative to a) above, the analyses indicate that neither fuel vapor nor stainless steel vapor were likely to have contributed significantly to fuel relocation over the early parts of these tests (~180 ms in L7, ~100 ms in L8), yet substantial fuel dispersals occurred over these time scales in the respective tests. Of course, streaming sodium probably also assisted in L7 and certainly played an important role in L8 since the test sections were not blocked at these early times.

It became apparent even before these tests were run that the fuel flow regime modeled in SLUMPY is unlikely to ever actually exist under LOF conditions and that fuel freezing and crust formation increase the impedance to the fuel flow. At the same time fission gas escapes from the fuel which is in predominantly annular flow and decreases the driving pressure. The escaping fission gas can partially explain the extensive voiding observed in these tests. The early slug-like fuel flow predicted by SLUMPY for L7, in contrast to the much less rapid motion observed by the hodoscope, support these statements. In summary, the sophisticated modeling frameworks provided by PLUTO2 and LEVITATE, with their several flow regimes, treatments of fuel freezing and plugging, and strong coupling between fuel and sodium dynamics appear to be supported by these tests. It is believed that additional information gained from further examination of the test sections will further support this latter conclusion.

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