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TREAT EXPERIMENTAL DATA BASE REGARDING FUEL DISPERSALS IN LMFBR LOSS-OF-FLOW ACCIDENTS

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by

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ABSTRACT

The reactivity feedback from fuel relocation is a central issue in the analysis of loss-of-flow (LOF) accidents in LMFBRs. Fuel relocation has been studied in a number of LOF simulations in the TREAT reactor. In this paper the results of these tests are analyzed, using, as the principal figure of merit, the changes in equivalent fuel worth associated with the fuel motion. The equivalent fuel worth was calculated from the measured axial fuel distributions by weighting the data with a typical LMFBR fuel-worth function. At nominal power, the initial fuel relocation resulted in increases in equivalent fuel worth. Above nominal power the fuel motion was dispersive, but the dispersive driving forces could not unequivocally be identified from the experimental data.

INTRODUCTION

Various aspects of hypothetical unprotected loss-of-flow (LOF) accidents in liquid-metal fast-breeder reactors (LMFBRs) have been simulated in a series of TREAT experiments. All of these LOF simulations were performed with oxide fuels, and were conducted in support of evaluations of the LOF accident in either the Fast Flux Test Facility (FFTF) or the Clinch River Breeder Reactor (CRBR). In this paper, the fuel motion data from the relevant TREAT experiments are used to assess the dispersive properties of $(Pu,U)O_2$ fuel associated with the voided subassemblies in the hypothetical LOF accident.

A central issue in the analysis of the LOF accident concerns the mitigating effects of fuel motion. In the absence of scram or an inherent engineered safeguard, neutronic shutdown in an LOF accident can be achieved by fuel dispersal. Fuel dispersals are categorized by their timing relative to fuel melting. Early fuel dispersals are defined to be those that occur at or slightly after fuel melting in the first set of subassemblies to experience sodium voiding, and are presumed to be caused by mechanisms such as the release of gaseous fission products trapped within the fuel matrix during the steady-state irradiation. Dispersals by fuel vapor pressure can occur later in the sequence, but earlier dispersals can be more effective in mitigating the accident consequences. The potential of early fuel dispersal as an inherent safety mechanism is assessed by Deitrich (1).

The TREAT experiments form a significant part of the data base that is available for evaluating accidents in LMFBRs. Past assessments have been based partly on qualitative interpretations of the fuel motion data from the relevant TREAT tests. More recently, a quantitative method has been developed to aid in evaluating the significance of such data (2). In the application of this methodology, the axial fuel-mass distributions measured during a transient test are converted to equivalent fuel worths by weighting the mass distributions with a typical LMFBR fuel-worth function. The approach is the experimental analog of the method used in accident analysis codes (3) to compute reactivity feedback caused by fuel relocation in the initiating phase of an LOF accident. Although fuel motion in the test region will not significantly affect the TREAT power, the reactivity feedback effect of fuel relocation in an LMFBR can be approximately simulated by pre-programming the test transient. In this paper, the fuel motion data from the relevant TREAT LOF experiments are presented as normalized fuel-worth variations so that assessments for safety analysis can be made.

TREAT EXPERIMENTS

The TREAT tests that form much of the experimental basis for the analysis of the LOF accident are listed in Table I. Dickerman et al. (4) summarized some aspects of the results from these tests. Except for Tests F1 and F2, the experiments listed in Table I were conducted in flowing sodium. The tests with fuel irradiated in the fast neutron spectrum of the Experimental Breeder Reactor II (EBR-II) had fissile fuel lengths of 340 mm, or about three-eights the length of FFTF and CRBR fuel. Of the experiments with typical FFTF fissile fuel lengths, only Tests L5, L6, and L7 contained irradiated fuel. This fuel had been irradiated in the thermal neutron spectrum of the General Electric Test Reactor (GETR). Clearly, the most desirable tests would be ones conducted with fuel elements having near-typical fissile fuel lengths and pre-irradiated in a fast neutron spectrum. However such an experiment has rot yet been done.

Most of the tests listed in Table I used the 0.5-m hodoscope collimator (5) for fuel motion detection. In Tests L5 and R3-R7, the fissile fuel length of the test elements was nearly twice the collimator height. For these tests, the methodology of weighting the axial fuel-mass variations with a fuel worth function is not meaningful, because fuel motion beyond the field of view could not be observed. Later in the experimental program, the field of view was expanded to 1.2 m. The 1.2-m hodoscope collimator provides adequate coverage for experiments with fuel having a fissile length typical of current commercial LMFBR designs. Because of the field-of-view limitation, the fuel-worth methodology was applied only to Tests L2, L3, L4, F1, F2, L6, L7, and R8.

Within a centrally located reactor subassembly, each element generates about the same power. In TREAT Tests L2, L3, and L4, the central element generated ~30% less power than the surrounding six elements. Consequently, phenomena affecting fuel motion could have been more incoherent in those tests than in the remainder of the experiments, in which the element-to-element power ratios were more nearly equal (as in an actual reactor subassembly). Despite these possible incoherency effects, the equivalent fuel worth was computed without regard to the order of fuel element failure within the test cluster.

FUEL WORTH CALCULATION

The equivalent fuel worth for a measured axial fuel-mass distribution is computed by the method described by Simms (2). The hodoscope monitoring the fuel motion consists of a vertical array of fast-neutron detectors arranged in a rectangular pattern of rows and columns. The axial fuel-mass distribution is obtained by averaging the data across each row. The equivalent fuel worth, $W(t)$, was computed from the fuel distribution using a specified fuel worth function:

$$W(t) = \sum_{i=1}^{N} w_i \, G_i(t) \tag{1}$$

where

i = row number,

w_i = fuel worth per unit mass in row i,

$G_i(t)$ = fuel mass in row i at time t (i.e., the measured axial fuel-mass distribution),

and

N = number of rows in the array.

The number of rows in the 0.5-m hodoscope collimator array is 21; in the 1.2-m collimator, N is equal to 36. The random uncertainties involved in using the weighting function are analyzed in the appendix.

The fuel worth distribution used in this analysis and shown in Fig. 1 was generated by assuming that the fuel worth, as a function of axial elevation, can adequately be represented as the square of a cosine. The full width at half maximum (FWHM) of the distribution was chosen to be typical of the FWHM in CRBR, when normalized to the fissile fuel length. The experimental fuel worth changes in the tests conducted with elements having the EBR-II fissile fuel length are probably exaggerated relative to the changes that would be expected in tests with fuel elements having the CRBR fissile fuel length. The magnitude of the fuel worth changes for a given test depends on the fuel worth distribution used to weight the experimental data. Because simple scaling laws governing the dependence of fuel motion on the fissile fuel length are not available, extrapolation of test results from short fuel to CRBR fuel depends on mechanistic analysis, which is beyond the scope of this paper.

Although an extensive fuel relocation in an LMFBR would alter the fuel worth distribution, we have used an invariant fuel worth function to simplify comparisons among the tests. The procedure chosen is believed to be adequate for assessing the significance of the fuel motion, and the method offers a simplified way of presenting the test data.

TEST RESULTS

Tests at Nominal Power

The initial experimental simulations were conducted mostly at nominal power. Tests F1, R8, L2, L3, and L4 are currently the only LOF simulations at nominal power amenable to a fuel-worth analysis.

Tests L2, L3, and L4, described by Barts et al. (6), were each conducted with seven $(Pu,U)O_2$ fuel elements having 340-mm fissile fuel lengths. The fuel elements used in Test L4 had been irradiated to a burnup of 4.3 at.% at 45 kW/m. The fuel for Test L3 had been irradiated to a burnup of 3.5 at.% at a power level that varied between 30 and 37 kW/m. Test L2 used fresh fuel. Each test was conducted in a Mark-IIA sodium loop. Because of the similar testing conditions, the results from these three tests can readily be compared with one another.

Figure 2 shows the fuel worth, as a function of time, in Test L2. The results from using Eq. 1 are normalized in Fig. 2 by dividing the equivalent fuel worth by the average worth for a base period during which the fuel is presumed to have been intact. The averaging interval is identified in this and in subsequent figures as the "base averaging period." Figure 2 shows an increase in fuel worth shortly after the calculated inception of fuel melting, correlating with transfer of fuel to the midregion from above. About 6 s after the onset of that relocation of fuel, there was an abrupt dispersal.

Figures 3 and 4 show the results from Tests L3 and L4. The sequences of events in Tests L3 and L4 were similar to the sequence in Test L2. However, the extent and rate of equivalent reactivity increases associated with relocation of irradiated fuel in Tests L3 and L4 were less than observed for the fresh fuel in Test L2. Molten fuel draining was apparently impeded by gaseous fission products released from the fuel matrix. An abrupt dispersal also occurred eventually in both Tests L3 and L4. Stainless-steel vapor pressure has been postulated (6) as being responsible for these abrupt dispersals; sodium reentry effects are another possibility.

In Test F1, a single fuel element was surrounded by a heated wall (7). The test element had been irradiated in EBR-II at ~39 kW/m to a burnup of 2.35 at.%. Because the test was to simulate only the thermal conditions of fuel in an LOF accident after sodium voiding, the test capsule did not contain sodium. The test was conducted with the TREAT power at the level needed to generate ~39 kW/m in the fuel. The result of weighting the axial fuel-mass variations with the fuel worth distribution is shown in Fig. 5. Because of the random variations, neither slumping nor dispersal could be distinguished from the systematic trend in the data. The random variations during the base period were greater in Test F1 than in Tests L2-L4, because the hodoscope counting rates in Test F1 were lower. Again the retarding effect of gaseous fission-product release on fuel movement is evident when the results of Test F1 are compared with those of Test L2.

A similar fuel-worth analysis (2) of Test R8 data indicates a consistent pattern of increases in equivalent reactivity for fresh fuel at the time of fuel melting. Test R8 was the only nominal-power test having fuel with a fissile length typical of FFTF or CRBR for which our analytical approach was possible.

Tests Above Nominal Power

Tests F2, L6, and L7 are the only tests amenable to a fuel-worth analysis where power increases caused by positive reactivity feedback in an LOF accident were simulated.

Test F2, described by Palm (8), was conducted with an EBR-II-irradiated fuel element in a test configuration identical to that of Test F1. However, the test element had been irradiated to only 0.35 at.% burnup. This fuel has characteristics similar to LMFBR fuel that has spent sufficient time in a reactor at power to have caused the fuel pellet stack to sinter together and restructure into regions of columnar and equiaxed grains, but which has only a limited gaseous fission-product inventory. Test F2 consisted of 6.5 s at constant power, followed by a rapid power increase peaking at ~12 times nominal power. The normalized fuel worth, as a function of time, is shown in Fig. 6. A fuel dispersal during the period of rising power is indicated by a change in fuel worth that is distinct from the systematic trend observable in the data during the constant-power portion of the transient. Figure 7 shows the data on an expanded time scale during the power burst. The fuel dispersal occurred at ~11.04 s, when the power was ~6 times nominal. According to Palm (8), the fission-product pressures may have been sufficient, despite the minimal fuel burnup, to produce the observed dispersal. Note also that the upper cladding blockage usually seen in LOF simulations with sodium did not form in Test F2, because the absence of sodium permitted the molten cladding to drain. Thus in Test F2, fuel motion past the top of the fissile fuel column was unimpeded.

Power increases to 10 and 20 times nominal, associated with the reactivity feedback from sodium voiding in a CRBR LOF accident, were simulated in Tests L6 and L7 (9). Three fuel elements, irradiated in GETR to 3 at.% burnup, were used in each of these tests. The fuel motion in both Tests L6 and L7 was dispersive (9). The dispersal in Test L7 was about a factor of three greater than observed in Test L6. To examine the possible effect of fuel vapor pressure in the two tests, the fuel worth variations and the maximum fuel temperature occurring anywhere in the fuel are plotted as a function of the reactor energy in Fig. 8. (Because fuel temperatures for Tests L6 and L7 should be similar as a function of energy, a time plot would obscure a temperature-energy correlation.) The temperatures were estimated using a SAS3D calculation that ignored fuel motion.

Vapor pressure of irradiated mixed-oxide fuel depends on temperature, but the magnitude of the pressure is uncertain. Here, 4000°C was chosen as the temperature above which fuel vapor pressure can be a significant driving force. At 4000°C, the fuel vapor pressure is estimated to be 6-20 atm. From Fig. 8, one concludes that significant fuel vapor pressures were not generated in Test L6, because the maximum fuel temperature did not exceed 4000°C during the test. However, the maximum fuel temperature in Test L7 exceeded 4000°C after 600 MJ, when the equivalent fuel worth had declined by only 4¢ per dollar from an intact geometry. Fuel vapor pressures could therefore have contributed to the fuel dispersal observed in Test L7 after 600 MJ. A thermal analysis including the effects of fuel motion in the experiment might show an extended period after peak power during which other fuel-motion driving mechanisms, such as fission-gas release, could have operated without a contribution from the fuel vapor pressure.

POTENTIAL DATA APPLICATIONS

Important objectives in accident analysis are to determine the accident progression and to estimate the resulting energetics. Because reactor subassemblies do not all have the same nuclear and thermal-hydraulic characteristics, heatup and sodium voiding in the subassemblies will occur incoherently across the core in an LOF accident. Analysis of the initiating phase of an LOF accident is concerned with evaluating the competing reactivity feedbacks from sodium voiding, Doppler and axial fuel expansion, and, ultimately, from disruptive fuel motion. An evaluation for a given LMFBR design also includes estimates of the sensitivity of the accident energetics to uncertainties in the best-estimate parameters. The analytical results tend to be design-specific.

The direct applicability of the TREAT experimental data is limited because the experimental simulations do not necessarily duplicate subassembly accident conditions. The approach at ANL has been to develop experimentally verified analytical models of subassembly behavior (including fuel motion) for incorporation in the accident analysis. The basis of fuel motion model verification for licensing purposes includes TREAT experiments that approximate reactor subassembly conditions. An example of a comparison of fuel motion models with experimental data is described in Ref. 9: SLUMPY and LEVITATE calculations were compared with the normalized fuel worth variations in Test L7. In this comparison, LEVITATE produced a better match with the weighted experimental data.

The experimental fuel motion results can also be used in conjunction with a whole-core accident analysis to provide guidance as to the probable accident sequence. For example, an analysis using the fuel motion results from Test L7 (Ref. 9) suggests that the potential for termination of an LOF accident in the homogeneous CRBR core due to early fuel dispersal in the lead subassemblies would be marginal.

CONCLUSIONS

The available TREAT experimental data base for estimating fuel motion in the LOF accident has been reviewed. Where possible, the axial fuel distributions in an experiment were transformed to equivalent fuel worths, using a typical LMFBR fuel-worth distribution. At nominal power, irradiated fuel with a significant gaseous fission-product inventory compacted to a lesser extent and at a slower rate than fresh fuel at the time of fuel melting. Above ~6 times nominal power, there are indications of fuel dispersals, but fuel vapor pressure in Test L7 could have been a significant contributor to the driving forces for dispersal. At the power levels of interest for LOF accidents in LMFBRs with heterogeneous core designs, the TREAT tests indicate that the fuel motion would be dispersive (1).

To date, all the tests at nominal power with irradiated fuel have had fuel columns considerably shorter than the design length for commercial LMFBRs. A test at nominal power using fuel of typical length would be desirable. Above nominal power, fuel vapor pressure effects may need to be distinguishable from gaseous fission-product effects in order to provide a more complete experimental basis for analyzing the LOF accident.

APPENDIX

EXPERIMENTAL UNCERTAINTIES

Because fuel worth is a weighted average computed from the axial fuel-mass distribution, the fuel worth will exhibit a smaller random variation than does the mass distribution. The fractional standard deviation in equivalent fuel worth is related to the fractional standard deviation in mass per row (assuming the same random error for all rows and an intact geometry) by:

$$\sigma_w = \frac{\sigma_r}{N^{1/2}} \left[R_n \cdot \frac{\langle w^2 \rangle^{1/2}}{\langle w \rangle} \right] , \qquad (2)$$

where

σ_w = fractional standard deviation in fuel worth,

σ_r = fractional standard deviation in mass per row,

N = number of rows in the hodoscope array extending to the limits of fuel worth function.

R_n = the ratio of N to the number of rows covering the fuel,

$\langle w^2 \rangle^{1/2}$ = root-mean-square (rms) value of the worth distribution,

and

$\langle w \rangle$ = average worth for fuel of uniform distribution in the fuel zone.

For typical collimator parameters and LMFBR fuel-worth distributions, the quantity in brackets in Eq. 2 is about 1.35, and σ_w can be expected to be less than σ_r by about a factor of $N^{-1/2}$.

For the test results presented in this paper, the hodoscope data were averaged over time intervals that gave all experimental points (the fuel mass distributions) nearly equal counting uncertainty. Consequently, the random error associated with a given experiment can readily be estimated by examining the data from the portion of the transient during which the fuel is presumed to have been intact.

During the period of intact geometry, the equivalent fuel worth from the experiments with the 1.2-m collimator show a spurious systematic trend (2). Except for Tests F1 and F2, the 0.5-m collimator data apparently do not contain a similar trend. Because the source of the trend is unknown, we have not removed it from the weighted test results. For experiments involving significant power changes, the trend can potentially be extrapolated into the region involving fuel relocation according to time, energy, or power. The data may therefore be interpreted differently, depending on the extent to which the post-failure data depart from the pre-failure trend.

Additional sources of systematic error, associated with the conversion of the original count-rate data to fuel mass distributions, are potentially more significant than either the random counting uncertainty or the spurious trend. These additional errors are evaluated by De Volpi et al. (10).

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TABLE I. TREAT EXPERIMENTS SIMULATING LOSS-OF-FLOW ACCIDENT CONDITIONS

Test Desig- nation	Number of Elements	Fissile Fuel Length, mm	Preirradiation Neutron Spectrum	Hodoscope Collimator Viewing Height, m	Peak Transient Power ÷ Nominal Power[a]
L2	7	340	None	0.5	1
L3	7	340	Fast	0.5	1
L4	7	340	Fast	0.5	1
L5	3	864	Thermal	0.5	6
L6	3	864	Thermal	1.2	10
L7	3	864	Thermal	1.2	20
R3	1	914	None	0.5	1
R4 - R6	7	914	None	0.5	1
R7	7	914	None	0.5	15
R8	7	914	None	1.2	1
F1	1	340	Fast	0.5	1
F2	1	340	Fast	0.5	12

[a] Ignoring preheat power phase, if any.

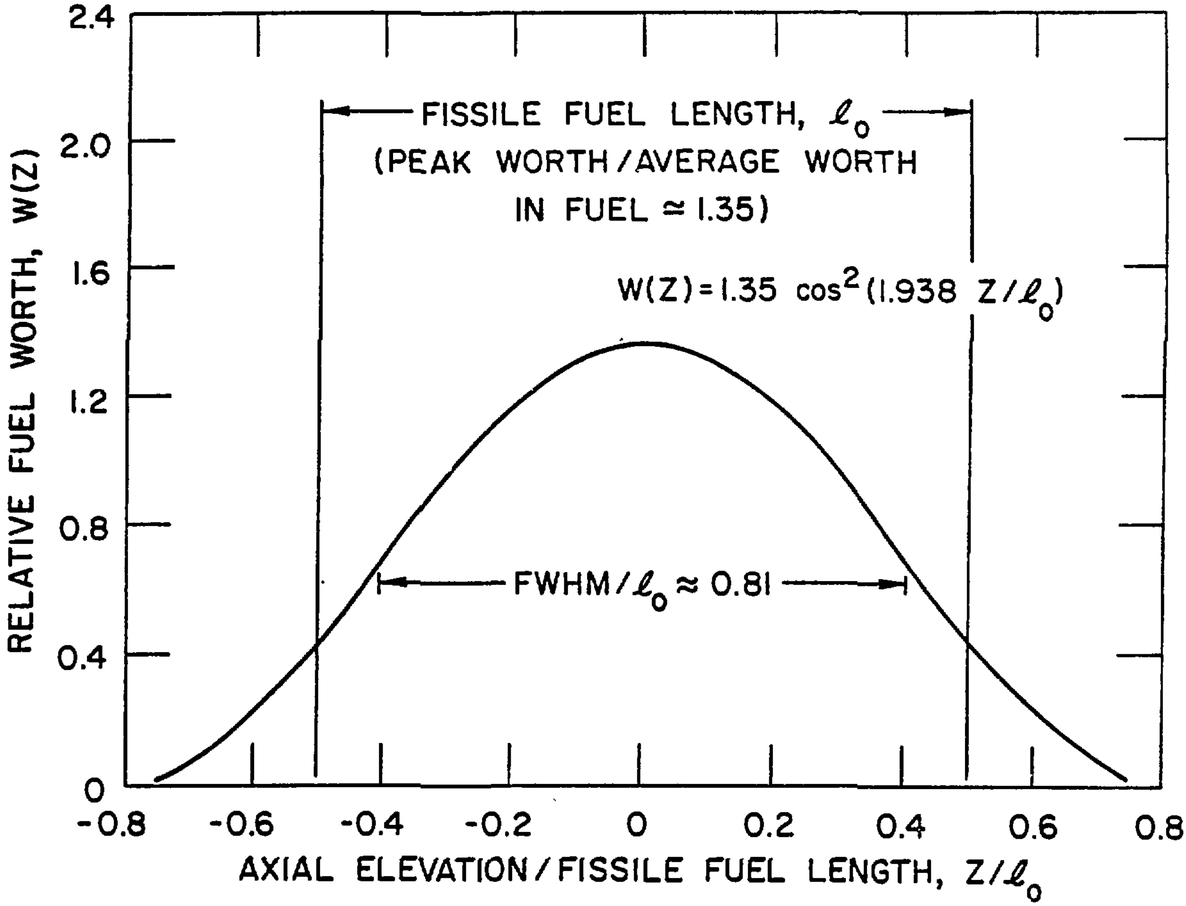

Fig. 1. Fuel worth function used in the analysis.

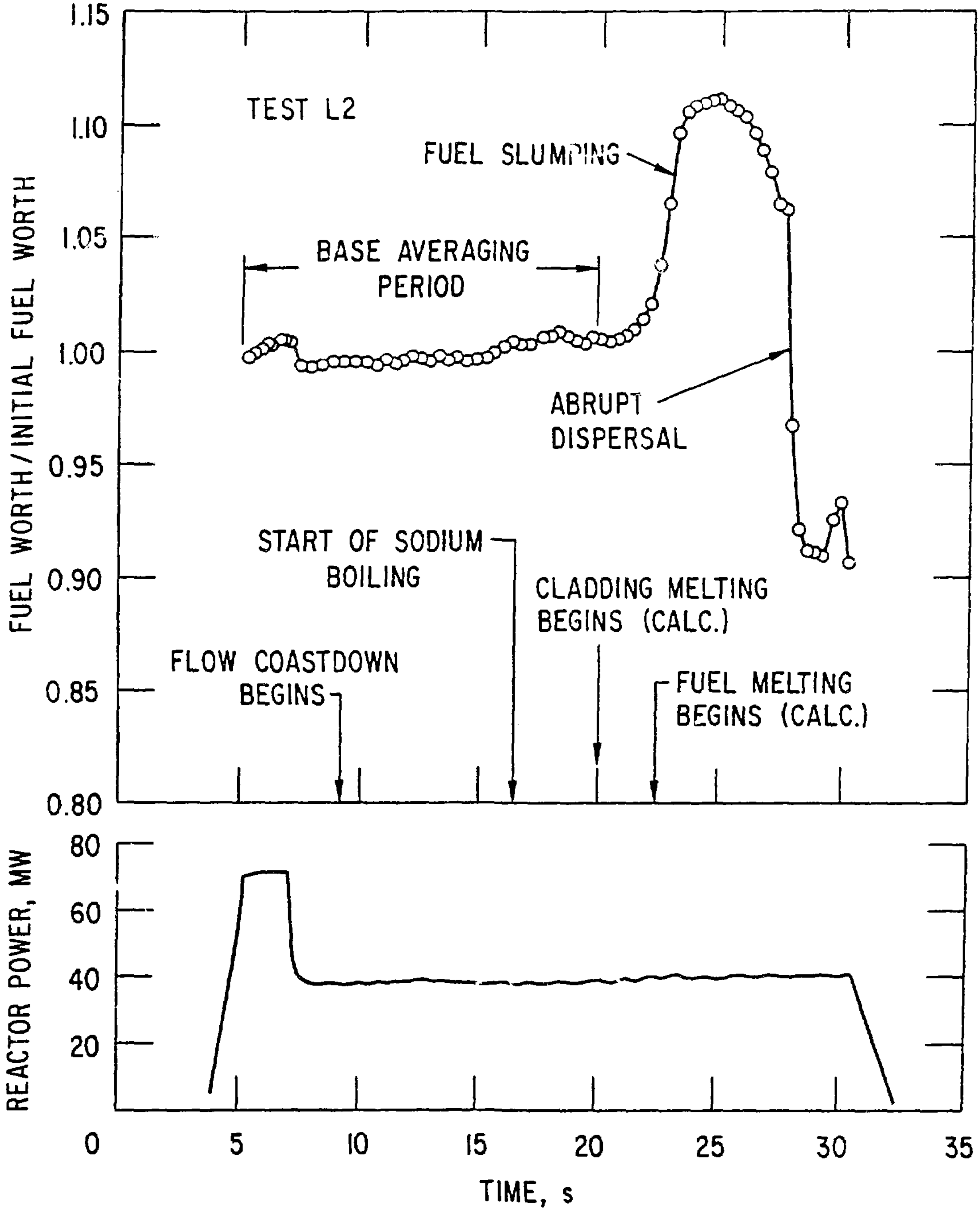

Fig. 2. Normalized fuel-worth variations in Test L2.

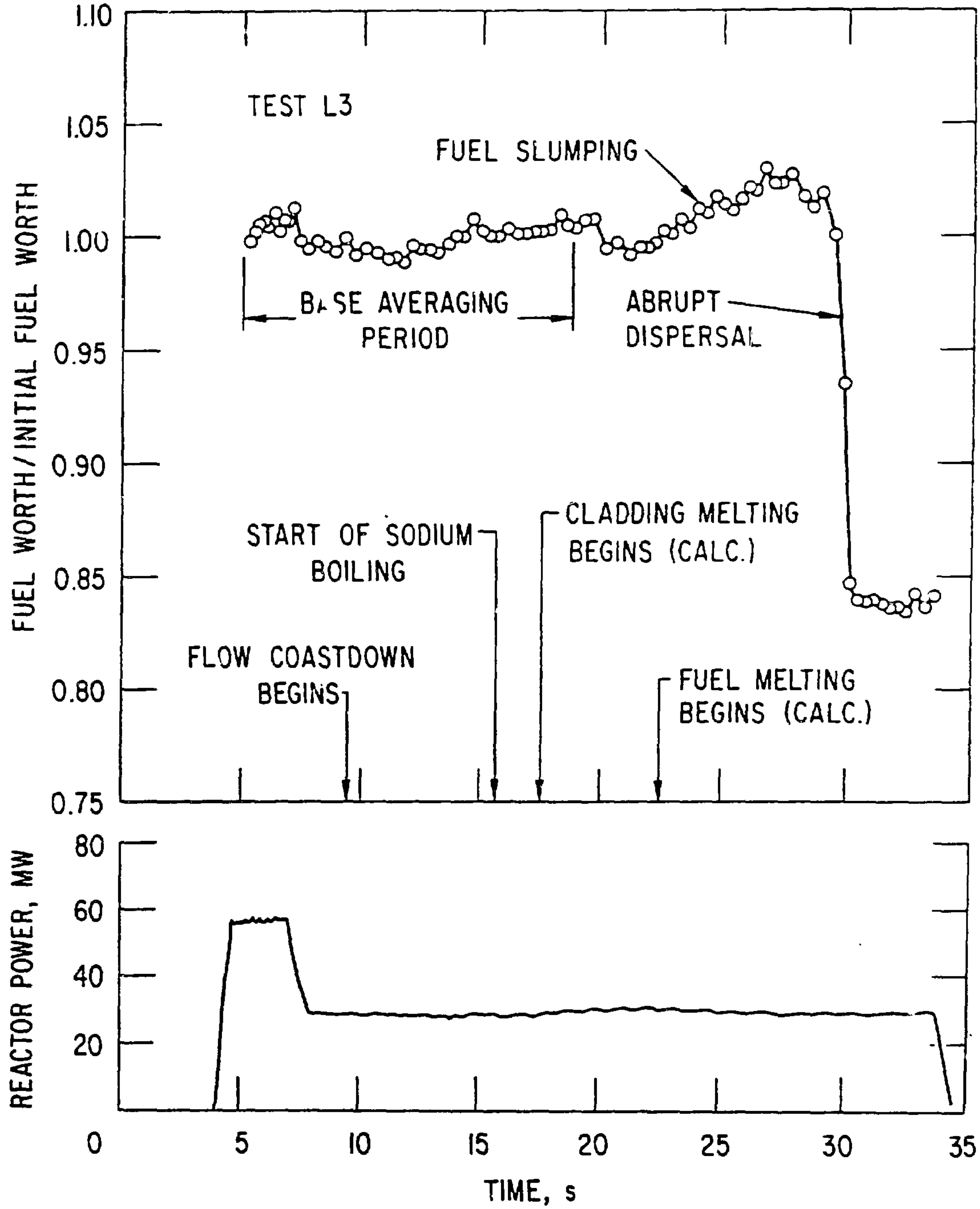

Fig. 3. Normalized fuel-worth variations in Test L3.

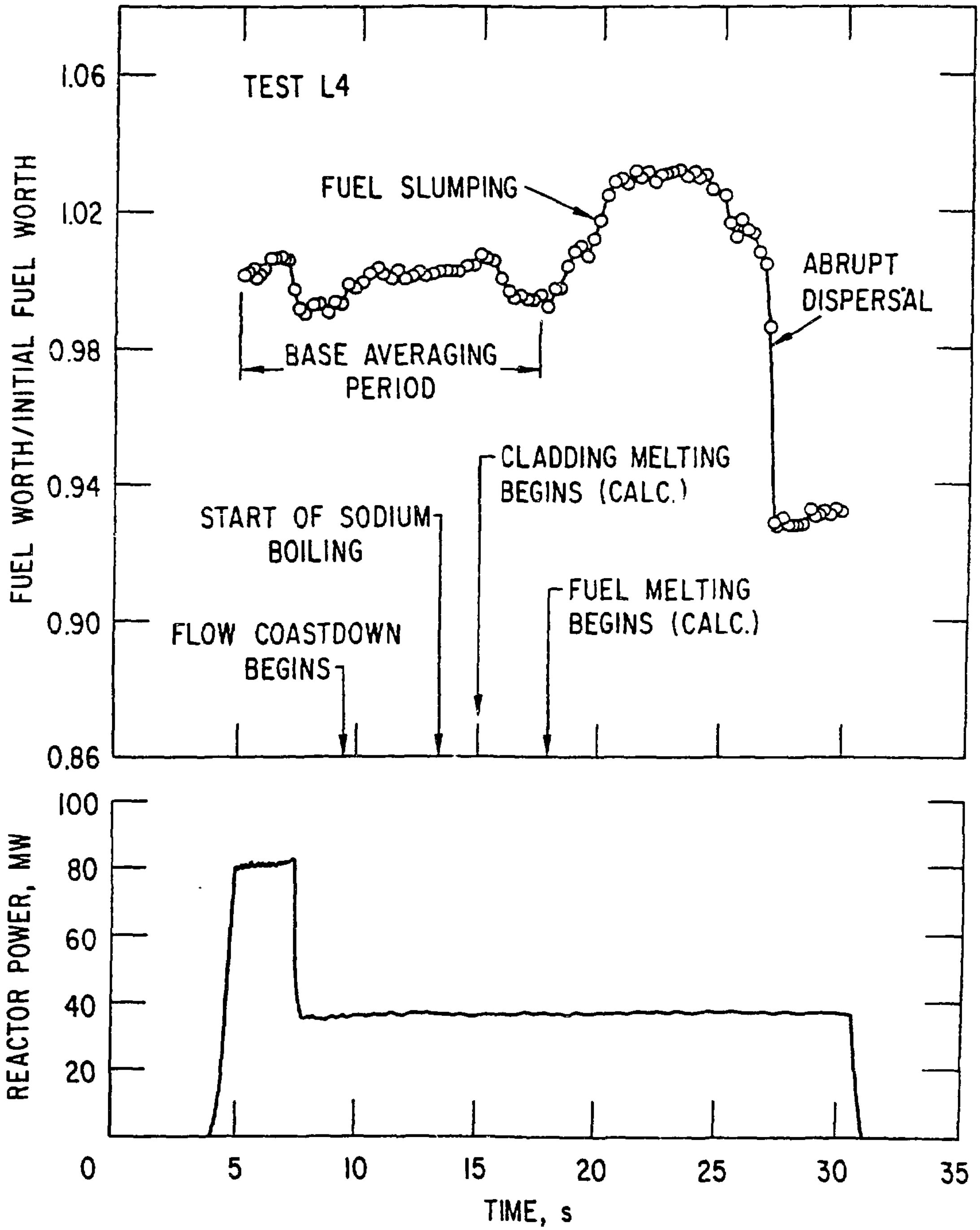

Fig. 4. Normalized fuel-worth variations in Test L4.

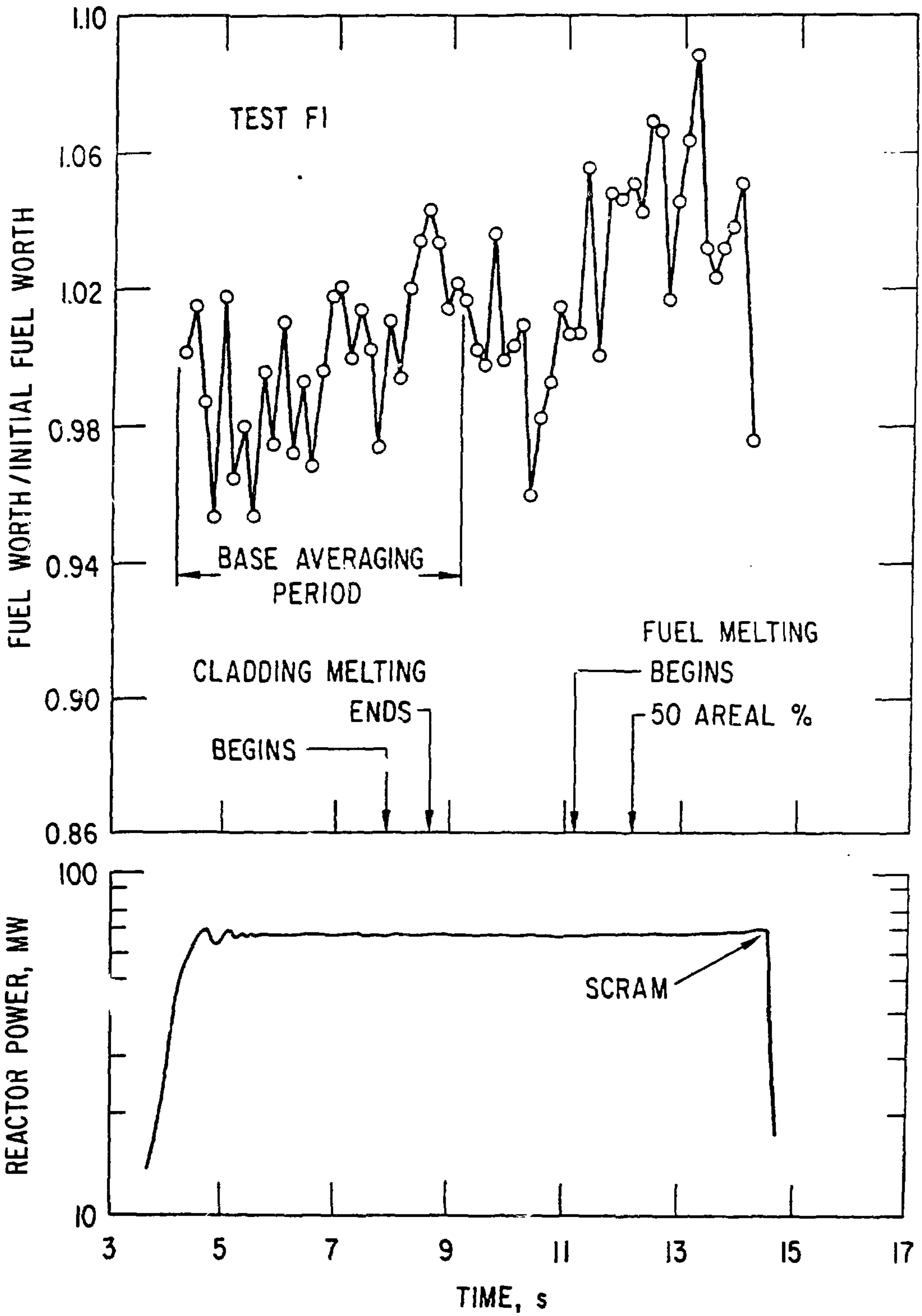

Fig. 5. Normalized fuel-worth variations in Test F1.

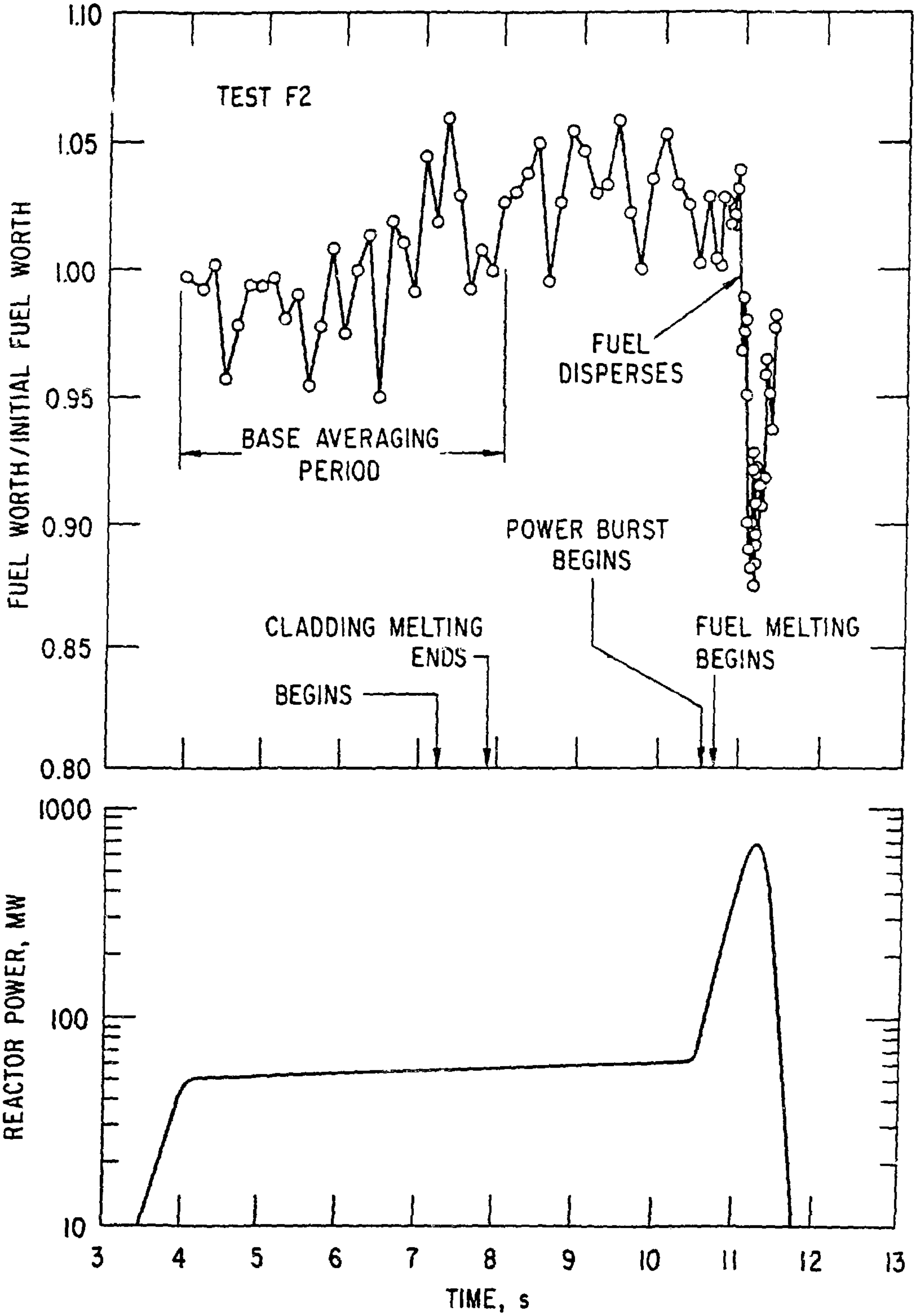

Fig. 6. Normalized fuel-worth variations in Test F2.

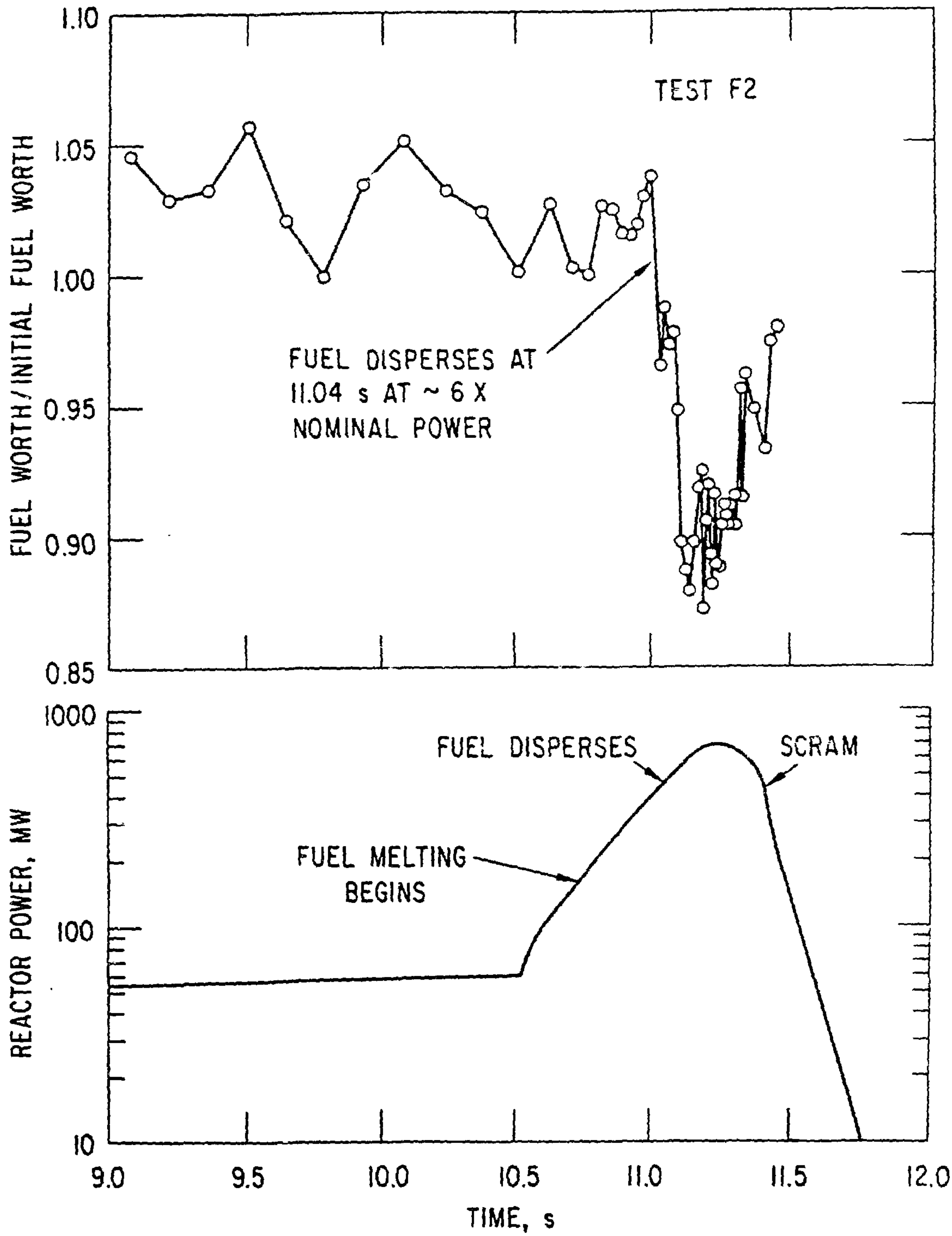

Fig. 7. Normalized fuel-worth variations in Test F2 during the time interval of the power burst.

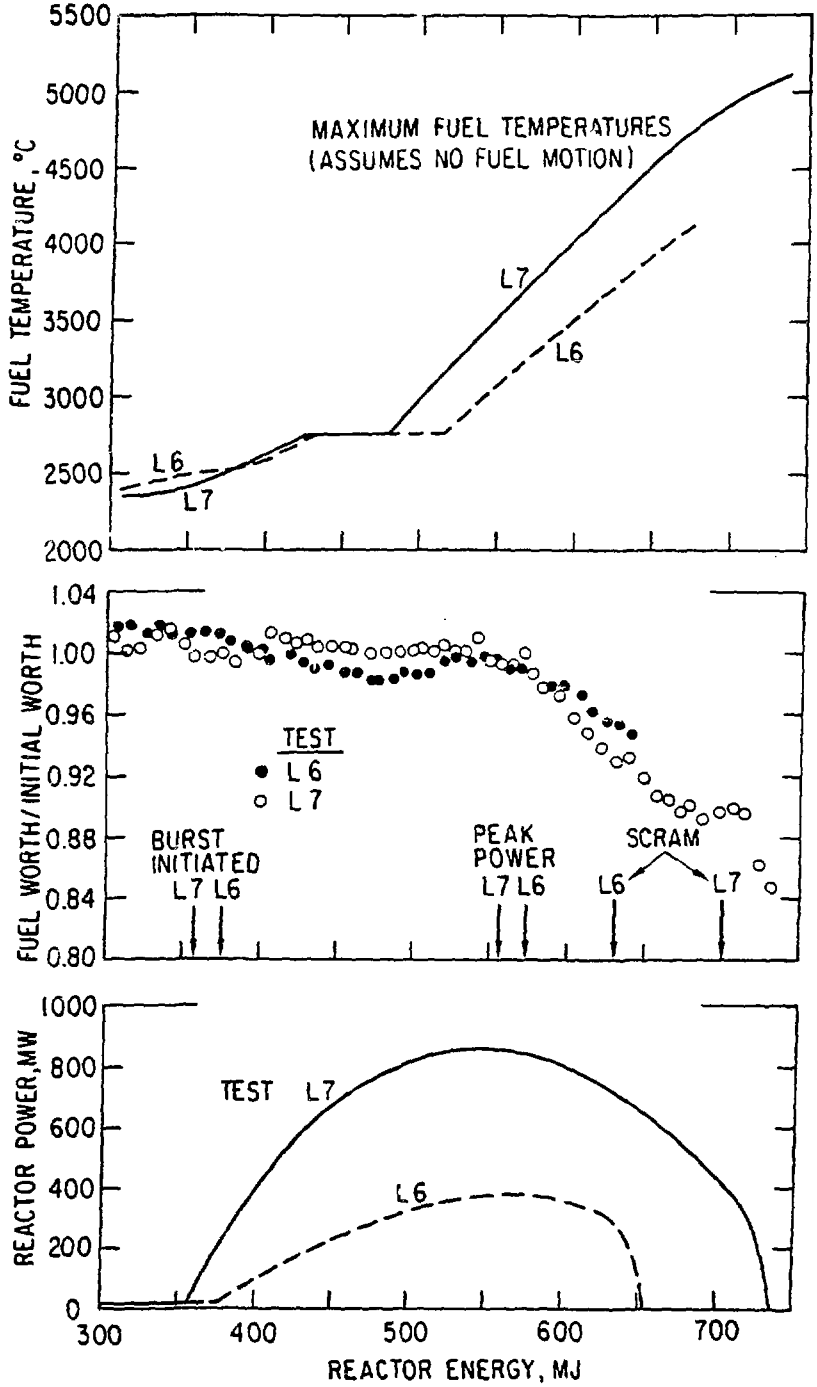

Fig. ~~11~~ 8 Comparison of fuel motion in Tests L6 and L7 as a function of reactor energy.