ONGOING EXPERIMENTS --- DIAGNOSTICS REQUIREMENTS

C. E. Dickerman

Argonne National Laboratory
Argonne, Illinois 60439, U.S.A.

ABSTRACT

This paper will review the fuel motion diagnostics needs for ongoing LMFBR safety experiments over approximately the next five years. It will center the discussion on TREAT, and will not present specific requirements for future fuel motion tests in CABRI or the Annular Core Pulse Reactor. However, these comments certainly have implications for experiments in these facilities, also. Brief comments on the direction in which clad motion diagnostics requirements are expected to develop will also be presented.

INTRODUCTION

The period of time to be covered is one in which the scope of the TREAT experimental program will broaden beyond the single to seven-pin level of today which is directed toward the early movements that affect initial reactivity changes in hypothetical LMFBR accidents. Studies will be begun of extended fuel motion in many fuel "channels," in order to provide data needed to resolve safety issues on the degree of whole core involvement, recriticality, and early stages of post accident movement.

It should be noted that the ongoing TREAT requirements are those for an existing program with well-developed fuel motion diagnostic capabilities. Thus, these requirements are neither targets nor design specifications; rather, they are real experimental needs developed through analysis of information needs, and they are typical of requirements developed in the past to guide TREAT instrumentation development.[1]

Unique Capabilities Required

The need to understand and predict fuel motion in hypothetical LMFBR accidents results in requirements for basic and unique in-pile fuel detection capabilites. These are summarized below:

Unique Fuel Motion Detection Needs

1. Capability to detect fuel uniquely with discrimination against structure, coolant, and experiment containment.

2. Capability to be sensitive to entire amount of fuel within region viewed by a single channel without self-shielding.

3. Capability to detect fuel distribution as unique distributions, at least in one horizontal plane.

4. Capability to detect fuel distribution over a wide range in power levels, from initial test phase (to establish initial conditions) through fuel motion at power levels programmed to simulate accident conditions, and at the end to determine final distributions (post-scram if possible).

5. Capability to read out fuel distributions as a function of time with sufficient time resolution to describe the movements as they occur, rather than isolated "snapshots".

Items 1-5 are well met by the TREAT neutron hodoscope. There is some overlap. For example, the use of a system with neutron detection and threshold energy discrimination to satisfy the first, also satisfies the second. It should also be noted that the first also implies a relative freedom in choice of experimental conditions such as use of sodium coolant, choice of apparatus configuration, wall thicknesses, materials*, etc. Items 1-5 are adequate scope for guiding or validating fuel motion analyses performed to assess the consequences of hypothetical LMFBR accidents. However, the need to obtain phenomenological data for detailed modelling of fuel behavior can lead to another requirement:

6. Capability to determine detailed modes of fuel breakup/motion, e.g. dust cloud, swelling, jets, etc.

This particular requirement leads to photographic experiments. There is an inherent conflict between 2. (needed for fuel motion data) and 6. (needed for phenomenological data) which results in a need for two different diagnostic systems. At this time, we have no proven techniques which permit 6 to be met for samples run in a sodium environment. However, for tests in which the conditions imposed by photographic systems are acceptable, a hodoscope system can be run in parallel. Photographic system requirements will not be discussed further in this paper.

Requirements

1. Sources

Given the basic requirements presented above, specific and numerical requirements can be established to meet specific information needs. Analyses provide guidance on the sequences of events which will be produced by a given set of hypothetical LMFBR accident conditions. Given a sequence, analyses

---

*Of course, if additional fuel materials are incorporated into the test section for experimental reasons, the detectors cannot distinguish between test fuel and additional fuel, and this causes a loss in signal to background ratio. TREAT tests F1 and F2[2,3] for example, did incorporate additional fuel to flatten radial temperature distributions, with the result that the signal to background in those two single pin tests was intermediate between that for a single-pin and that for the central-pin in a cluster of seven pins.

will then provide guidance on the quantities of fuel whose movement is needed to play a significant role in the accident (e.g., to shut down the reactor by dispersal in higher power "lead" subassemblies). Analysis can also supply the velocities or, more accurately, the distances and time intervals which are required if the fuel movements predicted are to be significant. Calculations of quantities and velocities are also obtained, but the actual numerical values are model-dependent and can change significantly with various choices of physically-reasonable parameters. The actual experimental data provide sequence data which may not match the analytical predictions. Thus, there is feedback between data and analysis in the case of safety issue requirements which should be continually reviewed.

Calculations of Fast Fuel Test Reactor and Clinch River Breeder Reactor hypothetical accidents[4] are the principal source of current specific requirements. These requirements will be presented in the following categories: sensitivity, temporal, spatial and post transient considerations.

2. Sensitivity

One major factor that serves to mitigate consequences of hypothetical LMFBR accidents is incoherence - events do not occur simultaneously throughout the core. Thus, in general, the amount of material needed to be dispersed to terminate a transient and shut down the reactor well subcritical is restricted to a limited number of subassemblies. Thus the fraction of fuel moving in the subassemblies affected, may be more than an order of magnitude larger than a fraction of fuel moving expressed relative to the total amount of fuel in the core.

Fuel Movement Involving Sodium Vaporization

Extensive analytical* and experimental work[7] is underway to characterize fuel dispersal involving sodium vaporization. Traditionally such events were treated as transient overpower (TOP) accident phenomena, but they can also arise in transient undercooling-driven-overpower (TUCOP) accidents. This includes the case of fuel failure after boiling[3] as well as prior to boiling.[9] Reactivity changes arise due to fuel motion in the fuel channels and within the fuel pins. Calculations indicate that typical reactivity ramp hypothetical accidents in an FTR-like reactor can be terminated, and the reactor driven well sub-critical, by a total movement of the order of 20 g per pin ($\sim$10% of the fuel) occurring in a few lead subassemblies. This movement is calculated to occur within a time interval <100 ms.[10] For motions of this type to be characterized, a sensitivity to changes over a few cm of axial length of one g or less per pin is needed in order to follow the fuel as it moves from the failure site within coolant channels, within each pin toward the failure site and is dispersed above the top of the initial fuel stack. For a typical seven-pin experiment, viewed with 5 vertical columns, this implies that we wish to detect clearly and unambiguously amounts fuel $\lesssim$7 g per horizontal row, or $\lesssim$1.4 g/individual channel. For 61 pins (10 columns), this implies $\lesssim$61 g/row, or $\lesssim$6 g/channel. Individual channel data are needed as well as row-integrated data (which may be particularly useful[11] for comparison of experiment

---

*Cf. Refs. 5 and 6.

with the single channel movement models currently available[5,6]) in order to check the effects of bundle incoherence effects, as well as to test for the possible existence of local events or test section boundary anomalies. Fig. 1 illustrates what is actually encountered. Shown is the distribution of fuel, per unit of axial length, for the total of seven oxide fuel pins with fuel stacks initially 34 cm long, run in test E8.[11] Hodoscope data were integrated over all five vertical columns to obtain one axial distribution curve for each time interval, for convenience in comparison against PLUTO I[5] calculation output. The relatively large time intervals (∿10 ms or more) were found to be adequate to characterize the changes in distribution. Note that averaging 5 channels into one at each axial node enhances sensitivity. Further improvement is obtained by integrating over longer time intervals than the readout intervals whenever it is justified. This test used a sodium flow setting scaled down to match the short fuel stack to obtain realistic axial temperatures at the time of failure. Other tests with higher flows may be expected to produce significantly more (and faster) axial movements.

For LMFBR designs with substantial local positive sodium void coefficients of reactivity, the positive reactivity changes associated with voiding must be folded into the analyses of fuel (and clad) motion-induced reactivity changes. In general, this effect raises the magnitudes of fuel whose motion has significant effects, so that the above comments on fuel sensitivity still apply. The time intervals of interest may be significantly reduced, however, as will be discussed briefly below.

Movement After Channel Voiding

Movements associated with events occurring after channel voiding can occur for a wide range of power levels. For an FTR-like reactor, this motion is calculated to occur at transient undercooling (TUC) accident power levels[2], that is, at one to a few times nominal power[3], and the magnitudes of fuel whose movement is significant is comparable to those of the cases discussed above. For dispersals at ∿100 times nominal power[12], however, the expected (and significant) movement is, to first order, characterized by a "front-like" movement of the end of the fuel. For current pin designs, a single pin experiment would have a change of 0 to ∿2 g/cm length as the "front" moved completely through a channel. This implies that one should clearly and unambiguously detect a change $\lesssim$1 g/channel.* For seven pins (five channels per row) this implies $\lesssim$1.4 g/channel. For 61 pins (10 columns) this implies $\lesssim$6 g/channel. Complex motions have been predicted (as fuel ends dropping, central sections dispersing upward/downward through end "stubs", etc.) and some complex motions have been detected (local fuel "eructations") within a completely disrupted fuel region. The above sensitivities appear to be adequate to characterize them.

---

*Two channel heights are available at TREAT, one of about 2 cm and one of about 3.5 cm. See below. The former would view a change of 0 to 4 g/channel as the front moved through, the latter, 0 to 7 g/channel.

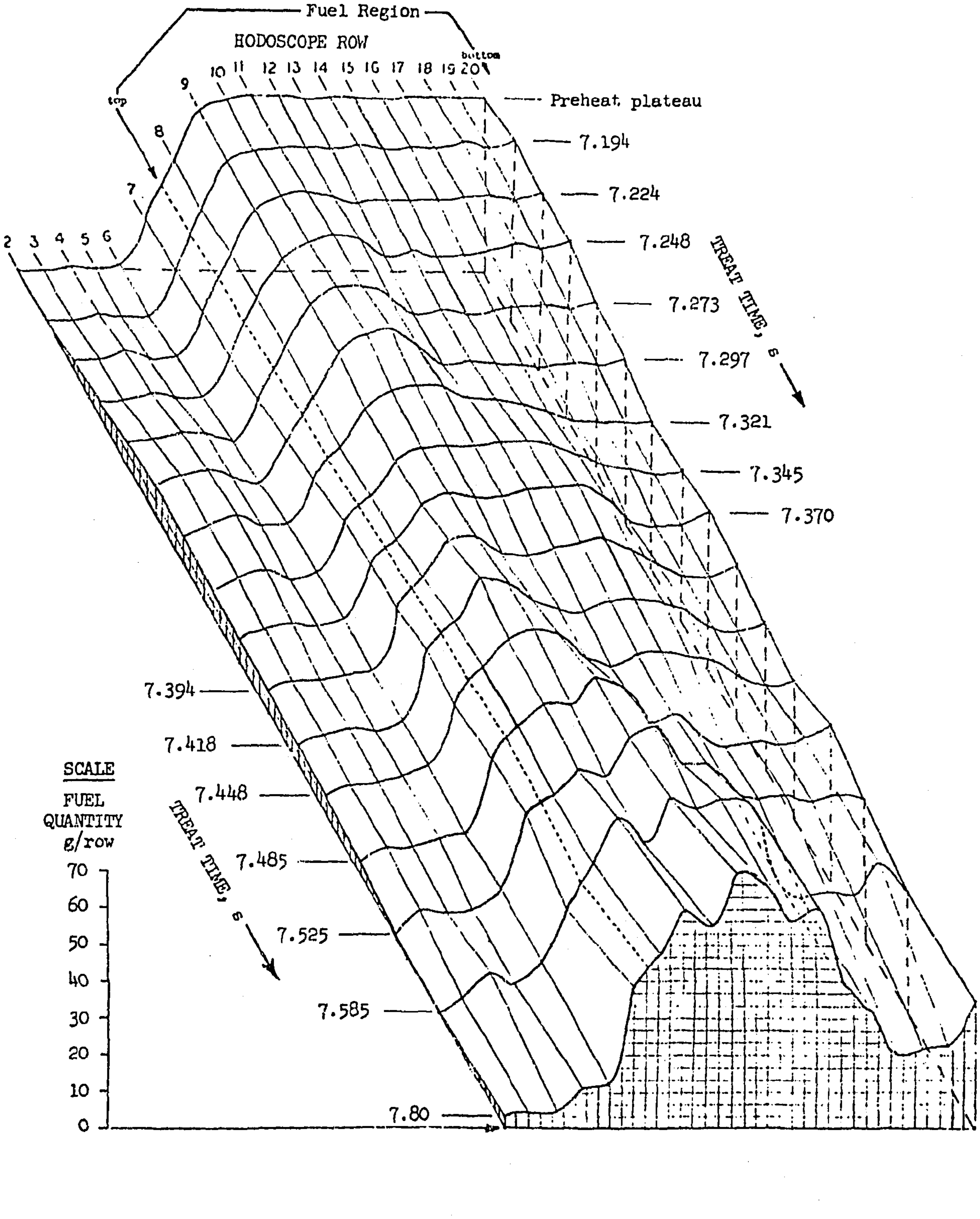

Fig. 1 Representation of Hodoscope Fuel Motion Data from TOP TREAT Test E8

Comments on Transition Phase Experiments

"Transition phase" experiments are planned to study the core behavior after a core disruptive hypothetical LMFBR accident, as the core boils up under a continued decay heating and disperses to its final configuration. During this time, the core debris is well-subcritical, and there is concern over whether or not the core material could in some fashion compact enough to cause recriticality. For the development of this accident phase, sensitivity adequate to follow continued dispersal of the reverse of the initial dispersal is needed. That is, it appears that sensitivity adequate to follow the accident dispersal phase should be adequate for study of the development of the subsequent dispersal phase.

3. Temporal Resolution

Sensitivity and time interval are related, since the longer the time over which counts are integrated, the greater becomes the statistical precision with which the fuel quantity is measured per channel. In advance of a test it is necessary to determine a time interval for hodoscope data readout which is equal to that needed to detect the movements of material quantitities (sensitivity requirements) which represent the anticipated (or significant) motions. If the data indicate that longer intervals are sufficent, then counting data can be accumulated over two or more time intervals to obtain better statistics and enhance the quality of data.

Fuel Movement Involving Sodium Vaporization

For typical TOP case calculations the most significant movements appear to occur over a time interval ∿20 ms; and movements ∿5 ms appear to be adequate. On this basis, readout intervals ∿2 ms are required. The number of intervals over which counting data are integrated should be determined after initial data analysis. For a voiding reactivity-driven power burst, a burst duration of about 5 ms has been calculated.[4] Here, a readout interval ∿1 ms is required to follow the dispersal which terminates the burst. For the somewhat longer bursts studied with TREAT, therefore, 1-2 ms readout intervals would be adequate.

Movement after Channel Voiding - Existing Data

Existing data indicate that movements occurring at power levels ∿ normal or a few times normal can be characterized adequately with time intervals significantly longer than those for the dispersal by vaporizing sodium. Fuel fall or acceleration under a few g can adequately be characterized - for the distances of interest - by time intervals >10 ms. So this class of phenomena is also covered by the 2-3 ms readout interval. At high power levels, for example ∿100 times normal like the case under study in the EOS tests, the time scales of significant fuel movements require readout intervals of 1-2 ms.

Comments on Transition Phase Experiments

Some guidance on time intervals needed to follow the development of a transition phase dispersal is provided by the "eructuations" detected in tests L2, L3 and L4,[13] and the "slow" dispersal detected in E7.[14] For these events, intervals of 10-20 ms are quite adequate. However, shorter readout intervals ∿ a few ms would be desirable initially, since data can be integrated over as many readout intervals as desired, based on the initial analyses of the hodoscope data. One recent[15] calculation of the upper surface height of a boiling pool of fuel and steel, has predicted height increases of about 1 cm occurring over a time span of about 100 ms (4000°K fuel) to about 500 ms (3100°K fuel). To follow this type of event, which might be run at sample power ∿5-20% of nominal, time intervals ∿ of 20 ms appear to be quite adequate, and integration of data over much longer intervals may be justified once actual data are available for guidance.

4. Spatial

Spatial resolution is desirable on as fine a scale as possible, to assist in defining specific phenomena and refining calculational models. Very fine spatial subdivision of a hodoscope system is not feasible, because the resulting counting statistics would be inadequate. Thus it is necessary to ascertain the spatial subdivision actually needed to follow fuel movements for LMFBR accident analyses. The typical "cell" for movement is that defined by a single fuel pin and the channel around it. A horizontal subdivision comparable to this "cell" diameter is needed to check single channel fuel motion calculation predictions, and to check for possible incoherence across the pins of a test cluster, or to check for possible boundary effects. In some cases, it is actually desirable to integrate data over several channels on the same vertical position to check analytical results.[11] Vertical node separation ∿2 cm is normally quite adequate for the reactivity calculations. Vertical subdivision of the hodoscope adequate to provide data with vertical resolution ∿2 cm is required.

Spatial dimensions of the hodoscope channels are set by the collimators, which were designed on the basis of the above requirements. Current fuel designs have centerline to centerline fuel separations of about 0.7 cm or larger. The original hodoscope collimator views elements 0.38 cm wide by 2.25 cm high at the core center. The new collimator views elements 0.67 cm by 3.45 cm. Finer spatial subdivision of fuel motion data to one half or less the element separation can be obtained by unfolding spatial distributions.

Axial coverage is provided with the new collimator adequate to view 91 cm fuel stacks plus an additional 30 cm for extended fuel motion above and below the fuel. Radial coverage is adequate for a 61 pin cluster, or a 61 pin core within a 91 pin bundle.[16]

5. Post Transient Considerations

Post transient fuel motions are a special case. Originally, it was expected that no significant post-transient capability could be developed. However, the hodoscope as developed has a wide dynamic range which can be further exploited by integrating count data over many collection intervals to build up statistics for low countrate post-scram events in TREAT experiments. The need to accumulate counts over much longer intervals than during the transient somewhat restricts post-scram fuel motion data requirements to "slow" motions such as the following: post-scram collapse under gravity of molten samples, determination of the frozen stable post-experiment configuration for a test in which the removal of test apparatus from the reactor could result in collapse of fragile columunar remains slow dispersal continuing after scram, and gross identification of fuel "eructation" events occurring after scram.

Post-experiment <u>in-situ</u> radiography may be regarded as a special case of post-scram diagnostics. Its basic requirement is determination of the frozen, stable, post-experiment configuration prior to movement of the test apparatus. Performance of such scans must be planned carefully and in general may require that the loop sodium remain molten until completion of the scan. The TREAT power level necessary to obtain a good scan in a reasonable operating time may be high enough that frozen test section sodium could be melted, particularly in a test resulting in complete or partial flow channel blockages. In such a case, cycles of freezing and thawing of sodium trapped in fuel fragments could cause disturbance to the fuel.

Discussion

1. Fuel Motion

General requirements can be identified for a wide range of fuel motion experiments. Sensitivity is basically a function of the size of test bundle. It ranges from a single pin value of one gram of fuel per hodoscope channel up to 6 g/channel for 61 pin test bundles. Data readout intervals are typically set small, and then count data are averaged over as many collection intervals as the preliminary velocity data permit in order to enhance the quality of the motion data. Intervals down to 1-2 ms may be employed, although data may be integrated over intervals of 20 ms or longer.

It must be emphasized that the requirements are those being developed for TREAT experiments which are being guided by mechanistic analyses of the physical phenomena expected to be present in hypothetical LMFBR accidents, analyses of which in turn have been guided by previous TREAT data. Some use has been made of the real incoherences existing in real reactors. More detailed treatments of incoherences within subassemblies and from subassembly to subassembly would be expected to migitate these accidents and broaden the time spans of interest.

Application of the above requirements to other test reactors must be done carefully, with due attention to the actual phenomena to be studied. For example, if one wishes to study LMFBR accident termination by post-failure fuel dispersal in "lead" subassembly in initially sodium-filled channels, using a short period reactor, it may be possible to obtain the required sample energy at failure only in a power burst with a few ms duration. However, the essential "lead" subassembly post failure movements which must be followed in order to guide or verify analyses of the shutdown may occur over ∿50 ms. In this case, therefore, requirements for "post burst" fuel motion detection are as important as those at transient power levels.

2. Cladding Motion

Development of cladding motion capabilities and requirements is still in a relatively early stage. Initial calculations[18] of steel blockages at the top of the fuel tended to greatly overpredict the amounts of steel (the blockages actually found in post-mortem examination were a few mm in thickness).* It appears to be difficult, if not impossible, to consider detection of thin, planar, channel steel blockages. Gross loss or gain of steel in lead subassemblies in amounts comparable to the fuel sensitivity will provide finer "resolution" than that for fuel, when reactivity effects on the LMFBR are compared. Finally, filling of sodium channels with steel and the subsequent movement of gross channel inlet blockages during the early post-accident movement phases are phenomena which should be followed by clad diagnostics capabilities.

REFERENCES

1. A. De Volpi, "Fuel and Cladding Motion Surveillance," Proc. Intl. Meeting Fast Reactor Safety and Related Physics, Chicago, 1976.
2. R. G. Palm, R. R. Stewart, S. M. Gehl, A. B. Rothman, and A. De Volpi, "Loss of Flow Test F1 on an FFTF-Type Fuel Element," Trans. Amer. Nucl. Soc. 22. 427 (1975).
3. R. G. Palm, S. M. Gehl, C. L. Fink, R. R. Stewart, and A. B. Rothman, "F2 Phenomenological Test on Fuel Motion," Trans. Amer. Nucl. Soc. 23, 354 (1976).
4. W. R. Bohl and R. J. Henninger, "Some Comments on CRBRP LOF Analysis using SAS 3A," Trans. Amer. Nucl. Soc. 22, 401 (1975).
5. H. U. Wider, J. F. Jackson, L. L. Smith, and D. T. Eggen, "An Improved Analyses of Fuel Motion During an Overpower Excursion," Proc. Conf. Fast Reactor Safety, Beverly Hills, CONF-740401, 3, (1974).
6. A. E. Waltar, et al "MELT III - A Neutronics Thermal Hydraulic Computer Program for Fast Reactor Safety," HEDL-TME-76-47 (Dec. 1974).
7. A. B. Rothman, C. E. Dickerman, R. G. Palm, L. A. Semenza, R. Simms, and H. U. Wider "Results of Recent TOP and LOF Experiments in TREAT," Proc. Intl. Meeting Fast Reactor Safety and Related Physics, Chicago, 1976.
8. R. N. Koopman, B. W. Spencer, N. A. Kramer, F. J. Testa, L. A. Semenza, R. E. Holtz, and A. De Volpi, "TREAT Transient Overpower Experiment R9," Trans. Amer. Nucl. Soc. 24 (1976).
9. R. Simms, A. B. Rothman, W. F. Murphy, "Post Test Evaluation of Transient Overpower TREAT Test E8 on Preirradiated FFTF Type Fuel," Trans. Amer. Nucl. Soc. 22, 425 (1975).
10. A. E. Waltar and N. P. Wilburn, et al, "An Analyses of the Unprotected Transient Overpower Accident in the FTR," HEDL-TME-75-50 (1975).
11. G. S. Stanford, A. De Volpi, R. Simms, H. U. Wider, L. A. Semenza, J. P. Regis, and R. R. Stewart, "Fuel Motion in TREAT Transient Overpower Test E8," Trans. Amer. Nucl. Soc. 24 (1976).
12. J. P. Tylka and C. E. Dickerman, Argonne National Laboratory, unpublished.
13. A. De Volpi, G. S. Stanford, R. R. Stewart, J. P. Regis, and L. W. Deitrich, "Comparative Fuel Motion Effects of Fresh and Pre-irradiated Pins in Loss-of-Flow Simulations," Trans. Amer. Nucl. Soc. 22, 430 (1975).
14. R. C. Doerner, G. S. Stanford, W. F. Murphy, A. De Volpi, J. P. Regis, R. R. Stewart, "Fuel Failure Sequence for TREAT Test E7," Trans. Amer. Nucl. Soc. 23, 356 (1976).

REFERENCES (Contd.)

15. P. B. Abramson, "FX2 POOL - A Dynamic Two-Dimensional Multifluid Hydra/Thermodynamic and Neutronics Model for Boiling Pools," Trans. Amer. Nucl. Soc. 21, 284 (1975).

16. A. De Volpi, A. R. Jamrog, R. J. Pecina, D. J. Travis, C. L. Fink, R. R. Stewart, N. A. Kramer, and P. Hofine, "Design, Installation, and Operation of New Hodoscope Collimator at TREAT," Trans. Amer. Nucl. Soc. 24 (1976).

17. C. L. Fink, "Advances in Clad Blockage Detection," Second Technical Exchange Meeting of Fuel- and Clad-Motion Diagnostics for LMFBR Safety Facilities, Chicago (1976).

18. W. R. Bohl and T. J. Heames, "A Cladding Motion Model for LMFBR Loss-of Flow Accident Analysis," Trans. Amer. Nucl. Soc. 17, 358 (1973).

19. B. W. Spencer, M. A. Grolmes, R. E. Holtz, F. J. Testa, and N. A. Kramer, "Summary and Evaluation of R-Series Loss of Flow Safety Tests in TREAT," Proc. Intl. Meeting Fast Reactor Safety and Related Physics, Chicago (1976).