ANL-78-73

ARGONNE NATIONAL LABORATORY
9700 South Cass Avenue
Argonne, Illinois 60439

FAILURE OF A HIGH-POWER PIN IN
A SIMULATED $\$3/s$ TOP ACCIDENT:

Test E6 Final Report

by

R. C. Doerner, W. F. Murphy,*
D. Stahl,* and G. S. Stanford

Reactor Analysis and Safety Division

August 1978

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Department of Energy, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

*Materials Science Division

Released for Announcement in Energy
Research Abstracts. Distribution Limited
to Participants in the LMFBR Program.
Others request from TIC 71A

U.S. ENERGY RESEARCH & DEVELOPMENT ADMINISTRATION
MAJOR CONTRACTOR'S RECOMMENDATION FOR
DISPOSITION OF SCIENTIFIC AND TECHNICAL DOCUMENT

*See Instructions on Reverse

1. ERDA Report No. ANL-78-73	3. Title FAILURE OF A HIGH-POWER PIN IN A SIMULATED \$3/s TOP ACCIDENT: Test B6 Final Report by R. C. Doerner, W. F. Murphy, and G. S. Stanford August 1978
2. Subject Category No. UC-79p	
4. Type of Document ("X" one) ☒ a. Scientific and Technical Report ☐ b. Conference paper: Title of conference _____ Date of conference _____ Exact location of conference _____ ☐ c. Other (Specify, Thesis, Translation, etc.): _____	
5. Copies Transmitted ("X" one or more) ☒ a. Copies being transmitted for standard distribution by ERDA-TIC. ☐ b. Copies being transmitted for special distribution per attached complete address list.* ☐ c. Two completely legible, reproducible copies being transmitted to ERDA-TIC.	
6. Recommended Distribution ("X" one) ☒ a. Normal handling (after Patent clearance): no restraints on distribution except as may be required by the security classification. ☐ b. Make available only to U.S. Government agencies and "new contractors." ☐ c. Make available only within ERDA and to ERDA contractors. ☐ d. Make available only within ERDA. ☐ e. Make available only to those listed in item 12 below. ☐ f. Other (Specify): _____	
7. Recommended Announcement ("X" one) ☒ a. Normal procedure may be followed.* ☐ b. Recommend following announcement limitations: _____	
8. Reason for Restrictions Recommended in 6 or 7 above. ☐ a. Preliminary information. ☐ b. Prepared primarily for internal use. ☐ c. Other (Explain): _____	
9. Patent Clearance ("X" one) ☒ a. ERDA patent clearance has been granted by responsible ERDA patent group. ☐ b. Document has been sent to responsible ERDA patent group for clearance.	
10. National Security Information (For classified document only, "X" one) ☐ a. Document does contain national security information other than restricted data. ☐ b. Document does not contain national security information other than restricted data.	
11. Copy Reproduction and Distribution a. Total number of copies reproduced 385 b. Number of copies distributed outside originating organization _____	
12. Additional Information or Remarks (Continue on separate sheet, if necessary)	

13. Submitted by (Name and Position) (Please print or type)*
E. Newman Pettitt, Classification Officer

14. Organization
Argonne National Laboratory

15. **E. Newman Pettitt** 16. Date **1-10-79**

INSTRUCTIONS

Who uses this Form: All ERDA contractors except those specifically instructed by their ERDA contract administrator to use the shorter Form ERDA-427.

When to Use: Submit one copy of this Form with each document which is sent to ERDA's Technical Information Center (TIC) in accordance with the requirements of ERDA Manual Chapter 3201.

Where to send: Forward this Form and the document(s) to:

USERDA-TIC
P.O. Box 62
Oak Ridge, TN 37830

Item instructions:

- Item 1.** The first element in the number shall be an ERDA-approved code to be determined as follows: (a) The responsible field office may request TIC approval of a unique code for a contractor, e.g., BNL, BMI, HNL, etc.; (b) A program division may request TIC approval of a unique code for a program or series of reports, e.g., PNE, VUF, etc.; (c) An operations office may instruct a contractor to use the code approved for the operations office, i.e., COO, ORO, IDO, SRO, SAN, ALO, RLO, NVO; and (d) Program divisions shall use the code ERDA for reports which they themselves prepare unless there is reason to use some other approved code.

The code shall be followed by a sequential number, or by a contract number plus a sequential number, as follows: (a) Contractors or programs with unique codes may complete the report number by adding a sequential number to the code, e.g., HNL-101, HNL-102, etc.; or PNE-1, PNE-2, etc.; or they may add the identifying portion of the contract number and a sequential number, e.g., ABC-2105-1, ABC-2105-2, etc.; (b) Contractors using the operations office code shall complete the report number by adding the identifying portion of the contract number and a sequential number, e.g., COO-2200-1, COO-2200-2, etc.; (c) Subcontractor reports shall be identified with the code used by the prime contractor; and (d) Program divisions using the ERDA code shall complete the report number by adding a sequential number which they request from the Library Branch, Division of Administrative Services.

- Item 2.** Insert the appropriate subject category from TID-4500 ("Standard Distribution for Unclassified Scientific and Technical Reports") or M-3679 ("Standard Distribution for Classified Scientific and Technical Reports") for both classified and unclassified documents, whether or not printed for standard distribution.

- Item 3.** Give title exactly as on the document itself unless title is classified. In that case, omit title and state "classified title" in the space for item 3.

- Item 4.** If box c is checked, indicate type of item being sent, e.g., thesis, translation, etc.

- Item 5.** a. If box a is checked, the number of copies specified for the appropriate category or categories in M-3679 or TID-4500 shall be forwarded to TIC for distribution.

b. If box b is checked, complete address list must be provided TIC.

c. If box c is checked, at least one copy shall be original ribbon or offset and be completely legible. A clear carbon copy is acceptable as a second reproducible copy.

- Item 6.** If box a is checked for an unclassified document, it may be distributed by TIC (after patent clearance) to addressees listed in TID-4500 for the appropriate subject category, to libraries in the U.S. and abroad, which through purchase of microfiche maintain collections of ERDA reports, and to the National Technical Information Service for sale to the public.

If box a is checked for a classified document, it may be distributed by TIC to addressees listed in M-3679 for the appropriate subject category.

If a box other than a is checked, the recommended limitation will be followed unless TIC receives other instructions from the responsible ERDA program division.

Box f may be checked in order to specify special instructions, such as "Make available only as specifically approved by the program division," etc.

- Item 7.** a. Announcement procedures are normally determined by the distribution that is to be given a document. If box a in item 6 is checked for an unclassified document, it will normally be listed in the weekly "Accessions of Unlimited Distribution Reports by TIC" (TID-4401) and may be abstracted in "Nuclear Science Abstracts" (NSA).

A classified document, or an unclassified document for which box b, c, d, e, or f, in item 6 is checked, may be cited with appropriate subject index terms in "Abstracts of Limited Distribution Reports" (ALDR).

b. If the normal announcement procedures described in 7a are not appropriate check 7b and indicate recommended announcement limitations:

- Item 8.** If a box other than a is checked in item 6, or if 7b is checked, state reason for the recommended restriction, e.g., "preliminary information," "prepared primarily for internal use," etc.

- Item 9.** It is assumed that there is no objection to publication from the standpoint of the originating organization's patent interest. Otherwise explain in item 12.

- Item 10.** If box a is checked, document cannot be made available to Access Permit holders (Code of Federal Regulations, 10 CFR, Part 25, subpart 25.6); if box b is checked, TIC will determine whether or not to make it available to them.

- Item 11.** Self explanatory.

- Item 12.** Use this space if necessary to expand on answers given above, e.g., item 6f and item 8.

- Item 13.** Enter name of person to whom inquiries concerning the recommendations on this Form may be addressed.

- Item 14-16.** Self explanatory.

TABLE OF CONTENTS

	<u>Page</u>
ABSTRACT	1
I. INTRODUCTION.	2
A. Purpose.	2
B. Relation to FTR	3
C. Relation to Other TOP Tests	4
II. TEST FUEL	5
III. EXPERIMENTAL HARDWARE	9
A. Fuel Holder	9
B. Instrument Section.	12
C. Bayonet and Baffles	12
D. Loop Outfitting and Instrumentation	12
E. Monitor Wires	13
IV. EXPERIMENT CALIBRATION	13
A. Flow-detector Calibration.	14
B. Fuel-pin Power.	14
V. TEST DATA	17
A. Loop Data	17
B. Hodoscope Data.	22
C. Posttest Metallography.	24
VI. THERMAL-HYDRAULIC CALCULATIONS	28
VII. DATA ANALYSIS	34
A. Loop Data	34
B. Failure Potential.	42
VIII. SUMMARY AND CONCLUSION	43

TABLE OF CONTENTS

	<u>Page</u>
 APPENDICES	
A. Details of Posttest Examination	47
1. Neutron Radiography	47
2. Loop Disassembly	47
3. Examination Results	50
a. General.	50
b. Flow Blockages	58
c. Extent of Melting	60
d. Structure of Fuel and Cladding	62
e. Fuel-element Plenum Region	67
4. Conclusions	69
 B. Hodoscope Analysis of Fuel Motion in Test E6	 73
1. Data-processing Codes.	73
2. Differential Hodographs	77
3. Effect of Spurious Power Images on Low-event-rate Data.	77
4. Test Results.	80
5. Detection of Upward Motion.	81
6. Fuel Motion	83
a. Fuel Motion from 9.052 to 9.082 s	83
b. Fuel Motion from 9.082 to 9.150 s	88
c. Fuel Motion from 9.150 to 9.211 s	89
d. Fuel Motion from 9.211 to 9.294 s	91
e. Fuel Motion from 9.294 to 9.712 s	94
7. Axial Fuel Profiles	96
8. Comparison with Posttest Radiograph	96
9. Estimate of Fuel Lost to Hodoscope Field	98
10. Effect of Boron Flux Shapers on Fuel-motion Detection	100
11. Fabrication Gas as a Cause of Prefailure Fuel Motion in TOP Tests	104
a. Formulas for Derived Quantities	107
b. Results	107
c. Conclusions	108
 C. Thermal-Hydraulic Calculations	 110
1. Flow-channel Geometry	110
2. Thermal Conductivity.	113
3. Heat Capacity	114
4. Thermal Expansion	115
5. Gap Conductance	115
6. Miscellaneous COBRA Input Constants	116

TABLE OF CONTENTS

	<u>Page</u>
D. Digital-test Data	117
ACKNOWLEDGMENTS	130
REFERENCES	131

LIST OF FIGURES

<u>No.</u>	<u>Title</u>	<u>Page</u>
1.	Identification of Fuel-pin Parts and Comparison between Pins . . .	6
2.	Metallographic Cross Section of HEDL-NF-013 Sibling Pin	7
3.	Estimated Fission-gas Distribution in Central Pin from Sibling-pin Measurements and from LIFE-3 Calculations	8
4.	Cross-sectional View of Loop and Test Train about 70 mm above Bottom of Fuel Pins	10
5.	Assembly and Part Identification for E6 Test Loop	10
6.	Schematic Diagram of Axial Flow-channel Geometry and Loop Outfitting	11
7.	Pin, Sector, and Channel Identification for Test E6	15
8.	Radial Power Shapes for Fresh Pins and Density Distribution after EBR-II Preirradiation of Central Pin.	16
9.	Axial Power Shape for Edge and Axial Fuel-density Function Used as a Weighting Function for Axial Power Shape in Central Pin	16
10.	Inlet and Outlet Flow Data for Test E6.	17
11.	Inlet and Upper-plenum Coolant Temperatures	18
12.	Temperature Signals at Inlet and Outlet Showing "Cross Talk". . .	18
13.	Coolant Temperatures at Outlet, Pump Return, and Gas above Top Sodium Surface	19
14.	Power and Energy Histories for Test E6	19
15.	Details of Outlet and Inlet Flow Data and Reactor Power during Failure Periods.	20
16.	Inlet and Outlet Pressure Data and Reactor Power during Failure Sequence	20
17.	Coolant Temperatures at Pump Return, in Upper Sodium Head, and Gas Temperature between Top Sodium Surface and First Baffle during Failure Sequence.	20
18.	Relationship between Hodoscope Channels and Test Geometry . . .	22
19.	Axial Fuel Motion	23
20.	Horizontal Fuel Motion	24
21.	Posttest Neutron Radiograph of Test E6.	25

LIST OF FIGURES

<u>No.</u>	<u>Title</u>	<u>Page</u>
22.	Comparison of Measured and Calculated Outlet Temperatures up to Time of Pin Failure	29
23.	Comparison of Axial Coolant-temperature Increase from Steady-state MELT-III/SAS Calculation and COBRA Results at End of Preheat.	30
24.	Comparison of Radial Temperature Distribution Calculated by MELT-III/SAS during Steady State and COBRA Results for Central Pin into Hottest Channel in Test E6	30
25.	Fuel, Cladding, and Coolant-temperature Distributions as Calculated by COBRA at Time of Failure	31
26.	Axial Extent of Melting for Selected Pin Sectors as Times Approach Failure Time.	32
27.	Melt Fraction for Each Pin Sector at $Z/L = 0.7$ as Failure Is Approached.	33
28.	Details of Inlet Flow Showing Initial Slug Ejection Leading to Reverse Flow, Followed by Chugging.	34
29.	Details of Inlet Flow during Approach to and Time after Failure	35
30.	Composite of Inlet and Outlet Flow during Initial Failure Sequence	35
31.	Upper and Lower Void-Coolant Interfaces as Determined from Integrals of Outlet and Inlet Flows, Respectively	36
32.	Initial Void Growth as Determined from Differences between Outlet and Inlet Flow Volumes	37
33.	Void Volume during and after Pin Failure and Holder-wall Rupture	37
34.	Flow-slug Accelerations in Test E4 at Initial Failure.	38
35.	Flow-slug Accelerations in Test E6 at Initial Failure.	39
36.	Flow-slug Accelerations in Test E7 at Initial Failure.	39
37.	Relative Inlet Flow Velocities during Initial Failure for Tests E4, E6, and E7	40
38.	Relative Outlet Flow Velocities for Tests E4, E6, and E7	40
39.	Calculated Product of Fuel and Coolant Enthalpies at $Z/L = 0.77$	42
40.	Calculated Failure Potential for Central Pin in Test E6 Using Enthalpy Calculations from COBRA.	43

LIST OF FIGURES

<u>No.</u>	<u>Title</u>	<u>Page</u>
A.1.	Identification of Sections Cut from Loop and Pins for Post-test Examination	49
A.2.	Photograph of Inside of Bellows toward Rupture Site	51
A.3.	Photograph of Inside of Bellows Away from Rupture Site	51
A.4.	Views of Partly Exposed Elements Showing Melted Cladding and Fluted-tube Rupture	52
A.5.	Top View of Section A1 Showing Condition of Fuel Pellets.	53
A.6.	Plenum Sections of Elements E6-4 and -6 with Attached Fuel Particles	54
A.7.	Three Views of Elements in Section A4 after Removing E6-4 and -6, Showing Deposited Melted Fuel and Steel.	54
A.8.	Transverse Section A10 through Cluster of Elements at Bottom UO ₂ Insulator Pellets.	55
A.9.	Transverse Section A8 through Cluster about 60 mm from Bottom of Fuel Columns	56
A.10.	Transverse Section A15, 222 mm from Bottom of Fuel Columns	57
A.11.	Partial Transverse Section A27, about 12 mm down from Top of Fuel Columns	57
A.12.	Transverse Section A11, 55 mm above Top of Fuel Columns, through Peripheral Reflector Rods	58
A.13.	Blockage of Flow Channels by Melted Fuel Just above Rupture in Fluted Tube	59
A.14.	Longitudinal Section 38 mm Down from Top of Fuel Column, Showing Melted Fuel Blockage and Relocated UO ₂ Pellets	60
A.15.	Transverse Section through Center Element of Section A16, Showing Extent of Center Melting	61
A.16.	Radial Transverse from Outside into Melted Fuel of Center Element, Section A16	63
A.17.	Peripheral Fuel-element Pellets Fused End-to-End, Showing Central Void and Columnar Grains	63
A.18.	Flowed Fuel on Inside of Central Void in Pellets of Fig. A.17	64
A.19.	Metallic Intrusions into Startup Cracks in Fresh Fuel	65
A.20.	Metallic Particles Dispersed in Melted Fuel from Section A8	66

LIST OF FIGURES

<u>No.</u>	<u>Title</u>	<u>Page</u>
A.21.	Melted Steel between Fuel and Cladding and Outside of Cladding from Section A8	66
A.22.	Bulge in Almost-melted Cladding	67
A.23.	Cladding Cracking in Peripheral Element in Reflector-rod Region.	68
A.24.	Melted Fuel against a UO ₂ Pellet.	68
B.1.	EFFI Output	78
B.2.	Power-transient Portion of E6, as Given by Hodoscope Power-monitor Channels and by TREAT Power Monitor.	80
B.3.	Time Plot of Ratio of Array-average Counting Rate to Power-monitor-average Counting Rate for Transient E6	82
B.4.	Differential Hodographs for E6 from 8.932 to 9.115 s, Referenced to Preheat Plateau.	84
B.5.	Differential Hodographs for E6 from 9.052 to 9.150 s, Referenced to Premotion Time	85
B.6.	Differential Hodographs for E6 from 9.151 to 9.211 s, Referenced to Premotion Time	90
B.7.	Differential Hodographs for E6 from 9.211 to 9.294 s.	92
B.8.	Differential Hodographs for E6 from 9.294 to 9.712 s, Referenced to Premotion Time	95
B.9.	Axial Profiles of Fuel Distribution in E6	97
B.10.	Fission-product Profiles from Gamma Scans of Central H3 Pin with and without Boron Flux-shaping Collars	101
C.1.	Geometry Used in Computing Channel Flow Areas, Heated and Wetted Surfaces, and Duct-wall Lengths	110

LIST OF TABLES

<u>No.</u>	<u>Title</u>	<u>Page</u>
I.	Composition and Characteristics of FTR and E6 Test Fuel.	5
II.	Measured and Calculated Grain-structure Regions in Sibling Pin.	8
III.	Instrument Calibration Factors for Test E6.	13
B.1.	Fuel Lost to Hodoscope Field	99
C.1.	Calculated Values of Thermal Conductivity for Fresh PNL-17 Pins and Preirradiated HEDL-NF Pin Used in Test E6 .	113
C.2.	Calculated Values of Heat Capacity for $(U_{0.75}Pu_{0.25})O_{1.98}$	114
D.1.	E6 Test Data Listed in 50-ms Time Increments	118
D.2.	Inlet and Outlet Flow Data with Integrals since 9.000 s, Tem- peratures, and Indicated Void	122

**FAILURE OF A HIGH-POWER PIN IN
A SIMULATED $\$3/s$ TOP ACCIDENT:
TEST E6 FINAL REPORT**

by

**R. C. Doerner, W. F. Murphy,
D. Stahl, and G. S. Stanford**

ABSTRACT

This report describes the Fuel Dynamics Test E6 and analyzes the test data. A cluster of six fresh FTR-type fuel pins surrounding a previously irradiated pin was tested to failure in a simulated $\$3/s$ FFTF accident. It is shown that:

- 1. The central 34.3-cm-long test pin is thermodynamically equivalent to a one-third scale model of the 91.4-cm-long FFTF pins.**
- 2. Failure occurred 70 ms earlier than predicted in the PSAR.**
- 3. Postfailure fuel motion was principally upward in direction and from the center of the cluster, with no more than 10 g of total fuel loss.**
- 4. The outlet blockage was formed in stages.**
- 5. The irradiated fuel is more mobile than fresh fuel.**
- 6. There were no significant fuel-coolant interactions.**
- 7. The lower one-third of the test pin suffered only minor cladding damage and no inlet blockage was formed.**

It is concluded that the mechanisms that led to initial failure can be reliably applied to the FTR. Characterization of the initial fuel release in amount, location, structure (solid, liquid or foam), and rate were reasonably prototypic. Post-failure coolant dynamics, however, were not very prototypic. Although the amount of fuel swept out is probably realistic, the formation of an outlet blockage and its impact on adjacent channel hydraulics is clearly nonprototypic.

I. INTRODUCTION

This report describes Test E6 and analyzes the test data. An interim report¹ was released before the hodoscope and posttest metallographic examinations were completed. Much of the detail given in the earlier report is condensed, eliminated, or compressed into an appendix of the present report. New information, not previously reported, is summarized in the text of this report. Some additional detail is also presented in the appendices. Periodic progress on the development, preparation, and execution of the experiment, and the analysis of the results have been reported in a series of Reactor Development Program Progress Reports.²⁻⁹

The fuel and hardware used in Test E6 are described in Secs. II and III. Detecting instruments, their responses, sensitivities, and calibrations are presented in Sec. IV. Radial and axial power shapes for the fuel-pin calibration factors are also given in Sec. IV. Some of the more pertinent test data and calculational results are given in Secs. V and VI, respectively, with details given in Appendix C. Additional details appear in Refs. 1-9. Failure-threshold predictions based on the thermal-hydraulic calculations and the "failure potential" are given in Sec. VII.

In summary, Test E6 was a test to failure of six "green" FTR-like fuel pins surrounding a prototypic high-power pin in FTR. Hydraulics of the sodium-coolant flow were established by the design of the fuel holder and the characteristics of the Mark-IIA loop used as the test vehicle for the experiment. Initial fuel and coolant temperature profiles in both the axial and radial directions were established by a 3-s steady-state irradiation at 167 MW in the TREAT reactor in which the experiment was performed. The 33/s FTR accident conditions were simulated by a TREAT power rise to 2250 MW on a 183-ms period at the end of the preheat. Test-fuel failure occurred about 50 ms after peak power. Pressure pulses, flow velocities and temperatures at various locations in the coolant stream were recorded on analog magnetic tape for later analysis. Dynamic fuel motions were recorded by the hodoscope, and posttest examinations identified the ultimate postfailure fuel and cladding redistributions.

Power tilting across the cluster produced unequal heating in the pins. The hottest outside pin was originally believed to be the first pin to fail. Subsequent analysis⁹ suggested that the first pin to fail could have been the central pin. A comparison of the coolant dynamics at the time of initial failure between the E6 data and data from a fresh-pin test (E4)¹⁰ and a cluster of seven preirradiated pins (E7)¹¹ led to the conclusion that the central preirradiated pin most likely failed simultaneously with one of the edge pins.

A. Purpose

Before Test E6, only Test E3,¹² had been performed to study the behavior of moderate-burnup fuel under rapid transient heating. Fuel pins used

in Test E3 had short fuel-column lengths (145 mm) and small diameters (4.4 mm). They had previously been irradiated in the MTR to burnups of 5-6 at. %, but with noncharacteristic fluence-to-burnup ratios for LMFBR fuel. The central fuel pin used in Test E6 had a longer fuel column (343 mm) and a larger diameter (5.8 mm), and was previously irradiated in EBR-II to a burnup of ~4 at. %, but at a more prototypic fast fluence (4×10^{22} nvt).

The major purpose of Test E6 was to identify the sequence of failure events associated with high-power fuel in a hypothetical \$3/s transient-overpower (TOP) accident in the FTR. Of particular interest are the timing of events, the magnitude of any fuel or cladding thermal interactions with the coolant, the rate and total amount of fuel that is redistributed, and the propensity for cladding and fuel relocations, including the formation of blockages.

A secondary objective of Test E6 was to contribute to the body of data used in verifying failure models built into the large accident-analysis codes. To this end, failure thresholds and coolant-dynamics models in such codes as SAS3A and MELT-III have been partially verified by TREAT experiments.

B. Relation to FTR

Two types of accidents are identified in the FTR safety analyses: a loss of sodium-coolant flow due to a pump failure or a pipe rupture (LOF), and a TOP excursion due to the accidental insertion of reactivity. Both have been extensively analyzed by the detailed accident-analysis codes SAS¹³ and MELT-III.¹⁴ Since many of the phenomenological models built into these codes have not been, and indeed, may never be, tested, the loop experiments provide important support to the sequence and magnitudes of postulated events.

In the analysis of the TOP accident, it was postulated¹⁵ that the maximum reactivity available in all the control rods was added at the maximum rate possible. It was further assumed that the plant-protection system (PPS) failed to shut the reactor down. An uncontrolled rod withdrawal in FTR produces a reactivity ramp of 6 β /s to a total insertion of as much as \$5 reactivity. A ramp rate of about an order of magnitude higher than this (50 β /s) was chosen as the base case in the PSAR. A \$3/s ramp, corresponding to the design limit of the FFTF PPS, was studied parametrically for rate-dependent effects. A power history corresponding to the \$3/s PPS limit was used in Test E6.

Predictions of failure time, fuel and coolant temperatures, and fuel motion in a TOP accident in the FTR are based on MELT-III calculations. Depending on the location of the individual subassemblies in the core and the previous irradiation history, fuel in each subassembly will behave differently. To make the calculations tractable, one to seven subassemblies having similar characteristics were lumped into 20 channels. Three different times during the reactor life were studied, beginning of life (BOL), beginning of cycle 4 (BOC-4), and end of cycle 4 (EOC-4). At initial FTR startup, all fuel is

"green." BOL calculations assumed a previous history of 10 days at full power operation, and truly "green" fuel was not included in the analysis. Every 100-day cycle, one-third of the fuel is replaced or moved to yield a relatively uniform power shape across the core. Cycle 4 is representative of most fuel throughout the FTR lifetime.

It was concluded in the MELT-III analysis that the TOP accident in FTR corresponding to a 50-¢/s initiating ramp leads to failure at 2.7 s and a peak power of 2050 MW. For a \$3/s ramp, failure occurred at 0.618 s and the peak power was 11,300 MW. In both cases, the accident is self-terminating due to fuel sweepout. Test E6 failed ~0.55 s after the overpower ramp began.

As failure is approached, fuel temperatures do not change significantly and the Doppler coefficient remains essentially constant. The sodium-void coefficient is relatively small; hence, the extent of voiding is important only as it affects the axial extent of failure. Although the parametric studies of ramp-rate dependence indicate that the initial failure site moves toward the center of the pin for increasing ramp rates, the consequences do not seem sensitive to either the rate or the amount of fuel plateout as long as some sweepout occurs. Thus the major contribution of Test E6 is to verify the predicted incoherences for the time of failure relative to a \$3/s ramp-accident calculation and to demonstrate the existence of fuel sweepout, and the dependence of fuel plateout and local blockage at the failure site on the extent of failure. Early failure (by 70 ms) in E6 supports the calculations for an incoherent failure sequence for FTR by MELT-III.

C. Relation to Other TOP Tests

Relative to the analysis of the TOP accident in FTR, Test E6 is the companion to the 50-¢/s ramp accident studied in Test H4. In all other respects, these tests were identical. A similar test using seven previously irradiated fuel elements (E7,¹¹ performed in March 1973) and a single-pin test of fresh fuel (E4,¹⁰ performed in November 1970) are used to separate effects of fresh-pin failures from those caused by the irradiated pin in E6. Other tests in the E (\$3/s ramps) and H (50-¢/s ramps) series used "low-power" pins having microstructures similar to the top third of ring 12 at EOC-4 in FTR. Again these were the first to fail in this cycle.

II. TEST FUEL

Test fuel for Test E6 consisted of six fresh PNL-17-type mixed-oxide elements surrounding a previously irradiated HEDL-NF element. Composition and physical characteristics of both types of pins are listed in Table I. Note from Table I that the fissile enrichment in the fuel (65-77% in uranium and 85% in plutonium) is considerably higher than in FTR fuel (normal uranium, 86% in plutonium) and the fuel-column lengths are shorter (344 compared to 914 mm in FTR). Other differences are illustrated in the various fuel-pin sketches shown in Fig. 1. An Inconel rod is used as the upper reflector in the PNL-17 and FTR pins, whereas a tube is used in the HEDL-NF pin. Effects of the different upper pin structures on the fuel-failure scenario are discussed in Sec. VII.

TABLE I. Composition and Characteristics of FTR and E6 Test Fuel

Composition	PNL-17 ^a		HEDL-NF-056 ^b		FTR ^c
	Enrichment, wt %	Weight, g/pin	Enrichment, wt %	Weight, g/pin	Enrichment, wt %
Fuel Column					
²³⁴ U	0.452	0.2	0.61	0.26	-
²³⁵ U	65.10	28.805	76.88	32.92	0.7 (Natural)
²³⁶ U	0.175	0.077	0.24	0.10	-
²³⁸ U	34.2	15.132	22.28	9.46	99.3
²³⁸ Pu	0.047	0.021	0.09	0.04	-
²³⁹ Pu	85.88	12.678	85.65	12.137	86.46
²⁴⁰ Pu	11.77	1.730	11.51	1.638	11.69
²⁴¹ Pu	2.083	0.305	2.47	0.358	1.67
²⁴² Pu	0.214	0.031	0.28	0.04	0.18
¹⁶ O		6.03		7.55	
O/M	1.96		1.97 ± 0.02		1.96
Total, g	67.04		64.35		
Density, g/cm ³	10.24 ± 0.07 (92% TD)		10.01 (90% TD)		10.05 (90.4% TD)
Length, mm	343.8		343.5		914
Insulator (Natural UO ₂)					
Density, g/cm ³	10.42		10.4		10.4
Cladding OD, mm	5.836		5.842		5.842
ID, mm	5.072		5.067		5.08
Total Length, mm	784.5		1091.8		2375.

^aAverages of six pins used in test.

^bFill gas is helium with xenon tracer at room temperature and pressure.

^cFrom Ref. 16.

Part ID		Dimensions, mm			Description
		PNL-17	HEDL-NF	FTR	
End Caps					
Lower	(1)	85.7	85.7	66.0 ^a	SS-316, 20% cold work
Upper	(10)	25.4	40.0		
Reflectors					
Lower	(2)	None	None	144.8	Inconel-600
Upper	(7)	152.4	127.2 ^b	144.8	4.825-mm diameter
Insulators					
Lower	(3)	12.7	12.7	20.3	Normal UO ₂
Upper	(6)	12.7	170.1	20.3	4.82-mm diameter
Fuel Column	(4)	343	343	914	25 wt % PUO ₂ + 75 wt % UO ₂
Plenum	(8)				4.94-mm diameter
Length		152.4 ^c	287.4 ^d	939.8	
Vol, cm ³		5.5	4.95	18.52	
Spring	(9)	152.4	24.1	124.5	HEDL-NF Inconel-X750
Cladding	(5)	5.842 OD x 0.381 wall			PNL-17 302-SS
					SS-316 20% cold work
Spacer-wire					
Diameter		1.37	1.02	1.37	SS-316 17% cold work

^aCombined length of both end caps.

^bTube (4.67-mm OD x 3.91-mm ID) with Type 316 stainless steel end plug and 1.57-mm-dia axial hole.

^cSame as spring.

^dNot including spring length.

Fig. 1. Identification of Fuel-pin Parts and Comparison between Pins

Previous irradiation in EBR-II of the central pin, HEDL-NF-056, was at peak power of 38.94 kW/m (11.87 kW/ft) and a sodium inlet temperature of 655 K. LIFE-3 calculations indicated the peak burnup was 4.64 at. %, the influence was 4.1×10^{22} nvt, and fission-gas pressure in the pin plenum was 2.8 MPa. A sibling pin (HEDL-NF-013) having a similar EBR-II irradiation history (37.83 kW/m, burnup 4.68 at. %, fluence 4.14×10^{22} nvt) was destructively examined for microstructure (see Fig. 2).

CV: CENTRAL VOID	E: EQUIAXED GRAIN REGION
C : COLUMNAR GRAIN REGION	U: UNRESTRUCTURED REGION

Fig. 2. Metallographic Cross Section of HEDL-NF-013 Sibling Pin. ANL Neg. No. 900-4005.

Measurements of the grain structure from samples taken from the top and bottom pellets of the HEDL-NF-013 pin are compared to the LIFE-3 predictions of the different grain regions in Table II. Comparisons of measured grain structure to those given in Ref. 15 for BOL (pp. 5-28), BOC-4 (pp. 5-8), and EOC-4 (pp. 5-21) identify this pin as being equivalent to the first pin to fail (channel 3) in BOC-4 of FTR.

TABLE II. Measured and Calculated Grain-structure Regions in Sibling Pin

Axial Position	Outer Radius, mm					
	Void		Columnar		Equiaxed	
	Sibling	LIFE-3	Sibling	LIFE-3	Sibling	LIFE-3
Ends	None	0.27		0.30		1.96
6.3 mm from ends	0.46	0.55	1.4	1.72	1.95	2.13
Central 250 mm	0.58	0.60	1.6	1.83	2.06	2.19

The retained fission-gas distribution in HEDL-NF-056 was estimated (see Fig. 3) from comparisons between measurements and calculations for a similar preirradiated PNL-17 pin.¹⁷ Results of the LIFE-3 calculations are also shown in Fig. 3 for ratio of height to fuel-column length (Z/L) of 0.6. Analysis of fission gas in the plenum of the sibling pin gave 11% krypton isotopes, 75.5% xenon isotopes, 13.1% helium, and 0.2% other gases. LIFE-3 assumes 89.2% xenon and 10.8% krypton. After the xenon tag gas was subtracted, the total volume of fission gas was 34.03 cm³ and the average release was 56.2% of the fission gas generated. LIFE-3 calculations predict 56-cm³ production and 81% release. Fission-gas concentration, together with the temperature and temperature gradients in the unrestructured grains, are the determining factors for fuel swelling, cladding loading, and the failure threshold in the preirradiated pin. This is discussed further in Sec. VII.

Fig. 3

Estimated Fission-gas Distribution in Central Pin from Sibling-pin Measurements and from LIFE-3 Calculations for $0.5 \leq Z/L \leq 0.7$

III. EXPERIMENTAL HARDWARE

Fuel is pinned to a fluted holder, the holder is attached to an instrument section, the instrument section is attached to a bayonet piece, the bayonet piece is attached to a closure flange, and the entire assembly is called the test train. The loop is filled with sodium, the test train is inserted into the loop, the closure flange secures the test train to the loop, the loop is installed in the TREAT reactor, and the experiment is performed. Various details of the pieces and their assembly are shown in the sketches of Figs. 4-6, and are discussed below. After the test, the filter material was stripped from the loop and the loop was neutron radiographed. With the radiographs as a guide, the loop was sawed into pieces at HFEF, and shipped to MSD at ANL-East for further cutting and examination. These results are reported in Sec. V.C and Appendix A. Fuel motion was monitored by the hodoscope and is reported in Sec. V.B and Appendix B. The TREAT reactor,¹⁸ the hodoscope,¹⁹⁻²¹ and the Mark-II loop^{22,23} are described in the literature.

A. Fuel Holder

A fluted tube, as shown in Fig. 4, provided a prototypic hydraulic environment for the seven test pins, and the insulating gas provided nearly adiabatic wall conditions similar to those existing for an interior group of seven pins in a 217-pin FTR cluster. A mixture of helium, at a pressure of ~1.0 kPa, in argon at a pressure of 0.1 MPa, was used as the insulating gas. The helium served as a convenient vehicle for leak-testing the holder with a helium leak detector. Fuel-holder features of special note include the following:

1. At the time of fuel-pin failure and fluted-tube meltthrough, the insulating gas mixed with the sodium flow stream, and the cross-sectional area could have increased by a factor of 2.
2. Locking pins that secured the fuel elements to the holder at the bottom provided axial constraint only. The upper end of the longer central pin was radially constrained by a support tube, partially visible in Fig. 5, Part A.
3. Downward forces exerted by belville washers at the closure flange (Fig. 5, Part F) seated the inlet of the flow channel into the shoulder of the loop (Fig. 5 at Ref.)
4. Bowing, bulging, or bending of the fuel cluster as observed by the hodoscope before failure was constrained by the spacer wires to about 1.5 mm toward the pump in the midregion ($Z/L = 0.57^*$) and away from the pump at the ends of the fuel column ($Z/L = 0.13$ and 1.01 ; see Fig. 6). Such motion was suggested in the hodographs from 9.05 to 9.11 s.

*A reference length L is defined as the length of the fuel column, 342.9 mm.

Fig. 4. Cross-sectional View of Loop and Test Train about 70 mm above Bottom of Fuel Pins. Dimensions are in millimeters. View is looking down from the top.

Fig. 5

Assembly and Part Identification for E6 Test Loop. A. Upper sleeve to support central pin; B. Tops of PNL-17 fresh pins; C. Outlet pressure port; D. Overflow to return surplus sodium to dump tank; E. Outlet flow return to pump; F. Top closure flange to attach test train to loop; G. Flowtube extension to attach fuel holder to bayonet assembly; H. Bayonet assembly; I. Top of Central HEDL-NF-056 preirradiated pin; J. Location of Outlet flow detector; K. Location of inlet flow detector; L. ALIP; M. Locking pin to hold fuel elements in place; N. Adiabatic fuel holder; O. Inlet pressure-transducer port; P. Rupture disk to dump loop sodium to dump tank. Ref. Bottom of fuel pins used as "O" reference in Fig. 6.

Fig. 6. Schematic Diagram of Axial Flow-channel Geometry and Loop Outfitting. Linear dimensions are in millimeters relative to the bottoms of the test pins. Flow areas are in cm^2 . Orientation of the spacer wires (viewed from the top, looking down) is shown to the right of the figure. Here the hodoscope is downward and the pump is to the right (Fig. 4 rotated 90°).

5. A 0.15-mm-thick bellows in the outer wall (see Fig. 6) relieved axial differential thermal expansion to prevent buckling of the holder wall.

6. Geometry of the flow channels is constant over the length of the shorter-edge pins ($Z/L = 2.1$).

B. Instrument Section

As illustrated in Fig. 5, the top of the fuel holder was attached to a 31.75-mm-OD, 1.57-mm-wall Type 304 stainless steel tube with cutouts to allow coolant flow to enter the return tee (part G) and to allow pressure measurements by a transducer mounted on the loop wall (part C). A 273-mm-long Type 304 stainless steel sleeve (9.5-mm OD, 1.4-mm wall), held in position by two spiders, kept the top of the long central pin centered in the loop (part A, Fig. 5).

C. Bayonet and Baffles

The bayonet piece is essentially a 616-mm-long rigid Type 304 stainless steel bar that joins the instrument section to the closure flange. Four equally spaced baffles are located at $Z/L = 3.3, 3.5, 3.8$, and 4.0 to decelerate a potentially high-velocity sodium slug. Each baffle is 31 mm in diameter and covers 72% of the cross-sectional flow area. They incoherently distribute the ejected slug impulse to the closure flange.

D. Loop Outfitting and Instrumentation

Several aspects of the loop outfitting are illustrated in Figs. 4 and 6. Filter material consisted of a 50 wt % mixture of B_6Si powder and Pyromark high-temperature paint. This mixture was painted onto a 1.016-mm-thick 16-mesh stainless steel screen tack-welded to the loop. After air drying, additional layers, as shown in Fig. 6, were located at the ends of the test fuel columns to prevent power peaking.

Electrical clamshell heaters were used to bring the loop to the initial temperature of 670 K. During the test, the heaters were turned off. A fibrous insulating material surrounded the heaters.

Electromagnetic flow detectors and unbonded strain-bridge-type pressure transducers were mounted on the loop body, as illustrated in Fig. 5. A capillary tube connected the ports on the loop to the strain-bridge elements. NaK was used in the capillary tube and was separated from the loop sodium by a bellows-mounted diaphragm inside the attaching flange. Every effort was made to locate the strain-bridge element outside of the high-temperature and high-radiation field. Despite these precautions, such elements had an undesirably high sensitivity to temperature and radiation.

Sealed Chromel-Alumel thermocouples, grounded at their junctions, were located in the sodium flow stream as indicated in Fig. 6. Note that TC7

was located about 140 mm above the free surface of sodium and was used to monitor the motion of the ejected coolant slug at the time of failure. Characteristic response times for all the thermocouples were 25-35 ms.

E. Monitor Wires

Two monitor wires were used in this experiment to verify the fuel-pin calibration constants and to normalize the results of this test to others in the E and H series. Both were located at the axial centerline of the fuel column; one was between the fuel-holder walls, and the other was external to the loop between the overflow pipe and the pump. Due to schedule delays, the internal monitor wire has not been reclaimed and a direct verification of the calibration factors has not been made. The external monitor wire was removed and radiochemically analyzed for fissions within 11 days of the test. Results of this analysis corrected to the test time, gave 6.45×10^{10} fissions per gram of wire per megajoule in the transient. The wire consisted of 3.6% uranium, enriched in ^{235}U to 93.118 wt %, and 96.4 wt % zirconium. A similarly shaped 810-MW-s transient in the H3 calibration measurements gave 3.32×10^{10} fissions/g·MJ, and the 1395-MW-s transient of Test E7 gave 2.76×10^{10} fissions/g·MJ. Differences between what are believed to be nominally identical conditions remain unexplained.

IV. EXPERIMENT CALIBRATION

Flowmeters and pressure transducers were calibrated by static measurements with an orifice and with a dummy fuel bundle in the fuel holder. Pressure transducers were independently calibrated by pressurizing the plenum of the loop and recording the strain-gauge signals for both increases and decreases in pressure and as a function of sodium temperature. Results of these measurements are listed in Table III. Quoted errors are estimates from the spread in data for increases and decreases in pressure and in temperature.

TABLE III. Instrument Calibration Factors for Test E6

	Sensitivity	Range
Flow		
Inlet	$635 \pm 50 \text{ (cm}^3\text{/s)/mV}$	0 to $\pm 15 \text{ mV}$
Outlet ^a	$2082 \pm 400 \text{ (cm}^3\text{/s)/mV}$	0 to $\pm 9 \text{ mV}$
Pressure		
Inlet	$6.6 \pm 0.5 \mu\text{V/psi}^b$	0 to 2020 psi
Outlet	$5.55 \pm 1 \mu\text{V/psi}$	0 to 2553 psi
Hodoscope		
Resolution	1.2 ms	
Framing rate	4000 frames/s	
Film type	2485	
Filter	28.6-mm lead	
Calibration Source	10 counts/s	

^aOutlet-to-inlet signal ratios just before the test varied from 0.27 at low flow rates to 0.33 at high rates; an average value of 0.3 was used. During the preheat period of the test, this ratio varied from 0.33 to 0.39. Just before failure, the ratio was 0.349, the value used in determining the voiding rate during failure.

^b1 psi = 6.895 kPa.

A. Flow-detector Calibration

Flowmeter calibrations are sensitive to the nature of the flow (turbulent or laminar), containments (principally oxides), entrained gases in the sodium, and the sodium and loop-wall temperatures at the point of measurement. Flow through an orifice can be precisely determined only for the downstream pressure measurement at the vena contracta. Downstream pressure losses in the fuel holder are difficult to determine, and orifice measurements have relatively large interpretation errors. This accounts for the large spread in reported calibration factors for what are nominally identical configurations. For tests performed in Mark-II loops, the following calibration factors have been reported for the inlet detector: H2 and E4, $630 \text{ cm}^3/\text{s}\cdot\text{mV}$; H4, $566 \text{ cm}^3/\text{s}\cdot\text{mV}$; H5, $580 \text{ cm}^3/\text{s}\cdot\text{mV}$; H3, $540 \text{ cm}^3/\text{s}\cdot\text{mV}$; E7, $538 \text{ cm}^3/\text{s}\cdot\text{mV}$; and L2, $660 \text{ cm}^3/\text{s}\cdot\text{mV}$.

In all cases, the outlet flow detector was calibrated relative to the inlet just before the test was performed. Standard calibration tables were used for the thermocouples. A reference junction temperature of 338.6 K was used.

B. Fuel-pin Power

Measurements of the power generated in the fuel pins relative to the TREAT power have undergone a long and varied history. Neutron-transport calculations²⁴ and test-fuel measurements²⁵ have been reported in detail. Results of these studies are generally applicable to Tests H3, H4, H5, E6, and E7 with only minor adjustments needed for fuel burnup, plutonium content, and TREAT core size. For calculational purposes, each fuel pin is divided into six equal azimuthal sectors, and each sector has a relative power shape assigned to it. This is shown in Fig. 7 for one-third of the seven-pin cluster.

In all the previous tests that used preirradiated fuel pins, the adjustments for burnup and fuel restructuring used PROMOD results as calculated by HEDL. In these calculations, a rather sharp drop in power (~10%) occurred at the columnar-equiaxed grain interface. In the present report, the radial and axial power shapes determined from fresh-fuel measurement are adjusted by the change in fuel density as calculated by the LIFE-3 code to account for burnup and restructuring in the central pin. In the absence of power-shape measurements for the irradiated pins, these calculations are believed to be more realistic and accurate.

Radial power shapes for fresh pins are shown in the left curve of Fig. 8, and calculated density distributions for the central pin are given in the right curves. Of the three shapes shown for the edge pins, the type-II distributions are used in pin sectors that face two other pins, type-III distributions are for sectors facing a single pin, and type-IV distributions face the holder walls. These are shown in the table in Fig. 7. The fraction of the total pin power for each sector and the pin calibration factors are listed in Fig. 7.

Pin	Calibration Factor	Radial Power Shapes		
		Sector	Type	Fraction
1	1.74	1, 2	I	0.1667
2	1.84	5	II	0.1111
		4	III	0.1742
		3	IV	0.1844
3	2.01	7, 8	IV	0.1844
		6, 9	III	0.1742
		10, 11	II	0.1111
4	2.18	12	II	0.1111
		13	III	0.1742
		14	IV	0.1844

Fig. 7. Pin, Sector, and Channel Identification for Test E8.
Pin ID numbers are shown in Fig. 4.

Transport of fission and fabrication gases in the axial direction during the EBR-II irradiation of the central pin led to a nonuniform axial density distribution. The use of this distribution to weight the measured fresh-pin axial power shape yields the appropriate axial distribution for the central pin. Results for both the edge and central pins are shown in curves of Fig. 9.

Some recent measurements have been made in support of Test E8 in which concentric shells were cut from selected fuel pellets and counted. Flux peaking near the surface of the pins was more pronounced in these measurements. About 70% of the total power generated was in the outer 1 mm of the pin. In the older data of Fig. 8, only 60% of the power was in the outer 1-mm-thick shell. Differences between the data of Fig. 8 and the E8 measurements are probably due to the use of cadmium as the filter material and a longer test vehicle (Mark-II C loop) used in the later measurements. Nevertheless, the E8 measurements confirm the general shape and the magnitude of the edge peaking in the older but less certain results.

Fig. 8. Radial Power Shapes for Fuel Pins and Density Distribution after EBR-II Preirradiation of Central Pin. Left curves apply to sectors (identified in Fig. 7) for edge pins, and top right curve is for central pin. Fuel-density distributions (lower right) are given for three different axial elevations.

Fig. 9

Axial Power Shape for Edge (Top Curve) and Axial Fuel-density Function (Lower Curve) Used as a Weighting Function for Axial Power Shape in Central Pin

V. TEST DATA

Test results from the experiment became available in three stages; the analog data recorded on magnetic tape at the time of the test; the posttest loop cutting and metallurgical examinations; and fuel motion during the test from an analysis of the hodoscope films. Data obtained during these stages are reported in the following sections.

A. Loop Data

Inlet and outlet flow, pressure, and temperature were recorded at locations indicated in Fig. 6. Summary views of the recorded data are shown in Figs. 10-14. Dynamic responses of the various sensors during the failure sequence are shown in more detail in Figs. 15-17. Flow and pressure data (see Figs. 10, 15, and 16) show that the initial failure occurred at 9.15 s, caused coolant to be ejected from both ends of the flow channel, and produced relatively small pressure pulses (<0.5 MPa). Thermocouple TC1 at the inlet (see Fig. 11) failed at or before 9.32 s by meltthrough of the sheath between the fuel-holder walls near the top of the fuel column. Failure of TC1 by this mechanism is clear from the posttest examination. For the thermocouple to fail at 9.32 s, hot fuel must have been deposited on the holder wall to cause meltthrough at an earlier time. Based on the dynamics of the outlet-flow slug, holder-wall failure is estimated to have occurred at 9.25 s. This is consistent with the hodoscope observation that the direction of fuel motion changed at 9.25 s.

Fig. 10. Inlet (Lower) and Outlet (Upper) Flow Data for Test E6 (0-25 s).
Flow signals normalized to $697 \text{ cm}^3/\text{s}$ from 1 to 5 s.

Fig. 11. Inlet (TC1) and Upper-plenum (TC6) Coolant Temperatures (0-20 s). TC 1 failed at or before 9.32 s.

Fig. 12. Temperature Signals at Inlet (TC2) and Outlet (TC3) Showing "Cross Talk"

Fig. 13. Coolant Temperatures at Outlet (TC4), Pump Return (TC5), and Gas above Top Sodium Surface (TC7) (0-20 s)

Fig. 14. Power (SAFI) and Energy (INTI) Histories for Test E6

Fig. 15

Details of Outlet (Upper Curve) and Inlet (Lower Curve) Flow Data and Reactor Power during Failure Periods. For clarity, flows have been displaced by $\pm 200 \text{ cm}^3/\text{s}$, respectively.

Fig. 16

Inlet and Outlet Pressure Data and Reactor Power during Failure Sequence

Fig. 17

Coolant Temperatures at Pump Return (TC5), In Upper Sodium Head (TC6), and Gas Temperature between Top Sodium Surface and First Baffle (TC7) during Failure Sequence (8 to 10 s)

Thermocouple TC2 (at the inlet) and TC3 (at the outlet) (see Fig. 12) had similar responses that were more characteristic of what was expected at the outlet temperature (TC4 in Fig. 13) but in no way representative of the expected or measured inlet temperature from TC1 (see Fig. 11). A statistical analysis of the data in Fig. 12 from 7 to 8.5 s showed a very high cross-correlation between TC2 and TC3 at lag times of about 100 ms. In the range of 0-7 Hz, the transfer function was unity. In this same frequency range, the coherence-squared varied from 0.98 to 0.81, indicating substantial cross-coupling, but not in the hard-wired sense. Since the origin of the cross-coupling cannot be identified, data from TC2 and TC3 were discarded as erroneous.

At 9.25 s, a substantial slug of hot sodium impacted on the first baffle (see TC7 response in Fig. 17). By 10 s, the slug had returned to the fueled region.

TREAT power and energy curves are shown in Fig. 14. The preheat irradiation was at 167 MW for the ~3-s interval from 5.65 to 8.6 s, and the power ramp had a period of 183 ms with a peak power of 2250 MW at 9.125 s. TREAT energy at the end of the preheat was 558 MJ and at the end of the transient at 9.5 s was 1281 MJ.

Pressure transducers in all previous loop tests have shown an unpredictable dependence on the TREAT power and energy in both the sign and the magnitude of their output signals. The curves in Fig 16 illustrate the superposition of transient pressure pulses on this response. The train of pulses at the outlet (lower curve) from 9.16 to 9.22 s is believed to be the strain-gauge response to a single pressure-producing event. Pulses at the inlet (see top curve of Fig. 16) probably correspond to three events at 9.16, 9.18, and 9.23 s. If this interpretation of the pressure data is correct, the events at 9.18 and 9.23 s occurred near the top of the flow channel, and were effectively isolated from the lower sodium slug and pressure transducer by a vapor layer.

The small "blips" in the flow signals and power trace at 9.32 s (see Figs. 15 and 16) are probably a system noise pulse, although this corresponds to the time of failure of TC1.

Note that the sharp increase in heating rate of all thermocouples above the fuel holder (see Fig. 17) occurred almost simultaneously with initial failure, indicating effective mixing in the upper plenum region. One final observation relative to the outlet flow rate in Fig. 10 after 12.5 s is that the large negative value probably does not represent true flow. After 25 s, the outlet flow increased in an exponential manner from $-1000 \text{ cm}^3/\text{s}$ to zero at about 50 s. An hour after the test, flow could not be reestablished, indicating complete channel blockage.

B. Hodoscope Data

About one-fourth of the 266 active hodoscope channels were focused directly on the test fuel. Counting rates in these channels are identified as R. Most of the remaining channels responded to fast neutrons from the TREAT core and provided an independent measure of the reactor power. Counting rates in these channels are identified as P. Figure 18 shows the relationship between Test E6 and individual hodoscope channels.

Fig. 18. Relationship between Hodoscope Channels (by Rows and Columns) and Test Geometry. Displacements, in millimeters, are relative to cluster center. Channels marked X were inoperative.

Hodoscope data are presented in the form of count rates per unit reactor power, R/P, as a function of time. Differences between R/P ratios for each channel at different times represent the actual amount of fuel motion during the interval. These differences can be displayed in diagrams called "differential hodographs." Details of the E6 fuel motion are given in terms of hodographs in Appendix B. Axial and horizontal fuel motion based on R/P data is summarized in this section.

In Test E6, the test fuel was high in the hodoscope field of view, making upward fuel motion difficult to detect. However, a comparison between the total counts in the power-monitor channels to those in test-fuel channels indicated that less than 30 g of test fuel moved out of the hodoscope field of view during the experiment. Accumulated differences between gains and losses in the fuel-monitoring channels indicated the actual loss was between 8 and 13 g, consistent with the observations in the posttest examinations and the loop radiograph.

A generalized picture of the axial fuel motion is most readily seen from sums of the R/P ratios over the columns that view fuel (columns 5-13) for each row. An equivalent picture of horizontal fuel motion can be seen from sums over rows for each column. These are shown in Figs. 19 and 20, respectively. Prefailure movement is noted from Fig. 19 as ~5-g losses in

Fig. 19. Axial Fuel Motion. R/P ratios are summed over columns 5-13 for each row.

Fig. 20. Horizontal Fuel Motion. R/P ratios are summed over rows 2-18 for each column.

rows 9-13 (the upper midregion of the fuel cluster) with equivalent gains at the top (rows 2 and 3). This motion began 100 to 150 ms before failure. Horizontal prefailure motion (see Fig. 20) appeared to be away from the center of the cluster (columns 8 and 9), with small apparent gains in the region opposite the pump (columns 11 and 12). Although some of this prefailure motion is undoubtedly a bowing of the cluster as a whole, losses at the center suggest some upward fuel flow to the top insulator region within the fuel pin.

Postfailure fuel flow is clearly from the central region (rows 7-11, Fig. 19) to the top (rows 2-5) and toward the pump (gains in columns 6 and 7, Fig. 20; losses from columns 9-11). Although the statistics of the hodoscope data become increasingly poor after 9.3 s, there is substantial indication of a second type of fuel motion that began about 100 ms after failure. Columns 6 and 12 show the most definitive changes at about 9.25 s. Since these channels view the adiabatic region of the fuel holder (see Fig. 18), the change in fuel motion must be associated with holder-wall rupture. The most significant conclusion from the hodoscope data is that 5-10 g of fuel moved from several central rows toward the top of the cluster during the test.

C. Posttest Metallography

After the test, the B₆Si filter mater. 1 was stripped from the loop, thermal-neutron transmission radiographs were made, and the loop was sawed into pieces without removing the sodium and sent to MSD at ANL/East for further examination. Examination of the posttest radiographs, shown in Fig. 21, shows a relatively small failure region starting 63 mm down from the top of the fuel column and extending downward about 50 mm. Most of the fuel and steel debris that left the flow channel appears scattered through a 250-mm region above the fuel column, with little evidence of material below the rupture site.

Gamma scans were made of the fuel holder before it was further cut up for detailed examination. Preirradiated fuel was found to be relatively uniformly distributed over the length of the original fuel column with a gradual decrease up to the tops of the fuel pins ($Z/L = 2$). Gamma scans of the bellows after they were removed and cut in half longitudinally indicated that most of the fuel deposited on the convolutions of the bellows was fresh fuel.

Remains of the test fuel were characterized by extensive cladding melting; widespread failure at $Z/L = 0.66$ to 0.81 ; a number of free-standing fuel pellets, some of which were fused together at their ends; a major deposit, largely of preirradiated fuel, at $Z/L = 1.3$ to 1.5 ; and the complete absence of any inlet blockage or any significant quantity of fuel/steel debris in the lower region. A major rupture of the fluted tube occurred at $Z/L = 0.65$ to 0.8 on the side away from the pump. This was the location at which TC1 was melted through. Cladding melting was observed as low as $Z/L = 0.15$ on the edge pins and $Z/L = 0.4$ on the central pin; was predominant on the side of the cluster away from the pump; and did not extend beyond $Z/L = 1$, except for occasional burnthroughs due to deposits of hot particulate on the outside cladding surface.

Fuel melting was extensive in both the edge pins and the central pin. Irradiated fuel appears to be more mobile than fresh fuel in the sense that most of the fuel in the upper half of the central pin had been displaced by insulator pellets that fell down from above. Motion of fresh fuel was not extensive, although there was evidence of flow within the once-molten central cavity. Resolidified irradiated fuel was spongy or frothy in structure; fresh fuel exhibited extensive grain growth, and had numerous bubbles throughout with a tendency to be larger toward the outside of the cluster.

At the time the hodoscope indicated prefailure fuel movement, the hotter edge pins were 70-80% molten. We speculate that the combination of increase in specific volume on fuel melting and the transport of fission gases provided the forces to push the molten core of the pins in an upward direction. Thermal-hydraulic calculations indicate that the melt fraction never gets much over 85%, so what was observed in the posttest examination was probably not much different than what existed during the prefailure period.

Although significant amounts of fuel and cladding were deposited on the holder walls in the rupture region, steel tended to concentrate on the pump side of the cluster and fuel on the opposite side. Some penetration of steel into startup cracks and trapping within the fuel porosity were observed at $Z/L = 0.95$. Had the fuel melted at this location, the vaporized steel could have dispersed the fuel. There was some evidence of trapped steel (or condensed steel vapor) in bubbles farther down where the fuel did melt.

Relative to other TOP tests in the E-series, E6 had more extensive cladding melting and less damage to the lower half of the fuel pins. There was no inlet blockage, and the principal outlet blockage extended from $Z/L = 0.8$ to 1.05 . Preirradiated fuel was observed throughout the blockage, suggesting that the central pin failed first or at the same time as the failure of one or more of the edge pins. In the blockage above $Z/L = 1.05$, melted fuel and steel were also present. Although they offered resistance to the flow of sodium, nowhere did they appear to have seriously plugged the flow channel. There was some tendency for steel to mix with molten fuel and for molten steel to move ahead of the melted fuel, either radially or upward.

VI. THERMAL-HYDRAULIC CALCULATIONS

One purpose of this and other Mark-II loop experiments is to provide a data base against which the large accident-analysis codes can be tested. However, the SAS3A¹³ and MELT-III¹⁴ codes assume identical characteristics for large numbers of pins within a particular fuel bundle. This is certainly not the case for TREAT experiments. They are better described by detailed multipin thermal-hydraulic codes such as COBRA-III.²⁶ Important aspects of the whole-core analysis codes involve the postfailure coolant dynamics and the fuel and cladding relocation models. Neither is modeled by COBRA. For the small clusters used in TREAT experiments, COBRA-III does provide realistic temperature histories in space and time up to the initial failure.

A version of COBRA-III²⁷ has evolved over the years within the ANL Fuel Dynamics Section which allows:

1. A varying fuel density and power as a function of radius.
2. A varying heat transfer from the duct wall to the bypass for each axial node.
3. A residual gap between fuel and cladding due to surface irregularities.
4. An axially dependent switch, which can turn off heat transfer between pin and coolant at each axial node.
5. Two different types of fuel pins within a single bundle; each has its own radial fuel density and power shape.
6. Various subsidiary results, such as average coolant outlet temperature, fuel enthalpy at each axial node, and thermal energy balance for each time step, as well as the facility to change the computational and output time steps at a predetermined point in the transient.

Boundary conditions on the flow channel require specification of the inlet enthalpy, inlet mass flow velocity, and exit pressure. Thus, flow reversal cannot be calculated, and the results obtained from COBRA-III are plausible up to the time of coolant boiling or loss of intact geometry. Details of these calculations are given in Appendix C. The geometry used in the COBRA calculations is illustrated in Fig. 7.

Results of the calculated coolant outlet temperature have been compared to the measured values as a means of verifying the adequacy of the computations. Calculated fuel temperatures at the end of the preheat period have been compared to the BOC-4 steady-state calculations for channel 3 as a measure of the representative nature of Test E6 to the FTR. Finally, the results at the time of failure are presented here as support to the interpretation of the experiment as given in the next section.

Due to the asymmetries in the azimuthal power shapes, as shown in Fig. 8, and difference in cross-sectional area in flow channels, temperature

Fig. 22. Comparison of Measured and Calculated Outlet Temperatures up to Time of Pin Failure. Channel 7 was hottest and channel 1 the coldest calculated (see Fig. 7 for channel identification). Area-weighted average of all channels, MEAN, is within 15 K of measured outlet temperature from TC4 (see Fig. 13).

differences as large as 60 K are calculated between the hottest and coldest flow channels at any given axial elevation. In the present eight-channel calculation, channel 1 was the coldest, channel 7 the hottest, and channel 2 closest to a mean temperature based on flow-area-weighted averages over all channels. Results for channels 1 and 7 and the mean are compared to the measured outlet temperature (obtained from TC4) in Fig. 22. At times less than 8 s, the differences between the calculated and measured outlet temperature was less than 3 K, well within the measurement uncertainty. After 8 s, the largest difference was 15 K. Although this difference could probably be reduced by decreasing the heat transfer to the bypass, this was not done, since the measurements were comfortably within the range of the calculations for the hottest and

coldest channels. From this comparison, it is concluded that COBRA does provide an excellent prediction of the measured temperatures in Test E6.

In both the TOP¹⁵ and the LOF²⁸ accident analysis for the FTR, steady-state temperatures for channel-3 fuel at BOC-4 were identical. MELT-III results (see Fig. B-5 of Ref. 15) are difficult to read from the figure, so computer output from SAS for the LOF analysis²⁹ was used instead. Steady-state axial temperature profiles for the coolant in channel 7 (the hottest) and channel 2 (the most representative of the mean outlet) as calculated by COBRA are compared to the SAS3A results in Fig. 23. Although channel-2 results produced the best agreement with the measurements during transient heating, channel 7 produces the best agreement with SAS calculations during steady-state conditions.

Radial temperature profiles in the fuel at the hottest axial node at the end of the preheat are compared to MELT-III/SAS calculations in Fig. 24. Since the hottest COBRA flow channel (channel 7) gave the best agreement with MELT-III/SAS3A, it was not surprising that the hottest COBRA pin sector would produce equally good agreement for fuel-pin temperatures.

From Figs. 22-24, it is concluded that flow channels and pin sectors can be selected from the COBRA calculations that agree quite well with both

the measurements and the SAS calculations. Accordingly, COBRA calculations at the failure time are expected to be at least as good as the SAS and MELT-III calculations.

Fig. 23

Comparison of Axial Coolant-temperature Increase from Steady-state MELT-III/SAS Calculation and COBRA Results at End of Preheat

Fig. 24

Comparison of Radial Temperature Distribution Calculated by MELT-III/SAS during Steady State and COBRA Results for Central Pin into Hottest Channel in Test E6. Slight differences calculated for the size of the central void are indicated.

Fuel and coolant temperatures at the time of failure are shown in Fig. 25. Radial fuel-temperature profiles for several different axial nodes

Fig. 25. Fuel, Cladding and Coolant-temperature Distributions as Calculated by COBRA at Time of Failure. Melt fractions are shown for selected elevations in the top curves. Measured coolant temperature at the locations of TC4, TC5, and TC6 are indicated on the lower curves.

are shown at the top of the figure. The axial coolant, fuel-, surface, and cladding-midpoint temperatures are shown in the lower curves. Of particular interest in these curves are the following:

1. The fuel solidus front has just reached the equiaxed-unrestructured grain interface.
2. Melt fractions and radial temperature profiles are surprisingly uniform from near the bottom to the top of the pin ($Z/L = 0.3$ to 0.7).
3. The peak coolant temperature has just reached the saturation temperature at $Z/L = 1$.
4. The fuel-surface temperatures peak (1740 K) at $Z/L = 0.8$, the region where initial failure was believed to have occurred.
5. Temperature gradients in the unrestructured fuel are ~ 6000 K/cm.

A decrease in coolant temperature above the top of the fuel column is due to heat-energy loss to the upper pin structure. Agreement between measured and calculated coolant temperature is excellent, especially for TC5 and TC6, which are located in the upper coolant plenum region. COBRA recognizes only the flow-channel geometry and cannot treat mixing in the plenum region. The calculated melt fraction near the bottom of the pin (45% at $Z/L = 0.06$) is slightly less than estimated from the posttest examination (60%), indicating slight additional melting after initial failure. Although the code results after failure are questionable, they do predict a maximum of 65% melting in this region.

Melting profiles for the various pins are shown in Figs. 26 and 27. Figure 26 shows the axial extent of melting at successive 50-ms time steps for

Fig. 26

Axial Extent of Melting for Selected Pin Sectors as Times Approach Failure Time (see Fig. 7). Melting progresses from the pin centerline outward, so complete melting of columnar grains corresponds to $MF = 0.46$, and of columnar + equiaxed grains to $MF = 0.74$. These regions are indicated in the lower curve for sector 1.

Fig. 27. Melt Fraction for Each Pin Sector at $Z/L = 0.7$ as Failure Is Approached. See Fig. 7 for sector identification.

the hottest fuel pin (Rod 4), an average pin (Rod 3), and the preirradiated central pin (Rod 1). Figure 27 illustrates the propagation of the melt front as failure is approached. Except for the coldest sector (sector 5 on the inside of pin 2 next to the pump; see Fig. 7), the fresh pins are ~80% above the solidus temperature at the time of failure. In the only other E-series test using fresh fuel (E4), failure did not occur until 50 ms after 100% melting had been reached. Thus, it is not likely that any of the fresh pins were the first to fail.

When the hodoscope first observed fuel motion (9.05-9.08 s), about 60% of the fuel in the edge pins was molten. The 10% increase in specific volume associated with the change in state could push fuel upward into the pin-plenum region to account for the observed loss of fuel in the midregion of the cluster.

VII. DATA ANALYSIS

In this section we examine some of the test data in more detail and tie the various pieces of experimental information together into a self-consistent failure scenario that has a meaningful relationship to the FTR.

A. Loop Data

Dynamics of the inlet and outlet flow slugs depend on the relative volumes, temperatures, and pressures of the fission gas and the fuel released from the pin, as well as the quality of the coolant flow at the time of failure. Figures 10, 15, and 28-30 show different features of the flow signals. In Fig. 10, it is doubtful that outlet flow data beyond about 11.25 s represents true flow. A reverse flow of $1000 \text{ cm}^3/\text{s}$ from 15 to 25 s is not real and probably reflects the flow-detector response to the passage of argon gas from the ruptured holder. After 23 s, the outlet flow exponentially returns to zero by about 65 s. Similarly, the inlet flow slowly drops from its indicated value of $125 \text{ cm}^3/\text{s}$ at 13 s to zero at 65 s. This suggests that early stages of the blockage formed between 15 and 25 s and development of its final configuration took an additional 40 s.

Chugging at the inlet at a nearly constant period (193 ms) is clearly seen in Fig. 28. One sequence of events that explains this behavior is as follows: Coolant, entering the mixing zone under constant pressure from the pump, was vaporized, and oscillated between this volume and the loop plenum volume. Oscillations of the outlet slug are heavily damped by the hydraulics at the tee to the pump return. Average flow after 9.5 s varies from 100 to $150 \text{ cm}^3/\text{s}$. This is probably not grossly erroneous since the posttest examinations suggested that the region at and below the inlet was probably never voided.

Fig. 28. Details of Inlet Flow Showing Initial Slug Ejection (at 9.15 s) Leading to Reverse Flow, Followed by Chugging (9.4-13 s)

Fig. 29. Details of Inlet Flow during Approach to and Time after Failure

Fig. 30. Composite of Inlet and Outlet Flow during Initial Failure Sequence

It is thus concluded that liquid sodium was vaporized in the mixing zone at a rate of $\sim 125 \text{ cm}^3/\text{s}$ ($\sim 0.87 \text{ g/s}$). If so, the cooling rate of the hot debris would be on the order of 3500 J/s in supplying the heat of vaporization.

In the more detailed view of the inlet flow (Fig. 30), two, and possibly three, incoherent events are distinguishable after the initial failure: an apparent fuel release at 9.18 s of comparable magnitude to the initial ejection, and events at 9.23 and 9.24 s. Flow recovery after 9.25 s is most probably due to

holder-wall rupture and the inrush of 37 cm^3 of sodium to fill the previously voided space. A total of 155 cm^3 is required to completely fill the gas space between the holder walls.

After 25 s, small pieces of blockage material are believed to have broken off, redistributed in downstream portions of the blockage and, by 55 s, completely blocked the through flow. On disassembly, the small powdery pieces possibly fell out to leave the observed channels in the upper blockage.

Outlet flow signals, shown in Fig. 30, show a corresponding response to events at 9.15, 9.18, 9.23, and 9.24 s. Coolant ejections, however, are markedly more sluggish than observed at the inlet, indicating the presence of two-phase compressible flow between the mixing zone and the outlet flow detector. Pressure pulses shown in Fig. 16 confirm this sequence as separate events. Note in Fig. 30 that the initial event starts slightly before 9.15 s and that outlet signals increasingly lag those at the inlet with increasing time.

Collapse of both inlet and outlet flow at 9.25 s is interpreted as the initial failure of the fluted tube by meltthrough. The hot fuel deposited on the thermocouple sheath inside the holder takes an additional 70 ms to melt through. After the fluted-tube rupture, the argon gas between the holder walls mixes with the flow stream to produce a noncondensable two-phase flow in the region of the flow detector. Timing, as indicated in Fig. 10, suggests an initial burst of gas at 11.2 s and a continuous ejection of gas bubbles from 12.5 to 25 s.

If the upper and lower coolant slugs are identified by well-defined interfaces at the mixing zone, the voided region can be determined from the integrated inlet and outlet flows. These interfaces are shown in Fig. 31 over

Fig. 31. Upper and Lower Void-Coolant Interfaces as Determined from Integrals of Outlet and Inlet Flows, Respectively

a time range in which the flow-detector response is least subject to interpretation errors. Differences between the integrated inlet and outlet flows define the total void. During the initial formation of the void, shown in Fig. 32, reasonably well-defined mixing-zone/slug interfaces are believed to exist. Voided volume after holder-wall rupture and injection of argon gas into the flow stream is less certain, and is shown in Fig. 33. Note that in Fig. 31, after failure, the maximum volume decrease in the lower interface is 15 cm^3 (85 cm^3 at 9.21 s to 70 cm^3 at 9.27 s , corresponding to 8 cm of fuel-pin length. To be consistent with an initial failure point at $Z/L = 0.7$ to 0.8 , and cladding melting on the edge pins as low as $Z/L = 0.15$ and on the central pin at $Z/L = 0.4$, the lower interface is pictured as an inverted conic section 20 cm long along the holder wall and 5 cm along the central pin.

Fig. 32. Initial Void Growth as Determined from Differences between Outlet and Inlet Flow Volumes

Fig. 33. Void Volume during and after Pin Failure and Holder-wall Rupture

Initial rates of void growth (see Fig. 32), appear to be in three parts corresponding the three failure events; the first and second develop at $1.5 \text{ cm}^3/\text{ms}$ and the third at 9.22 s at $2 \text{ cm}^3/\text{s}$.

The magnitudes of the flow accelerations during each of the failure events depend on the amount and temperature of the fuel ejected into the coolant stream, the quality of the coolant flow, the amount of fission and pin-plenum gas released, and the size of the cladding rupture. None of these parameters are known. Although the calculations are marginal, it is not believed coolant boiled before failure. Initial coolant boiling would have occurred at $Z/L = 1$, some 5-8 cm above the failure site. An indication of the relative magnitude of each of these events can be seen from a comparison between slug accelerations in a fresh-pin test (E4), an irradiated-pin failure (E7), and the present data. This is done in Figs. 34-36 for 200-ms intervals (starting 50 ms before failure). The outlet flow detector in E4 saturated during the initial slug ejection, and the reversal from 1.98 to 2.00 s is not real. In all cases, the vertical scale is in units of 100 L/s^2 per grid line.

Failure by gas release (E7; see Fig. 36) was characterized by small accelerations ($<10^5 \text{ cm}^3/\text{s}^2$) spread over a time period of several hundred milliseconds and having no strong inlet-outlet correlations. Fresh-fuel failure (E4; see Fig. 34) exhibited outlet-slug accelerations approximately larger by an order of magnitude. Test E6, shown in Fig. 35, seems to be a combination of both types of slug accelerations.

Fig. 34. Flow-slug Accelerations in Test E4 (Single Fresh Pin) at Initial Failure. Saturation of the outlet flow detector led to the apparent reverse acceleration during the 15- to 20-ms period after 1.98 s. Grid marks on the ordinate are in units of $10^5 \text{ cm}^3/\text{s}^2$. Different zeros are chosen for the inlet and outlet slugs.

Fig. 35. Flow-slug Accelerations in Test E6 at Initial Failure.
Grid marks on the ordinate are in units of $10^5 \text{ cm}^3/\text{s}^2$.

Fig. 36. Flow-slug Accelerations in Test E7 (Seven Preirradiated Pins) at Initial Failure. Grid marks on the ordinate are in units of $10^5 \text{ cm}^3/\text{s}^2$.

Flow signals for the three tests are shown in Fig. 37 for the inlet and in Fig. 38 for the outlet. In these figures, both the times of failure and the scale factor for the flow have been shifted to produce the results shown. On the basis of this type of comparison, it is concluded that E6 failed by the simultaneous release of fission gas from the central element and the injection of a

Fig. 38. Relative Outlet Flow Velocities for Tests E4, E6, and E7. Vertical scale is in units of prefailure steady-state flow. Results for E6 and E7 have been moved upward and downward, respectively, by one grid unit.

small quantity of molten fuel into the coolant flow stream. Findings of irradiated fuel near the top of the blockage suggest that at least some of the initial fuel ejection was from the central pin. The presence of insulator pellets in the fuel region during the posttest examinations would suggest that there was sufficient radial gap around the insulator pellets to allow free communication between the pin-plenum volume and the initial cladding rupture site. Accordingly, the inventory of 35-55 cm³ of plenum gas could have leaked out of the pin through the cladding breach. Absence of large changes in the R/P ratios for hodoscope channels that viewed the edge of the cluster suggests that the quantity of fuel ejected was small and most likely swept out of the top of the flow channel beyond the field of view.

Later events, at 9.176 and 9.221 s, were probably successive fresh-pin failures. They occur when the flow channel is partially voided and, hence, have smaller associated slug ejections than characterized by Test E4. Slight increases in R/P ratios for hodoscope columns 12 and 13 (see Fig. 20) and losses from channels 10 and 11 after 9.2 s suggest that the last fuel ejection at 9.221 s resulted in fuel deposited on the holder wall that caused the fluted tube to fail by meltthrough. By 9.25 s, pressures and flow conditions in the mixing zone allowed sodium (liquid and vapor) to fill the adiabatic space in the fuel holder and produce the flow collapse observed at this time (see Fig. 30). By 9.28 s, the void volume leveled off (see Fig. 33); the outlet flow had terminated (see Fig. 29) and the inlet flow began its characteristic chugging (see Fig. 28); lower slug accelerations have been damped (see Fig. 35), the reactor energy has reached 98% of the total (see Fig. 14), and the amount of statistically significant fuel motion is very small (see Figs. 19 and 20).

Although the thermal-hydraulics calculations become decreasingly reliable with increasing time after failure, they are used to illustrate one possible sequence of failure events. Cladding strength is expected to be inversely proportional to the coolant temperature. Cladding loading by fuel swelling and fission-gas pressurization is proportional to the fuel enthalpy. Thus, failure in any given pin sector may be expected to be proportional to the product of fuel and coolant enthalpies. In the E6 calculations, this product has a peak at $Z/L = 0.77$. In E4 and E7 calculations, the product had peak values of 2.12×10^6 at $Z/L = 1$ and of 1.3×10^6 at $Z/L = 0.86$, respectively. Values of this product for the hottest azimuthal pin sector at $Z/L = 0.77$ in Test E6 are shown in Fig. 39 as a function of time into the test. Values at the time of initial failure in Tests E4 and E7 are also shown. Failure times for fresh pins 4, 3, and 2 in Test E6 correspond surprisingly well to the observed failure time of the fresh pin in E4.

If the same agreement existed between the central pin of Test E6 and the hottest pin in Test E7, initial failure of the preirradiated pin might be expected as early as 9.115 s. It is possible in Test E6 to identify a possible earlier or later void formation from the integrated flow than shown in curves of Figs. 32 and 33 by choosing different time intervals for normalization of

Fig. 39. Calculated Product of Fuel and Coolant Enthalpies at $Z/L = 0.77$. At failure, this product was 2.12×10^6 and 1.3×10^6 J/g in Tests E4 and E7, respectively. Times of observed pressure/flow events in Test E6 are also indicated.

the earlier enthalpy history as well. The authors defined a damage parameter that included memory terms for earlier power history as well as the interaction between cladding strain and fuel enthalpy. When properly defined, the damage parameter would assume the same values at the time of failure under all types of circumstances. Fits to the available data suggest a value of 3.8×10^{-3} as the criterion for failure. Subsequent studies at HEDL to predict failure thresholds in low-power pins led to a revised parameter, called the failure potential.³¹

Essential concepts of the damage parameter were not changed. However, the failure potential limits the thermal upset to noncolumnar grains in the fuel, includes effects of fuel density, and is correlated to a larger data base of failure tests. Failure threshold is identified when the failure potential achieves a value of unity. Results of the calculations from COBRA were used to evaluate the failure potential of the central pin in Test E6 for each axial node. These are shown in Fig. 40. According to the criterion, initial failure is predicted at the top of the pin at 9.10 s, some 50 ms before actual failure occurred. During the next 60 ms, the failure site propagates down the length

the outlet flow signal to that at the inlet. Data shown in Fig. 10, for example, were normalized between 0 and 5 s, and show a slight void growth beginning at about 7.5 s. Data shown in Figs. 15 and 30 were normalized between 8 and 9 s. For this normalization, the data show that the major void growth began at 9.15 s. The small residual apparent void starting at about 9.1 s seen in Fig. 32 is believed due to the temperature sensitivity of the outlet flow detector.

It is concluded that one of the hot-test edge pins failed simultaneously with the central pin and that the enthalpy criterion for fresh-pin failure is similar to that observed in the Test E4.

B. Failure Potential

In an early attempt to correlate the time of failure in a number of ANL and HEDL tests, Scott et al.³⁰ reasoned that excessive cladding loading due to fuel swelling and fission-gas release was the cause of pin failure. Cladding loading, in turn, depended not only on the current fuel temperature (and enthalpy), but on

of the pin. Failure at the bottom is predicted at 9.15 s, the experimental failure time. Although the central pin was not damaged below $Z/L = 0.4$, the predicted failure threshold is well within the uncertainty limits set by the authors. This is not surprising since Test E6 was one of many used in establishing the initial correlation. What is important is that different computer codes used by different people using slightly different input parameters give essentially the same result.

Fig. 40
Calculated Failure Potential for Central Pin in
Test E6 Using Enthalpy Calculations from COBRA

VIII. SUMMARY AND CONCLUSION

A cluster of six FTR-type fresh fuel pins surrounding a single previously irradiated pin was tested to failure under simulated \$3/s TOP accident conditions. Comparisons of the pretest grain structure with FTR pins at different core cycles identified the central pin as being prototypic of the first pins to fail at the beginning of cycle four in FFTF. Comparisons of the COBRA calculations at the end of the preheat to both the measured outlet coolant temperatures and the SAS3A/MELT-III fuel-temperature profiles indicated that the 34.3-cm-long test-fuel column was thermodynamically equivalent to the 91.4-cm-long FFTF fuel column.

Failure occurred 550 ms after initiation of the overpower ramp, some 70 ms earlier than predicted in the two-channel MELT-III parametric studies. Some prefailure internal fuel motion was predicted when the molten fuel mixed with the fission gas in the central cavity. This mixing process implied some fuel movement before failure. Analyses of the hodographs and R/P ratios indicated that about half the total fuel that moved during the test (5 g) moved away from the central region of the cluster before cladding failure, but regions of corresponding fuel gains could not be identified.

Comparisons of the inlet and outlet flow-slug velocities and accelerations for other fresh (E4) and irradiated (E7) TOP failure tests suggest that the initial failure was a combination of fission-gas release and fuel squirting into the flow channel. These comparisons, together with the hodoscope analysis, suggest that 10-15 g of fuel was ejected, with perhaps half of this amount being swept upward (and out of the hodoscope field of view).

Sufficient clearance space existed between the inner cladding wall and the upper pin structure in the central pin to allow the insulator pellets to fall downward and displace some of the molten fuel. This same clearance space provided a channel for plenum gas to communicate with the cladding breach site.

Findings of preirradiated fuel throughout the length of the upper blockage during the posttest examination is consistent with the identification of the central pin as the first to fail. The relative uniformity of the preirradiated fuel distribution, compared to the more concentrated distributions of fresh fuel, indicated the greater mobility of the former. Very possibly, the irradiated fuel moved as a slush or foam, whereas molten fresh fuel would show a greater propensity for freezing and plate-out and, consequently, be considerably less mobile than irradiated fuel.

Fresh pins failed incoherently during the next 80 ms. Thermal interactions between hot fuel/steel debris and the coolant resulted in voiding the upper two-thirds of the flow channel. No fuel or cladding debris was found on the lower third of the cluster, indicating the absence of voiding and dryout in this region during the test. Extensive fuel melting near the bottom of the cluster was calculated and observed during the posttest examinations, but no evidence of cladding melting or rupture was observed. Fuel deposits caused the holder wall to rupture and release the argon insulating gas as an initial surge (at 9.23 s), followed by a slow leakage of the noncondensable holder gas into the vapor flow stream. This bubbling or leaking process of the argon gas appeared to have lasted about 10-15 s at an almost constant rate, and then slowly choked off during the next 40 s.

A delayed reaction of comparable magnitude to the initial failure has been observed in both loop and static capsule experiments. Hodoscope reports for LOF tests identify these delayed "eructations" as major fuel-motion events. In TOP tests, they occur long enough after the end of the overpower transient that the hodoscope statistics preclude the detection of fuel motion. No such delayed event was observed in Test E6, suggesting that different modes of postfailure fuel motion and blockage formation existed.

Before discussing the areas in which Test E6 represents postulated accident conditions, we should examine the role of a $\$3/s$ TOP accident in FFTF. Credible reactivity accidents are limited by control-rod worths and the maximum rate at which the operator can add reactivity. For FFTF, this

is less than $10 \text{ } \phi/\text{s}$. Thus, the role of the $\$3/\text{s}$ TOP accident is as a limiting case analyzed in the FSAR, and the most significant purposes of such tests are to demonstrate that fuel failures are incoherent, that fuel moves from regions of high to low reactivity worth, and that such an accident is indeed self-terminating. Although not used in the FSAR, such tests can also provide significant insight into failure mechanisms. For example, it is generally held³² that melting of high-burnup fuel progresses along grain boundaries, leaving islands of partially molten particles in a homogeneous mixture resembling a froth. For rapid transients in which the energy-deposition rate far exceeds the relaxation time for thermal conduction, froth formation is more likely than in a slower transient or an LOF test. Another example is the relatively small conversion of thermal energy to mechanical work observed in irradiated fuel tests. Melt fractions at the time of failure range from 10 to 50% in slow transients and up to 100% in rapid transients. Significantly different FCI's should be expected. Apparently the heat transfer from molten irradiated fuel (or froth) to the coolant flow or film is much less than from fresh molten fuel with the same thermal-energy content.

Comparisons between grain structures of the central pin in Test E6 and FFTF fuel and of the temperatures at the end of the preheat period showed that the 343-mm-long test fuel was an excellent one-third-scale model of the 914-mm FTR fuel pin. However, higher fissile density in the test fuel resulted in greater volumetric rates of heat generations during the overpower transient. Temperature gradients at the time of failure were probably greater than in FFTF, especially in the unrestructured grain region where the thermal inertia of the cladding holds down the fuel surface temperature. Because of fuel swelling, fuel that has been at operating temperatures for hours or days has no gap. Test fuel has been at operating temperatures for only a few seconds and, unless transient swelling is significant, the gap is determined by thermal expansion alone.

Thermal conductivity of the fuel can vary by a factor of two, depending on the O/M ratio and the distribution of metallic fission fragments. Another factor of two is associated with the porosity. These effects both depend on the temperature gradient in the unrestructured grains and the gap conductance. This dependence is through the transient gas release. Pre- and posttest examinations of the H4 pin demonstrated that transient gas release is nearly 100%. Except for the effects of fuel swelling, the inter- and intragranular fission-gas dynamics of Test E6 are expected to be prototypic of the FFTF fuel. Except for their plenum volume, the differences between the pin structures above and below the fuel column are probably not important. The smaller plenum volume in the test pin results in a $3\frac{1}{2}$ times higher fission-gas pressure for the same burnup and gas release. This is only partially compensated for by the lower temperatures of the upper structure in the test.

As melting progresses toward the top of the fuel column, the shorter test pin has greater downward forces to push fuel out of a cladding breach. This may or may not be important in comparing rates of fuel motion, depending

on the role assumed for the gas in the central cavity. If that gas is the primary contributor to the formation of a froth, then the small-volume, high-pressure plenum gas may eject a larger quantity of fuel over a shorter time interval. Larger quantities of fuel ejection lead to more energetic FCI's and higher pressures. If, on the other hand, the gas in the central void is the force that drives molten fuel out of the pin through cracks in the frozen shell, differences in plenum volume and pressure are probably not important, since the gas leaks into the coolant stream from the cladding breach through the space formed by clearance between the structure and the cladding.

The most nonprototypic feature of the test is the hydraulics of the flow channel. In FFTF, the flow area is $43.2 \text{ cm}^2/217 \text{ pins}$ ($= 0.20 \text{ cm}^2/\text{pin}$) and the axial pressure gradient is 0.74 MPa; in Test E6, the flow area was $1.8 \text{ cm}^2/7 \text{ pins}$ ($= 0.26 \text{ cm}^2/\text{pin}$) and the pressure gradient was about 10% of the FFTF value. Flow velocities in the test were about 275 cm/s; in FFTF they are 64 cm/s in high-power subassemblies. Linear power densities during the pre-heat period (630 W/cm) were about twice the steady-state FFTF values. The combination of higher linear power, smaller flow area, higher flow velocity, and lower pressure gradient in the test resulted in a coolant temperature rise of 180 K from inlet to outlet. At full power (400 MW) the heating in FFTF is 167 K. No significant effect is expected from the smaller spacer wire on the central pin, since the lattice pitch is preserved by the prototypic wire size on the outer pins.

In summary, Test E6 was thermodynamically prototypic of one-third-scale BOC-4 fuel in FFTF. Results of prefailure fuel motion and mechanisms relating to initial failure can be reliably applied to the FTR. Characterization of the initial fuel release in amount, location, structure (solid, liquid, or foam), and rate are reasonably prototypic. Postfailure coolant dynamics, however, are not very prototypic. Inlet flow reversal and channel voiding more than a few centimeters below the cladding rupture site are not expected in the FTR. Although the amount of fuel swept out is probably realistic, the formation of an outlet blockage and its impact on adjacent channel hydraulics are clearly nonprototypic.

APPENDIX A

Details of Posttest Examination

1. Neutron Radiography (See Fig. 21)

Posttest neutron radiographs indicated a region of failure in at least several elements starting 63 mm from the top of the fuel columns and extending downward about 50 mm. The region of failure was coincident with the bottom part of the bellows on the outer test-section tube. Damage to the bellows was doubtful, but the inner test-section tube appeared to be ruptured. Below the region of failure, the individual fuel columns appeared to be intact, but were bent and warped within the confines of the inner test-section tube. Evidence for downward motion of fuel was slight. A small amount of neutron-absorbing material appeared to be present on the bottom header joining the inner and outer test-section tubes. Some material, presumed to be stainless steel, was indicated by a gray shading around the fuel elements at various locations in the region below the rupture. A small gap was present in the fuel column nearest the pump at a location ~50 mm above the bottom of the fuel column. Neither stainless steel nor fuel appeared to have been deposited among the bottom end plugs of the elements. Clear-cut evidence for the presence of a deposit of neutron-absorbing material in the bottom bend of the loop was lacking on the neutron radiographs.

Above the failure region up to the top of the fuel column, the fuel columns seemed to be intact, but the overall density of fuel seemed to have increased in this region. Fuel appeared to be present among the elements around the fuel columns. Above the tops of the fuel columns scattered fuel and/or stainless steel deposits were evident up to the top header. A concentration of neutron-absorbing material extended from ~100 to 175 mm above the top of the fuel columns. Some fuel appeared to have lodged on the top rim of the upper header joining the outer test-section tube to the inner. The reflector rod and the spacer tube in the central element appeared to have moved downward ~33 mm. A few small neutron-absorbing patches of doubtful significance were observed above the top header up to the vicinity of the sodium outlet.

2. Loop Disassembly

The E6 loop was stripped of its outer hardware in the HFEF at Argonne-West. Following neutron radiography at TREAT, the loop was cut into sections at HFEF without removing the sodium. The following sections were received at ANL-East for further disassembly and examination in the MSD Alpha-Gamma Hot Cell Facility: (1) the part of the loop containing the test section, (2) the lower bend of the loop, (3) the upper loop arm to the pump, and (4) a small T-section containing the bottom pressure-transducer port.

The loop test section was marked with an orientation groove along the side toward the pump. Then a transverse cut was made with an abrasive cutoff wheel between the upper flowmeter and the pressure transducer. The upper of the two parts of the loop test section was designated A2, and all of the lower part was initially identified as A1. (Figure 4 identifies the various pins and their orientation in the cluster relative to the pump, flow-detecting probes, and pressure transducers.) Figure A.1 identifies the various cuts and photographs described in this appendix. Section A1 contained all six peripheral elements and most of the center element. The upper part of the spacer tube, the spring, and the top end plug of the center element were in section A2.

Section A1 was subsequently cut into many smaller pieces as indicated in Fig. A.1. Since the loop wall and the test section did not appear to be fused together, the next operation was to remove the loop wall. The loop wall was cut through on opposite sides in the plane of the vertical axes of the pump and the test section, care being taken to avoid cutting into the outer wall of the fuel holder. Heat was applied to soften the sodium bonding the loop wall to the fuel holder, and the loop wall was removed. A thin sodium film on the fuel-holder surface was removed by wiping with a cloth dampened with alcohol. The outer holder-wall tube was intact.

After circumferential cuts were made through the outer holder-wall tube at the top and bottom headers, the tube was slit in the same plane as the loop wall. Again heat was applied to weaken the bonding sodium, and the two halves of the outer holder tube were easily removed.

A large hole was melted through the fluted tube on the side toward the upper pressure transducer and at an axial location equivalent to the middle of the top half of the fuel column. Sodium from the outside surface of the fluted tube was removed by wiping with alcohol.

The fluted-tube section A1 was separated into three pieces by two transverse cuts--one 279 mm from the bottom of the section (182 mm above the bottom of the fuel column), and one 495 mm from the bottom of section A1. The bottom piece was identified as A1a, the middle piece as A3, and the upper piece as A4 (see Fig. A.1). Several loose pellets and pellet pieces fell out of the bottom of section A3 and the top of section A1a. These pellets and pieces were collected and saved.

Two of the flutes on the inner tube were removed from piece A1a on the side toward the pump to expose the elements. Four flutes were removed from section A4.

The three sections, A1a, A3, and A4, were soaked in ethyl alcohol to react the remaining sodium. They were then washed with a water-50% alcohol mixture and dried in a vacuum chamber. Two of the element sections in piece A4 came free as a result of the alcohol treatment. An attempt was made to remove the pins holding the bottom end plugs of the elements in the test section in piece A1a, but only one of the three pins could be removed.

Sections A1a, A3, and A4 were filled with epoxy to hold the fuel-element remains in their respective locations during subsequent cutting. Figure A.1 shows the relationship of the pieces cut from the test section to the test section and the elements contained there, through piece A18. Original sections A7 and A12 were cut longitudinally as indicated in the figure to produce new sections A17 and A18. In the splitting of section A12, piece A17 was appreciably larger than A12. Subsequently, additional pieces were cut from sections A4, A17, and A18 for metallographical examination.

Sodium was melted from the test section and drained out during initial disassembly. The remaining sodium was reacted with alcohol, and any insoluble residues were identified as to location and saved for subsequent examination. The sodium in the other parts of the loop (bottom bend, upper arm, and T-section) was also melted out and reacted with alcohol. Insoluble residues were separately collected for each piece.

3. Examination Results

a. General

The presence of sodium was observed at the bottom of the test section and at all bottom bend loop openings, except the side arm with the pressure-relief plug. The bottom pressure-transducer port (T-section) had a hole in the sodium where the pressure transducer had been removed. At the upper end of the test section, sodium was not present at the overflow, the openings to the pump and the pressure transducer, and the top of the section. The upper arm to the pump had sodium at the flange to the pump, but not at the end to the test section. The first transverse cut between the upper flow-meter and the upper pressure transducer revealed that there was little sodium at that location. The posttest sodium fill level was expected to be appreciably less than pretest due to volume between "adiabatic" holder walls. Because the sodium was melted at various places during disassembly, subsequent observations on the presence or absence of sodium were not informative.

Gamma-radiation readings were taken with a Jordan-type radiation meter on some of the loop parts. (Unless otherwise stated, all readings are at 25 mm.) With a background of $8.96 \text{ nC/kg}\cdot\text{s}$ (125 mR/h), the upper arm to the pump gave $0.18\text{--}0.22 \text{ }\mu\text{C/kg}\cdot\text{s}$ (2.5–3 R/h) at the flange end, which was filled with sodium, and $35.8 \text{ nC/kg}\cdot\text{s}$ (500 mR/h) at the cut end, which showed no sodium. After removal of the outer test-section tube from piece A1, radiation readings were taken on the two long pieces of the outer tube. At the ends of both pieces, the radiation readings were essentially background [$8.96 \text{ nC/kg}\cdot\text{s}$ (125 mR/h)]. In the region of the bellows, on the side toward the rupture in the fluted tube (see Fig. A.2), the deposited fuel gave a reading of $0.22 \text{ }\mu\text{C/kg}\cdot\text{s}$ (3 R/h). On the side away from the rupture (see Fig. A.3), the radiation reading was $28.7 \text{ nC/kg}\cdot\text{s}$ (400 mR/h).

Fig. A.2. Photograph of Inside of Bellows toward Rupture Site. Mag. $\sim 1.4X$. Neg. No. MSD-180570.

Fig. A.3. Photograph of Inside of Bellows Away from Rupture Site. Mag. $\sim 1.4X$. Neg. No. MSD-180575.

After the outer test-section tube was removed, gamma-radiation readings were made over the length of the test section. Over the fuel-column region, the readings were uniform at $8.6 \mu\text{C/kg}\cdot\text{s}$ (120 R/h) at 50 mm. At the bottom plugs of the fuel elements, the reading was $5.4 \mu\text{C/kg}\cdot\text{s}$ (75 R/h) at 50 mm. Above the fuel column up to the top of the peripheral elements, the readings gradually decreased to $16 \mu\text{C/kg}\cdot\text{s}$ (23 R/h) at 50 mm. In view of the high radiation readings over the fuel columns, the relatively low readings from the fuel deposited on the bellows probably indicate chiefly fresh fuel.

After the sodium was cleaned from the three test-section pieces (A1a, A3, and A4), they appeared as shown in Fig. A.4. The bottom part of the test section, after removal of two flutes from the pump side, is shown in Fig. A.4a. The bottom 276 mm of the seven elements was contained in this section. Extensive cladding melting occurred in the peripheral pins in the upper part of this section, but the cladding on the preirradiated center pin appeared to be intact. An end view at the top of this section before sodium removal is shown in Fig. A.5. During subsequent disassembly, some pellets fell out of the top of this section, thus accounting for the lack of pellets at the top in Fig. A.4a. Some of the pellets that fell out were fused end-to-end with an adjacent pellet.

(a) Section A1a

(b) Section A3

(c) Section A4

Fig. A.4. Views of Partly Exposed Elements Showing Melted Cladding and Fluted-tube Rupture. Mag. $\sim 0.8X$. Neg. No. MSD-181233.

Fig. A.5

Top View of Section A1 Showing Condition of Fuel Pellets. Mag. $\sim 2\frac{1}{2}X$. Neg. No. MSD-180637.

Section A3, 216 mm long, had a large hole melted through the fluted tube near its midlength. The part of the test section with the meltthrough is shown in Fig. A.4b. The fluted tube was mostly intact elsewhere on section A3. Around the outside of this hole, steel spatter seems to have moved upward and sidewise, but not downward, except for some dribbles. The melted steel near the upper part of the hole has been partly shaped by the bellows of the outer test-section tube. The fluted tube appears to have been slightly expanded at the location of the rupture, but the expansion appears to have been restrained by the bellows. Inside the hole, there was an assortment of pellet pieces, some of which appeared to be at least partly melted. All fuel elements had failed drastically at this location, which lies between 65 and 115 mm from the top of the 343-mm-long fuel columns. Of the two inlet thermocouples, the one that passed over the rupture in the fluted tube burned out. As shown in Fig. A.3, the bellows section adjacent to the hole was not perforated or obviously fused, but it was decorated on the inside with particles of fuel.

Section A4, shown in Fig. A.4c, contained the top 292 mm of the peripheral elements and 325 mm of the center element. Four of the six flutes have been removed from the inner test-section tube for this view. After the sodium was removed, two elements, E6-4 and -6, on the side of the cluster toward the pump were loose. They were removed, exposing the center element. These two elements are shown in Fig. A.6, and the cluster with these elements removed is shown in Fig. A.7. Both melted fuel and melted steel are present among the elements in this upper part of the test section (A4). The major deposit among the elements starts ~ 100 mm from the bottom of the piece and extends upward 64-76 mm. Gamma-radiation readings as high as $6.5 \mu C/kg \cdot s$ (90 R/h at 25 mm) were measured in the region of the major deposit. This high level of radiation probably implies that much of the fuel at this location came from the preirradiated center pin. A beta-gamma autoradiograph confirmed the distribution of radioactivity in this section.

Fig. A.6

Plenum Sections of Elements E6-4 and -6 with Attached Fuel Particles. Mag. $\sim 0.9X$. Neg. No. MSD-182488.

Fig. A.7

Three Views of Elements in Section A4 after Removing E6-4 and -6, Showing Deposited Melted Fuel and Steel. Mag. $\sim 0.8X$. Neg. No. MSD-181228.

The center element in section A4 (see Fig. A.4c) had a hole in the cladding 43 mm from the bottom of the section and ~98 mm above the original top of the fuel column in a region of UO_2 pellets. However, the space inside the cladding was empty at the hole. The hole apparently had melted through from the outside.

The top of the center, preirradiated fuel element, as removed from section A2, showed no signs of damage.

A cross section of the cluster of seven elements (A10) at the bottom UO_2 insulator pellets is shown in Fig. A.8. Neither melted steel nor melted fuel was found at this location.

Fig. A.8. Transverse Section A10 through Cluster of Elements at Bottom UO_2 Insulator Pellets. Mag. ~3.9X. Neg. No. MSD-182489.

Figure A.9 shows a cross section (A8) of the test section ~60 mm up from the bottom of the fuel column. The two missing flutes of the inner test-section tube were cut off; otherwise the tube was intact. With reference to the cluster of elements, the pump was located at about 10 o'clock in the figure. Claddings of the peripheral elements on the side toward the pump and the hodoscope were relatively intact, but had completely melted away on the opposite side of the cluster. The cladding of the center element was also intact. The fuel in the preirradiated center element was spongy in the middle,

where it seems to have melted, but there was an unmelted rim around the outside. The fresh fuel had mostly melted and resolidified as dense columnar grains. Evidence of unmelted fuel toward the outside could be seen in some fresh fuel elements. A central void was present in some fresh fuel pellets, but in others it seems to have filled in. The degree of fuel melting at this axial location ($Z/L = 0.2$) is generally consistent with that predicted by the COBRA calculations. Melted stainless steel was evident among the elements, but essentially no melted fuel was observed outside of the pellets. The material on the inside of the fluted tube at ~4 o'clock was debris from the cutting operation.

Fig. A.9. Transverse Section A8 through Cluster about 60 mm from Bottom of Fuel Columns. Mag. ~3.9X. Neg. No. MSD-181229.

Section A15, 222 mm from the bottom of the fuel column, is shown in Fig. A.10. This location is just below the large rupture in the fluted tube. The fluted tube is essentially intact, and four spacer wires are evident. All the cladding, except for a small section against the center pellet, melted and relocated elsewhere. The center element is represented by a spongy mass of fuel slightly to the left and below center. The remains of four melted fresh fuel elements are visible. This fuel has solidified in some unique configurations. A piece of a UO_2 pellet is present just to the right of center. The evidence indicates that the UO_2 is from the upper insulator stacks of the center element.

Fig. A.10. Transverse Section A15, 222 mm from Bottom of Fuel Columns. Mag. $\sim 3\text{--}3/4X$. Neg. No. MSD-181393.

ment originally had a fuel pellet at this location, but it has been replaced by a UO_2 pellet from the stack above.

Section A27 (the middle of section A17 in Fig. A.1), from about 12 mm from the top of the original fuel column, is shown in Fig. A.11. The pump was approximately to the left with respect to this figure. The fluted tube is essentially intact, but one region of melting can be seen on the inward dimple to the lower right center. The cladding has mostly melted off of the fuel. Melted steel is present, chiefly on the side toward the pump, and melted fuel occurs on the side away from the pump. None of the peripheral pellets show evidence of melting, but they appear to have been in a state close to melting. The center element

Fig. A.11

Partial Transverse Section A27, about 12 mm down from Top of Fuel Columns. Mag. $\sim 3\text{--}3/4X$. Neg. No. MSD-181392.

Figure A.12 shows transverse section A11 from 55 mm above the original top of the fuel columns. Again the fluted inner test-section tube is intact. Reflector rods are present in all but the center element. Some melting is apparent on the cladding of some of the peripheral elements, and melted steel spatter is also evident. The center element has a hole in the cladding. The hole may have been the result of the presence of hot fuel, since fuel

particles are still present at this location. A depleted- UO_2 pellet should have been present in the center element, but a gap was present instead. Some melted fuel and melted steel are present among the elements.

Fig. A.12. Transverse Section A11, 55 mm above Top of Fuel Columns, through Peripheral Reflector Rods. Mag. $\sim 3\text{--}3\frac{3}{4}\text{X}$. Neg. No. MSD-181230.

b. Flow Blockages

There were no significant flow blockages below the principal region of rupture where the fluted tube was melted through. Neutron radiography showed no fuel or melted steel among the bottom end plugs of the fuel elements. At the bottom UO_2 insulator pellets in section A10 (see Fig. A.8), neither melted steel nor melted fuel was present. In section A8 (see Fig. A.9), ~ 60 mm above the bottom of the fuel columns, some melted steel was present between the elements, but melted fuel outside of pellets in their original locations was absent. Other sections below the principal rupture showed much open space between the

elements. Melted fuel appeared to be confined to the pellets. Melted steel was not present in sufficient quantity to constitute a serious blockage to the flow of sodium. The fact that several loose pellets and pieces of fuel fell out of the bottom section A3 and the top of section A1a, when they were separated, indicated a lack of cohesive blockage in that region of the fuel columns.

There appeared to be a significant blockage just above the principal rupture that extended upward for ~ 25 mm (see Fig. A.13). Much, but not all, of the fuel in this region appeared to have melted into a porous mass. UO_2 pellets had replaced the fuel pellets in the center element. All the cladding had melted and relocated. No large conglomerates of melted steel were evident, but globules of melted steel were dispersed throughout this region. Figure A.14 is a longitudinal view through the center of the cluster showing melted fuel blockage and relocated UO_2 pellets in the region of the blockage. Above this blockage, stacks of fuel pellets from peripheral elements and a stack of UO_2 pellets from the center element, all with most of the cladding melted off, were present with considerable space among them.

(a) Section A12

(b) Section A17

Fig. A.13. Blockage of Flow Channels by Melted Fuel Just above Rupture in Fluted Tube. Mag. 1.4X. Neg. No. MSD-182595.

FIG. A.14. Longitudinal section 35 mm from top of fuel column showing melted fuel flow gaps and located fog pellets. Mag. $\times 4.1X$. Dev. No. M-4-1-1-14.

Both neutron radiography and cross-sectional views showed open spaces between the fuel elements above the principal blockage. Both melted fuel and melted steel were present around the upper parts of the fuel elements and, although they offered resistance to the flow of sodium, nowhere did they appear to have seriously blocked the flow channels (see Fig. A.7).

c. Extent of Melting

The cladding and spacer wire on the center element were intact for 188 mm from the bottom of the fuel column. Then for ~ 50 mm, the cladding was partly melted. Complete cladding melting had occurred for the next 86 mm. For approximately the next 25 mm, to the top of the original fuel column, some of the cladding of the center element was intact. Above the top of the original fuel column, spot melting occurred where heat was supplied by melted material moving up among the elements from below.

On the fresh fuel elements, the cladding appeared to be intact for 40-50 mm above the bottom of the fuel columns. Over the next 90 mm, partial melting had occurred, particularly so on the side of the cluster away from the pump (see Fig. A.9). From this location, 125-140 mm above the bottom of the fuel column, up to ~ 65 mm from the top of the fuel columns, complete melting of the cladding on the fresh fuel elements had occurred. Partly melted cladding occurred up to the top of the original fuel column, but higher up, cladding melththroughs became less frequent and depended on contact with melted fuel ejected from below. In the various cross sections examined, spacer wires generally showed less melting than cladding. The wires toward the outside of the cluster were generally more intact than those inside the cluster.

The center element in section A8 (see Fig. A.9) (60 mm up from the bottom of the fuel column) had about 60% melting of fuel on the cross section. In section A16 (170 mm from the bottom of the fuel column) the center element (see Fig. A.15) had 69% areal melting. The fuel in the center element in section A15 (see Fig. A.10), 222 mm from the bottom of the fuel column, apparently had completely melted. In all cases, the amount of apparent melted fuel, as indicated by its spongy nature, was less than that needed to account for the fuel initially present. The frothy fuel in these sections could move only upward because the cladding was intact around it. Most of the fuel in the center element above section A15 was displaced by unmelted UO_2 pellets, which moved down from above. The displaced fuel was most probably molten, and was moved upward and outward when the cladding failed.

Fig. A.15. Transverse section through center element of section A16, showing extent of center melting. Magn. 12X. NWA No. 5749-15-414.

The fresh fuel in section A8 (see Fig. A.9) had generally melted, except for a narrow band of apparently as-fabricated fuel on the outside of some elements, particularly where the cladding was present. Some elements had large central voids, and some did not. Melted fuel had apparently moved to bridge the void at a few locations. The resolidified fuel formed dense columnar grains. Since the fresh fuel in section A27 (see Fig. A.11) did not melt, and since this section was 12 mm from the top of the fuel column, flux symmetry and coolant flow would imply that the bottom end of the fresh fuel columns was similarly unmelted for some small distance.

The outer test-section tube showed little evidence of melting, even where the fuel had been deposited against it at the bellows.

The melting of the fluted, inner test-section tube was chiefly localized at the site of the major meltthrough. Some small isolated holes were melted in the tube for ~30 mm above the major meltthrough. Local superficial melting was also observed in a few cases on the inside of the fluted tube, where hot fuel probably touched it (see Fig. A.11). These regions of superficial melting were generally above the large hole. An inlet thermocouple had melted at the large rupture in the fluted tube.

d. Structure of Fuel and Cladding

As a result of the transient, the preirradiated center element melted to 60% areal in section A8, and up to apparently 100% farther up the fuel column. The presence of fission gases and volatile fission products appears to have been responsible for the frothiness of the melted fuel. The grains of fuel in the froth tend to be fairly large and equiaxed, with no particular evidence of directionality. Two levels of porosity exist in melted fuel--large pores surrounded by grains of fuel and small pores within the fuel grains. In the cross section of the center element from section A16 (see Fig. A.15), the melted fuel is rather sharply separated from the unmelted fuel. The quantity of melted fuel is obviously too small to have filled the area from which the fuel was molten. Figure A.16 is a higher-magnification view of the fuel structure, showing a radial transverse from the outside of the fuel pellet into the region of melted fuel. The boundary between the melted and unmelted fuel appears to extend over several grain diameters of the equiaxed grains. The white, metallic particles are believed to be fission products.

The fresh fuel in the peripheral elements originally had an "as-fabricated" structure. The pellet density was 93% and the smeared density 87% TD. Most of the fuel in the fresh elements melted and resolidified in dense columnar grains. No evidence of frothiness was observed. Since there were no fission products in these elements, the observations of metallic particles indicated the probable presence of stainless steel. However, metallic uranium has been observed in UO_2 heated to high temperature.

Motion of the fresh fuel was not extensive. Evidence of flow within the central void is present where bridging has occurred. Figure A.17 shows two pellets fused end to end. They were from the region of the top of the original section A1a and the bottom of section A3. Most of the fuel is columnar in nature in the radial direction. On the inside of the columnar region a layer of melted fuel seems to have flowed along the surface before solidifying with some radial directionality. This material differs from the main body of fuel in containing metallic particles probably stainless steel. The region of greater thickness is shown in Fig. A.18.

Outside

Fig. A.16

Radial Transverse from Outside into Melted Fuel of Center Element, Section A16. The outside surface is at the top of the figure. Mag. 207X. Neg. No. MSD-182443.

Fig. A.17

Peripheral Fuel-element Pellets Fused End-to-End, Showing Central Void and Columnar Grains. Mag. ~10.2X. Neg. No. MSD-181395.

Fig. A.18. Flowed Fuel on Inside of Central Void in Pellets of Fig. A.17.
Mag. 80X. Neg. Nos. (a) MSD-181421; (b) MSD-181422.

In Fig. A.11, three practically whole fresh-fuel pellets appear to show different stages in the formation of a central void in unmelted fuel. The differences probably arose from temperature differences due to position. The pellet near the bottom center has numerous bubbles throughout the central portion, and the bubbles tend to be larger on the side toward the outside of the cluster. Grain growth has occurred, but no melting. The pellet to the left indicates a later stage in which bubbles have merged, but surface tension has not yet smoothed out the resultant irregularities. The pellet on the right has a large smooth-surface internal void displaced toward the outside (hot side) of the cluster. This appears to represent a stage in which surface tension has acted to smooth the internal void.

In the fresh-fuel pin in section A27 at the bottom of Fig. A.11, penetration of melted steel from the surface into the fuel can be observed at four locations. Two of these metallic intrusions are shown in Fig. A.19. The cracks into which the metal penetrated appear to be startup cracks tapering inward from the surface. The cracks terminate one-tenth to one-fourth of the radius toward the center of the pellet, where appreciable grain growth has occurred in the fuel. Small globules of steel are in the fuel in the vicinity of the end of the steel intrusion.

Fig. A.19. Metallic Intrusions into Startup Cracks in Fresh Fuel.
Mag. 160X. Neg. Nos. (a) MSD-181477; (b) MSD-181478.

These observations on the steel intrusions may be explained as follows. The startup cracks form first. The cladding melts and flows off, wetting occurs, and capillarity pulls some of the melted steel into the cracks in the fuel. As the fuel temperature increased, grain growth occurred along with thermal expansion and some increase in plasticity in the interior of the pellet. The cracks are pinched off and steel globules are trapped within the fuel, where they occupy whatever porosity is available. If the fuel should subsequently melt, as did not happen in this case, the high temperatures could vaporize the dispersed metal.

Figure A.20 shows steel dispersed into fuel at a later stage. This section (A8) is from a location 60 mm up from the bottom of the fuel column. In this case, the fresh fuel had melted and resolidified. Liquid steel in contact with the fuel has entered voids in the fuel, either as a liquid or by condensation of vapor.

Melted and flowed steel as shown in Fig. A.21 has solidified both on the inside and outside of cladding, which retained its cold-worked structure. The steel on the inside of the cladding was between the cladding and the fuel, as can be seen around the pellet at about 2 o'clock in section A8 (see Fig. A.9).

Fig. A.20. Metallic Particles Dispersed in Melted Fuel from Section A8.
Mag. 152X. Etched: oxalic acid. Neg. No. MSD-181434.

Fig. A.21. Melted Steel between Fuel and Cladding and
Outside of Cladding from Section A8. Mag. 80X.
Etched: oxalic acid. Neg. No. MSD-181435.

A bulge in the almost melted cladding of the center element occurred at the fuel surface, as shown in Fig. A.22. The location is at the top of section A18, about 140 mm above the bottom of the fuel column (see Fig. A.1). A large mass of melted steel lay against the cladding at this location, and heat transfer from this mass apparently caused the cladding to soften locally. Cladding cracking is shown in Fig. A.23. Here fissures are associated with a bulge in the cladding of a peripheral element in the reflector-rod region, about 100 mm from the bottom of section A4 and toward the inside of the cluster of elements. Presumably the fuel adjacent to the crack provided the heat, which resulted in the grain boundary melting. The bulges themselves are indicative of a pressure differential or perhaps local thermal stresses.

Contact between melted fuel and a UO_2 pellet is shown in Fig. A.24. The absence of metallic fission products and the general density of the fuel identify it as fresh fuel. The UO_2 is identified by the lack of melting, the absence of grain growth, and the presence of porous regions where grain separation has occurred.

e. Fuel-element Plenum Region

Relative movement of the tops of the fuel elements as a result of the transient appears to have been small. The center-element top plug, referred to structural parts of the loop, did not move upward more than 3 mm. The two peripheral elements on the side toward the upper pressure transducer (E6-2 and -3) appear to have moved upward ~3 mm relative to the other four, which appear to be at their original elevations.

Fig. A.22. Bulge in Almost-melted Cladding. Mag. 64X.
Etched: oxalic acid. Neg. No. MSD-181452.

Fig. A.23

Cladding Cracking in Peripheral
Element in Reflector-rod Region.
Mag. 40X. Etched: CuCl_2 . Neg.
No. MSD-181766.

Fig. A.24

Melted Fuel against a UO_2 Pellet.
Mag. 40X. Neg. No. MSD-181464.

The top of the spacer tube inside the center element was 59 mm from the top plug. Since the spring occupied 25 mm of this space, the spacer tube has moved down 34 mm. The reflector rod and the stack of UO_2 pellets must have also moved down the same distance. However, UO_2 pellets were found down in the fuel region of the center element, at a location indicating that the bottom of the UO_2 stack had moved down at least 70 mm. Therefore, a void or voids in the UO_2 column totaled 36 mm. The distribution of UO_2 pellets within the extended length was not determined.

The evidence with respect to the peripheral elements indicated reflector-rod movement of no more than ± 3 mm and a similar limit on the possible displacement of the UO_2 pellets.

The Inconel X750 spring from the center element, N056, had a free length of 25 mm as removed, compared to the fabricated free length of 35 mm. The measured spring constant was 5.6 lb/in. (981 N/m), compared to the specification of 4.0-4.8 lb/in. (700-840 N/m), for the as-fabricated spring. Both of these indicated changes most probably occurred during the EBR-II irradiation. After complete compression, the spring returned to its free length of 25 mm.

The Type 302 stainless steel spring of element E6-4 was also examined. Its free length after removal from the element was 152 mm compared to the as-fabricated free length of 182 mm. The spring constant in the elastic range was 0.74 lb/in. (130 N/m) compared to the specification of 0.73-0.95 lb/in. (128-166 N/m). The free length after full compression was 120 mm, indicating that yielding had occurred. The steel was apparently annealed by the high-temperature exposure during the transient.

Diameter measurements were made on the cladding on the upper 255 mm of elements E6-4 and 6 with the following respective results:

5.839 $\begin{smallmatrix} +0.036 \\ -0.025 \end{smallmatrix}$ mm and 5.821 $\begin{smallmatrix} +0.023 \\ -0.013 \end{smallmatrix}$ mm average for 8 and 10 measurements, respectively. Similarly, the top 255 mm of the center element measured 5.811 $\begin{smallmatrix} +0.018 \\ -0.023 \end{smallmatrix}$ mm. The specified outer diameter of the tube was 5.840 $\begin{smallmatrix} +0.025 \\ -0.025 \end{smallmatrix}$ mm in both cases. These measurements do not indicate any cladding expansion during the transient. Some diameter measurements were made from photographs of transverse sections of the cladding of both peripheral and center elements, and again no diameter expansions were indicated, but the locations were appreciably removed from the region of principal rupture.

4. Conclusions

Based on observations and findings during the posttest examination, the following events probably occurred during the test. During the approach to preheat (0.55 s), the fuel pellets, particularly the "as-fabricated" peripheral

elements, would develop startup cracks from thermal stresses. During the 2.955-s preheat, grain growth would begin in the fuel of the hottest peripheral pin (77 kW/m, max). The restructured fuel in the preirradiated center pin would not be altered appreciably during the preheat at 55.5 kW/m.

The ramp reactivity increase ($\sim 3/s$) began at 8.605 s, total elapsed time, and peak power was reached at 9.125 s. During this period, melting occurred in the interior of each fuel column. Neutron shielding by the pump tended to shift the center of melting away from the vertical axes of the fuel columns in a direction away from the pump.

In the peripheral pins, gases trapped in the fuel during fabrication became trapped in the expanding melted-fuel volume. The gas bubbles would tend to rise through the melted fuel in the interior of the stacks, and melted fuel would move downward. Evidence for this movement can be seen in the sections examined (see Figs. A.9, A.10, A.13, and A.17). These gases were not in great quantity and were initially present in the as-fabricated macrovoids as compared to fission gases in bubbles in irradiated fuel. The melted "fresh" fuel did not froth, but did show rather large bubbles.

In the center preirradiated pin, about 60% of the fission gas had been previously released from the fuel and was present in the central void and in the plenum. The gases retained in the fuel were released as small bubbles that coalesced and grew as melting progressed outward beyond the columnar-grain region. Some of this gas was incorporated into the melted fuel and resulted in frothy molten fuel.

In both the "fresh" and irradiated fuel, the gases generated internal pressure which was much greater in the irradiated fuel because of the greater quantity of gas. The center pin, although at lower temperatures than the hottest peripheral pin, may have failed by intergranular cladding rupture, because of the greater pressurization before any failures occurred by melting of cladding.

The first failure signal occurred at 9.15 s, 25 ms after peak power. The posttest examination did not contribute greatly to an interpretation of the initial failure in this test. However, the evidence was not contrary to the interpretation provided by the flowmeter data. The flow data indicated that both gas and fuel may have been released in the initial failure. The first failure event may have involved one or more peripheral pins as well as the central pin.

On the basis of power input as affected by the shielding action of the pump, the first peripheral element to fail would have been on the side of the cluster away from the pump, and the last would have been the element nearest the pump. The distributions of melted and unmelted fuel and of cladding on the various cross sections examined indicated that the order of failure of the

peripheral pins was generally related to this pattern of power input. However, local conditions, such as contact with melted fuel from the failed center element, could have affected the sequence of cladding failures. The most likely location for the rupture of the center element would be on the side toward the hottest peripheral pin.

Based on the distribution of melting, the axial location of the failures appeared to have been in the upper third of the fuel columns in the region of generally higher cladding temperatures. The initial failures were apparently not coincident with the meltthrough of the fluted test-section tube, but may actually have been closer to the tops of the fuel columns, as will be considered later.

As long as the cladding was intact and covered with sodium, the opportunity for radial fuel motion was restricted. When the initial cladding failure(s) occurred, the gas released from the element(s) probably blanketed the cladding higher up the fuel column. This gas, in conjunction with the expanding volume of vapor from boiling sodium, promoted melting of the cladding. Ultimately all the cladding from the position of the initial failure up to almost the top of the fuel columns melted on the peripheral elements and to a lesser extent on the center element. The internal pressure in the "fresh"-fuel columns was not great, and only minor radial or axial fuel motion from internal fuel pressurization resulted.

The skeletal forms of the peripheral fuel columns generally remained as observed in the neutron radiographs and during disassembly. The melted fuel in the center element was highly pressurized, and when the cladding failed, the fuel expanded outward and upward along paths of least resistance. The evidence suggests that the relatively large quantity of irradiated fuel that was found 75-100 mm above the tops of the fuel columns was carried up by the initial rapid expansion of sodium on vaporization and boiling.

After the sodium-vapor region became established, subsequent evolution of frothy fuel came from the lower half of the element, where the cladding was still intact. Sometime within this interval, the stack of UO_2 insulator pellets, lacking support from below, fell downward, displacing and cooling the froth. The impetus for the downward movement of the UO_2 pellets was gravity and perhaps pressure of gases still trapped in the plenum. Once the sodium-vapor volume was established, the upward movement of frothy fuel would be halted by freezing as the fuel moved into a region of heat sinks. The flow blockage at the top of the fuel columns is believed to have formed in this manner. The holes that burned through the cladding at locations above the fuel column occurred from contact principally with fuel on the outside with an inadequate heat sink inside.

In this test, the melted steel showed little tendency to mix with melted fuel. Melted steel in contact with melted fuel generally moved ahead of the

melted fuel, either radially or upward. On the peripheral elements, the melted cladding showed some tendency to flow downward. A potential mechanism for intimate mixing of melted steel and melted fuel was observed where capillarity had drawn melted steel into cracks in "fresh" fuel. If this fuel had subsequently melted, the steel would have reached its boiling temperature. Some flow of melted steel also occurred after solidification of the fuel.

On the basis of the evidence, the rupture of the fluted tube and the melting of the inlet thermocouple (TC1) may have been the last major event involving fuel movement in this TOP test. The thermocouple indicated a rapid temperature rise at 9.32 s. During disassembly, the only break observed in the thermocouples was at the location of the rupture in the fluted tube. There was no evidence of melted or unmelted fuel or melted steel anywhere in the vicinity of the junction of inlet thermocouple.

Shortly before the failure of the thermocouple, the flowmeter data indicated a drop in the position of the lower interface between liquid sodium and sodium vapor down to about the middle of the fuel column. The decrease of the level of liquid sodium would have exposed fuel still clad in stainless steel. This cladding would have melted, removing any restraint on the fuel columns, with melted fuel under some pressure. The collapse of the unmelted shell of fuel allowed melted fuel to impinge against the fluted tube in sufficient quantity to melt it through and destroy the thermocouple. Some of the melted fuel contacted the bellows and stuck to it. Some of the gas from between the inner and outer test-section tubes escaped into the test section.

Additional evidence for vapor blanketing of the elements down to 90 mm from the bottom of the fuel column is present from the melting of the cladding of peripheral elements.

In this test, primary fuel motion was associated with frothing of preirradiated fuel because of fission gases. Secondary fuel motion was associated with changes in the positions of the sodium liquid-vapor interface.

APPENDIX B

Hodoscope Analysis of Fuel Motion in Test E6

The neutron hodoscope consists of an array of fast-neutron detectors and collimators, arranged so that each detector was exposed to neutrons from a small portion of the test region in the TREAT reactor. Details of the construction and operation are given in Refs. 19-21.

Figure 18 shows where the test fuel was positioned in the hodoscope field of view for Test E6. The indicated "original fuel-cluster position" is as determined from the hodoscope data by the EFFI code, as described below. Each channel of the hodoscope array covered at the test region a spatial element nominally 3.6 mm wide and 22 mm high. Thus the channels are much more elongated in the vertical direction than they appear in Fig. 18. The actual dimensions are given by the scales at the left and bottom of the array. The symbol "X" marks channels that did not contain functioning neutron detectors.

In operation, the counts accumulated by the detectors are periodically displayed in binary form on a bank of 720 neon lights, and the display is photographed on high-speed film. It takes six frames to read out all 336 scalers (including four devoted to timing). Such a set of six readouts ("phases") is called a "cycle," and the cycle time can range upward from 1.5 ms, depending on the duration of the transient and the anticipated rapidity of fuel motion. In E6, a 1.5-ms cycle time was used.

To reduce the influence of piled-up gamma-ray counts, some lead is normally interposed between the collimator and the detectors. For E6, the lead thickness was 29 mm.

1. Data-processing Codes

The grid coordinates of the ignited lamps for each frame are determined from the recording film by the ALICE flying-spot scanner, which operates in conjunction with the PDP-10 computer in the ANL Applied Mathematics Division. The coordinates are recorded on magnetic tape, to be reduced to the desired counting-rate data by the DIGLITES code--also on the PDP-10 computer.

In Test E6, a synchronization problem caused the film to be of marginal quality, in that the density and contrast of the lamp images were not constant across the film. This necessitated a programming effort (conducted largely by James Wehmann of the ANL Applied Mathematics Division, in cooperation with RAS) to develop a scanning program (NOVA) that could cope with the defective film. The effort was successful in that a scan was obtained with an average of only one or two spurious lamp images, and not that many missed images, per frame of film. This level of noise in the data was satisfactorily handled by the DIGLITES code in the next stage of processing.

DIGLITES processing proceeds in two stages. In Level I, the lit-lamp positions as determined by ALICE are decoded into raw counts per cycle for each scaler, and the results are stored in an intermediate magnetic tape.

DIGLITES Level II is a versatile program that converts the counts to counting rates, making corrections for supralinearity (see below), scaler deadtime, and scaler efficiency. It also averages the counting rates over a specified number of cycles, which number can be a function of time or power level; calculates the array-average counting rate (i.e., the average counting rate for all the nonzero channels in a specified portion of the array); calculates the average counting rate of channels specified to be "power monitors" (channels that do not see test fuel at all during the transient, and which therefore respond only to the reactor power level); has provisions for generating a calculated power curve; and incorporates a subroutine (FUDG) that corrects obviously high datum points by subtracting the counts corresponding to spurious high-order lamp images, and that also--if the counting statistics permit--corrects obviously low points by adding the counts that correspond to missing lamp images.

An analysis of the data usually requires several Level-II runs, including early ones for determining the parameters for efficiency, supralinearity, and bad-point corrections, plus the parameters for the calculated power curve, if one is to be used. In E6, a calculated power curve was not required for the analysis.

Several final tapes are usually produced, each with the time averaging tailored to a particular purpose, for use in the PDP-11 computer.

Final processing of hodoscope data is done on one or both of the two PDP-11 computers that are available for the purpose. Several codes are used:

- a. SUPRA calculates parameters for correcting the individual counting rates for supralinearity and also can be used to determine optimum deadtimes for individual channels.
- b. EFFI is a code that can use a least-squares fitting procedure to determine both efficiency adjustments for the individual scalers and the probable location of the test fuel in the hodoscope field of view.
- c. FPLOTT produces, as a function of time, graphs of such quantities as the counting rates R of the individual channels, the average counting rate P of the power-monitor channels, the array-average counting rate A , the calculated power C , and also the ratios R/P , R/A , and R/C . (For convenience, the last three types of curves are often referred to as " R/P " plots.) FPLOTT can create plots of the average counting rates of groupings of adjacent scalers, and "profile plots," which are row-by-row (or column-by-column) plots of the data averaged over specified columns (or rows) and over specified time

intervals. The program can also operate in an "R/P-Change" mode, in which it plots the difference between the data for the time region of interest and the data averaged over a specified reference time interval, the reference interval typically being chosen to be prior to fuel motion.

d. HODO produces "differential hodographs," which schematically depict the changes in fuel distribution that occur between pairs of selected times.

In common with some of the in-core loop instruments in TREAT, the Hornyak buttons used as neutron detectors in the hodoscope show a nonlinear response to TREAT power. In the Hornyak channels, the response is supralinear until the counting rates become very large. The computer code SUPRA was used to correct the E6 hodoscope data for supralinearity. SUPRA uses a least-squares technique to generate a correction parameter for each detector, by comparing the detector response with the reactor power as given by the TREAT instrumentation. The comparison must be terminated before appreciable fuel motion takes place. In E6, the cutoff time used was 9.08 s, approximately the point at which significant fuel motion began.

For many of the counting channels, SUPRA did not produce an optimum fit to the data unless the scaler deadtime was changed to a value greater than the 0.5 μ s considered typical of the system.

To achieve uniform sensitivity, about 200 neutron-counting channels in the hodoscope are usually calibrated before each transient. With a movable neutron source, the gain and the discriminator level of the linear electronics are adjusted to achieve from 5 to 50 counts/s, depending on the expected peak power of the transient. In E6, with peak power of 2250 MW and a data-collecting interval of 1.5 ms, the detectors were calibrated at 10 counts/s. This resulted in peak counting rates near 300,000 counts/s for some of the fuel-viewing channels.

The calibration is at best approximate, partly because of limitations of time and counting statistics, and partly because there does not seem to be good correspondence between the relative efficiencies as indicated by the neutron source and as apparent in the data from an actual transient. The reason for this discrepancy is not understood. However, sensitivity variations by a factor of two are tolerable, since changes in counting rates are what is important, rather than the absolute rates.

On the assumption that the efficiency variations from channel to channel are approximately random, the hodoscope counting rates can be used to determine the probable location of the test fuel within the hodoscope field of view. It is necessary to do so, in fact, because the mechanical dimensions of the hodoscope/reactor/test-loop system are not well enough known to permit the fuel position to be calculated accurately with respect to the hodoscope. As mentioned above, the fuel-position can be determined by the EFFI code.

The efficiency corrections (and fuel position) were determined by EFFI on the basis of the counting rates (corrected for supralinearity) during the plateau phase of the test, during which time fuel motion was negligible. Although the counting rates were relatively low (<3000 counts/s) during the plateau, good statistics were obtained by averaging over a 0.5-s period. In essence, the method for determining the efficiency multipliers consists of settling upon an "ideal" counting-rate distribution (best fit as determined by EFFI) and then calculating the multipliers that make the counting rates conform to that ideal distribution.

EFFI has available several sets of options, including various possible functional forms for the background field (i.e., the counting rates with the effect of the test fuel subtracted), and the option of either specifying a fixed position for the fuel bundle or permitting the code to find the fuel position. In E6, which had a graded boron shield around each end of the test section, EFFI was used in one mode to find the fuel position, and then in another to determine the efficiency corrections, as follows:

For the fuel-position determination, the background-field function was specified to be a second-degree polynomial in both the x and y directions, symmetrical about the vertical centerline of the fuel. This permitted an accurate representation of the vertical distribution of counting rates, as affected by the boron shields. The result was that the center point of the fuel bundle was placed at row 9.6, column 9.1 (see Fig. 18). (The convention is that row 9.0 comes at the center of the channels in row 9.)

The graded thermal-neutron absorbers add to the uncertainty in the quantitative interpretation of the hodoscope data, because fuel as it moves upward into a region shielded by thicker boron will be exposed to a reduced thermal flux and will therefore have a reduced fission rate. The disposition of the fuel, in grams, is the information of primary interest. It would therefore be desirable to adjust the hodoscope efficiencies, if possible, to compensate for the expected loss in overall counting rate as fuel moves upward. In order to partially effect such a compensation, the scaler efficiency corrections were generated by EFFI under the following specifications: (a) background field uniform; (b) "uniform-pin" option; that is, the fission rate was assumed to be constant along the length of the fuel pins and the same in all pins; and (c) fuel position fixed with its center at row 9.6, column 9.1.

Specifications (a) and (b) represent an attempt to compensate for the boron flux-shaping filters and for the nonconstant axial flux distribution in the reactor. These specifications will lead to increased efficiency multipliers for channels whose counting rates are lower than the central ones, either because the fuel is behind boron, or because the neutron flux falls off with distance from the midplane. The compensation is probably less than perfect, because the signal from channels that view fuel that is within the boron will consist disproportionately of background, in view of the fact that most of the

background portion of the signal originates behind the boron, and hence is not affected by it, whereas the fuel portion of the signal is reduced by the boron-induced flux depression. In making its fit, EFFI will assume both a constant fission rate and constant background rate over the entire length of the fuel, and thus will generate efficiency multipliers that lead to a corrected signal that is constant, per gram of viewed fuel. Then, when the constant assumed background is subtracted later, the result will be an undercorrection for background at the ends of the fuel column, and consequent reduced sensitivity to fuel changes behind the boron.

As will be shown, the hodoscope data indicate that about 9 g of fuel might have disappeared from view during E6. Although some of this could just have disappeared behind the boron, remaining within the hodoscope field, the amount is consistent with what could have been carried upward by the sodium as the pins failed. Thus there is no indication as to whether the efficiency adjustments led to adequate compensation of the effects of the boron.

A portion of the EFFI output is presented in Fig. B.1, which shows the fuel distribution that EFFI produced by fitting the R/A data from the preheat plateau. The numbers in this figure are the result of subtracting a uniform background level of 142 units from all channels.

2. Differential Hodographs

The principal tool for interpreting the hodoscope data from E6 is the "differential hodograph." A differential hodograph depicts the change that occurs in fuel configuration between two time intervals. The differential hodographs in this report were produced by the PDP-11 program HODO. In these representations, a uniform gray shading in a channel indicates that very little net change took place in the (power-normalized) signal between the initial and final intervals. A solid symbol indicates an increase in signal, and a white one (absence of gray shading) a decrease. The larger the symbol, the greater the change. An approximate calibration in terms of fuel mass is given.

The calibration was determined as follows: The ratio of the average background signal to the fuel-region signal was 0.31. Also, the value of R/A is 1.9 at the center of the fuel region, where a single hodoscope channel views 8.5 g of fuel. Thus, of the 1.8 R/A units, the fraction 0.31 is background, leaving the background-corrected number of 1.33 R/A units to correspond to 8.5 g of fuel. The desired calibration factor, then, is $8.5/1.33 = 6.4$ g per R/A unit.

3. Effect of Spurious Lamp Images on Low-event-rate Data

As mentioned earlier, the basic hodoscope data for a TREAT test are accumulated in the form of pictures of an array of neon lamps, taken at high speed on 16-mm film. The results of the ALICE optical scan of this film are

STD DEV= 64.678 ITER= 4 09:18:36, 28-APR-77, TRANS 1467

FUEL ROW POS= 9.5898 +- 0.00000 COL POS= 9.0768 +- 0.00000

FUEL COL SIGMA= 0.76200 +- 0.00000 RFP= 78.288 +- 4.1158

COL=ROW=0 COEF= 185.49 +- 5.8568

EFFIC MULT														FIT-BKG															
	14	13	12	11	10	9	8	7	6	5	4	3	2		14	13	12	11	10	9	8	7	6	5	4	3	2		
2	2.56	0.05	1.47	1.37		1.12	1.82	1.13	1.94		1.62	1.82	3.11	2	0	1	19	76	113	101	112	66	14	1	0	0	0	2	
3	0.78	1.00	1.36	1.48	1.42	1.62	1.29	1.88	1.04		1.93	2.17	7.10	3	0	2	32	128	198	171	188	111	23	1	0	0	0	3	
4		0.97	1.54	1.83	1.10	1.15	0.69	0.78	1.41	0.76		1.71	1.19	4	0	2	36	142	211	198	210	124	25	1	0	0	0	4	
5		1.27	0.58	0.56	1.10	0.65	0.93	1.30	0.76	0.71		0.87	3.07	5	0	2	36	145	216	194	214	126	26	1	0	0	0	5	
6		1.65	0.06	1.02	0.94	1.24	1.22	0.75	0.98		2.05	1.27		6	0	2	36	145	216	194	214	127	26	1	0	0	0	6	
7		2.36	0.71	1.11	1.21	0.95	0.93		0.83	1.18	0.88		0.98	3.61	7	0	2	36	145	216	194	214	127	26	1	0	0	0	7
8		1.26	0.84	0.94	0.66	1.09	0.92	1.13	0.73	0.72	0.81	0.69	1.39		8	0	2	35	145	216	194	214	127	26	1	0	0	0	8
9		1.87	0.58	1.05	0.60	1.72	0.71	0.66	1.11	1.37	1.16	0.98	1.90	1.18	9	0	2	35	145	216	194	214	127	26	1	0	0	0	9
10		1.39	1.19	0.43	0.95	1.37		1.08	0.67	0.87	1.99	0.48	2.88	0.81	10	0	2	36	145	216	194	214	127	26	1	0	0	0	10
11		1.61	0.56	1.65	0.93	1.62	1.24	0.64	0.75	0.72	0.59	1.18	1.17	1.21	11	0	2	36	145	216	194	214	127	26	1	0	0	0	11
12		1.75	1.11	0.94	0.71	1.06	1.05	0.95		0.57	4.32	0.97	0.94	0.83	12	0	2	36	145	216	194	214	127	26	1	0	0	0	12
13		4.59	2.11	1.44	1.84	0.84	0.92	0.98	2.41	0.48	0.69	0.37	0.32	0.94	13	0	2	36	145	216	194	214	127	26	1	0	0	0	13
14		1.82	2.33	1.79	1.26	0.99	0.94	0.74	1.09	0.83	0.94	0.50	0.73	0.99	14	0	2	36	145	216	194	214	127	26	1	0	0	0	14
15		3.46	1.19	1.29	1.85	1.42	1.15	0.84	1.41	1.14	0.67	0.65	0.86	0.69	15	0	2	36	143	213	192	211	125	26	1	0	0	0	15
16		2.15	1.55	1.56	0.86	1.73	0.79	1.06	1.17	0.71	0.69	0.89	0.72		16	0	2	32	128	198	171	189	112	23	1	0	0	0	16
17		3.99	3.18	2.87	1.69	1.36	0.68	1.99	1.18		1.08	0.61	0.39		17	0	1	22	87	138	117	129	76	16	1	0	0	0	17
18		6.51	2.85	3.96	2.31	1.25	1.32	1.05	0.87	0.93	0.55	0.88	0.69	0.58	18	0	0	7	26	39	35	39	23	5	0	0	0	0	18
19			3.78	1.35	2.42	1.68	1.43	0.78	0.78	0.86	0.77	0.96	0.63	0.65	19	0	0	1	3	4	4	2	8	0	0	0	0	0	19
20		0.06	4.21		3.58	0.05	1.29	1.07	0.72	0.85	0.72	0.67	0.84		20	0	0	0	0	0	0	0	0	0	0	0	0	0	20
21				1.56	1.39	1.03	1.27	0.74	0.83	0.54	0.92	0.59			21	0	0	0	0	0	0	0	0	0	0	0	0	0	21
22				3.32	2.68	1.15	0.75	1.18	0.71	0.52	0.67	4.01			22	0	0	0	0	0	0	0	0	0	0	0	0	0	22
23															23														23

FIT														FIT-CPS														
	14	13	12	11	10	9	8	7	6	5	4	3	2		14	13	12	11	10	9	8	7	6	5	4	3	2	
2	185	186	124	181		207	217	172	119		185	185	185	2	64	-19	48	49		23	98	28	58		48	47	72	2
3	186	187	137	233	295	276	294	217	120		185	185	185	3	-38	8	37	76	87	185	66	182	5		51	57	91	3
4		187	141	248	317	295	315	238	131	186		185	185	4		-3	58	7	29	37	-142	-97	38	-34		44	17	4
5		187	142	258	321	299	319	232	131	186		185	185	5		23	-182	-18	28	-164	-26	53	-43	-44		-16	71	5
6	186	187	142	251	321	299	320	232	131		185	185		6	42	-17	2	-17	61	54	57	-76	-15		54	22		6
7	186	187	142	251	321	299	320	232	131	186		185	185	7	61	-44	14	44	-15	-3		-49	12	-27		-2	76	7
8	186	187	142	251	321	299	320	232	131	186	185	185		8	22	-21	-9	-129	26	-27	37	-85	-58	-25	-48	38		8
9	186	187	142	251	321	299	320	232	131	185	185	185	185	9	7	-79	8	-164	135	-122	-165	22	35	15	-2	58	16	9
10	186	187	142	251	321	299	320	232	131	186	185	185	185	10	30	17	-186	-12	87		0	-112	-28	53	-113	55	-25	10
11	186	187	142	251	321	299	320	232	131	186	185	185	185	11	48	-85	56	-18	123	57	-188	-76	-58	-75	16	15	18	11
12	186	187	142	251	321	299	320	232	131	186	185	185	185	12	45	11	-9	-103	19	15	-12		-98	82	-3	-7	-22	12
13	185	187	142	251	321	299	320	232	131	186	185	185	185	13	83	56	44	9	-62	-26	-5	136	-143	-48	-177	-228	-28	13
14	185	187	142	251	321	299	320	232	131	186	185	185	185	14	47	61	63	52	-4	-17	-114	18	-27	-7	-183	-38	-1	14
15	186	187	141	249	319	297	317	231	131	186	185	185	185	15	75	17	32	114	94	39	-59	67	16	-52	-56	-17	-48	15
16	186	187	138	233	296	276	294	217	126	186	105	185	185	16	56	38	49	-37	125	-73	17	32	-53	-43	-48	-12	-40	16
17	186	187	127	193	235	222	234	182		186		185	185	17	76	73	83	79	62	-183	15	28		8		-67	-168	17
18	185	186	112	132	144	141	144	129	118	125	105	185	185	18	89	63	84	75	29	34	7	-19	-8	-88	-14	-58	-77	18
19		186	188	189	189	189	189	188	188	186	185	185	185	19		78	28	63	44	33	-48	-38	-17	-32	-4	-62	-56	19
20	185	185		186	186	186	186	186	186	185	185	185	185	20	92	80		76	-15	24	7	-42	-19	-48	-52	-28	20	
21				186	186	186	186	186	185	185	185	185	185	21				38	38	3	22	-36	-21	-89	-9	-73	21	
22				186	186	186	186	185	185	185	185	185	185	22				74	65	14	-36	16	-44	-99	-53	79	22	
23														23														23

	14	13	12	11	10	9	8	7	6	5	4	3	2		14	13	12	11	10	9	8	7	6	5	4	3	2
--	----	----	----	----	----	---	---	---	---	---	---	---	---	--	----	----	----	----	----	---	---	---	---	---	---	---	---

Fig. B.1. EFFI Output. Upper left: Efficiency multipliers. Lower left: Fitted count-rate distribution. Upper right: Fit with background subtracted. Lower right: Difference between fitted and observed counting rates.

not free from noise, which is manifested as extra and missing lamp images. Used in the DIGLITES data-processing code is a subroutine (FUDG) that corrects for many of the extra and missing lamps, on the basis of certain statistical and consistency criteria.

When (a) the counting statistics are good (many counts per scaler per data cycle), (b) the fuel motion is not too rapid, and (c) scanning noise is not too great, then the majority of the significant extra and missing lamps can be correctly identified. Consider, however, a situation such as E6 after the reactor power has become very low. With a cycle time of only 1.5 ms, the number of counts per scaler per cycle is very low. In fact, most scalers in most cycles have a count of zero, and rarely is there a count greater than 1.

Clearly, a valid count of 1 can never be distinguished from a spurious one; therefore a count of 1 can never be rejected. Similarly, although a count of 2 can sometimes be rejected on statistical grounds, the true counting rate must be lower than 0.1/cycle. In practice, this means that only a small fraction of the spurious second-order lamps can be rejected.

Missing lamps, under such conditions of low counting rate, are a lesser problem, for two reasons: (1) The films are usually scanned with "noisy" settings, so that there is a greater tendency to record a lamp where there is none than to miss one that is there. (2) Even if the probability of missing an existing lamp at a given location were the same as the probability of recording a nonexistent one, so few lamps are lit at very low counting rates that there would be many more extra lamps than missing ones.

For the low-power tail of E6, the effect of the undetected spurious low-order lamps can be estimated, as follows: In the last 126 cycles of the E6 data, the FUDG routine detected (and corrected) 608 high counts, with all bit positions above second or third order approximately equally represented. Since there were 229 functioning scalers (12 bits/scaler), the number of bit positions where a spurious lamp would be detected was $10 \times 229 = 2290$, and the number of spurious lamps per bit position per cycle was $608 / (126 \times 2290) = 0.0021$.

In each cycle, 90% of the scalers had a true count of 0 and thus were candidates for a spurious first-order lamp. The number of spurious lowest-order lamps per cycle, then, was $0.9 \times 229 \times 0.0021 = 0.43$. As for second-order lamps, the counting rate in 60% of the scalers was such that the upper limit (for acceptable counts) was greater than 2, so that the number of undetected spurious second-order lamps per cycle was $0.6 \times 229 \times 0.0021 = 0.29$ (each such lamp contributing a spurious count of 2). Thus the total number of extra counts per cycle was $0.43 + 2 \times 0.29 = 1.0$. Since the cycle time was 1.5 ms, this translates to a spurious addition of 670 counts/s to the total count rate (all scalers), or about 2.9 (counts/s)/scaler. For the end of E6, this constitutes a spurious increase to the array-average count rate of about 5%.

If the spurious increases were uniformly distributed over all channels, the individual rates, the array average A , and the power-monitor average P would all be increased by the same amount, statistically. Since A/P is ~ 1.8 in E6 (see Fig. B.3 on p. 82), background noise that causes A to increase by 5% would cause P to increase by 9%. If statistics were sufficiently good, then one would expect to see a 4% reduction in A/P as the reactor power in E6 goes to zero, if the amount of fuel in the viewing area remains constant. As it is, however, the random scatter in the data entering into Fig. B.1 is sufficient to mask a 4% change in A/P . Thus the only practical effect on the E6 results of this type of experimental error is an increase in the random background. By similar reasoning, missed lamps also would increase the random background, and the bias they would introduce into the data would partially offset the effect of the extra lamps on A/P .

4. Test Results

The power-transient portion of the E6 power profile, as derived from the hodoscope data (circles) and the TREAT instrumentation (line), are shown in Fig. B.2. The hodoscope points are the average counting rate of the entire

Fig. B.2. Power-transient Portion of E6, as Given by Hodoscope Power-monitor Channels and by TREAT Power Monitor. Hodoscope data are normalized to the TREAT data at the peak.

array of neutron detectors, corrected for deadtime and supralinearity, and normalized to the TREAT power curve at the peak. The agreement between the peak/plateau ratios for the two curves is evidence that, as averaged over all channels at least, the supralinearity corrections have worked well.

As has been observed in other tests, such as E7 and E8, the hodoscope power curve is somewhat narrower than the TREAT curve. Several hypothetical causes of this discrepancy have been advanced, including gamma sensitivity in the ion chamber that is used to measure reactor power, loss of fuel from the hodoscope field (not confirmed by other indicators), incorrect balance between deadtime and supralinearity corrections, and a calibration factor that is a function of control-rod position.

Analysis of the hodoscope data is based primarily on the power-normalized counting rates R/P . For such normalization, it is desirable to use for a power curve one that has as little noise as possible. The hodoscope data permit one to determine both a "power-monitor-average" and an "array-average" counting rate, the former being the average of selected channels from the periphery of the viewing area, where there is no test fuel, and the latter being the average of all the channels in the field of view (or in any selected portion of that field).

We will show in Sec. 5 below that the array-average counting rate was not observably affected by the loss of fuel from the hodoscope field of view during the transient. That being the case, the array average, with its better statistics, was used in place of the power-monitor average in determining the power-normalized counting rates.

5. Detection of Upward Motion

In other tests in the TOP series, such as E8, early fuel motion has consisted of expulsion of molten fuel from the axis of a failing pin into the coolant stream. The fuel was carried rapidly upward to the region above the test-fuel zone, where it congealed in the cooler superstructure. The hodoscope was able to sense this process in E8, because in that test the fuel was positioned low in the hodoscope field of view, permitting fuel within the first few inches above the original fuel zone to be detected. In E6, however, the fuel was positioned so high in the field of view that detection of the rapid transport of small amounts of fuel to the upper region was precluded.

The hodoscope data for E6 do, however, permit us (a) to place an upper limit on the amount of fuel that left the hodoscope viewing area during the transient, by means of the ratio of the array-average counting rate to the power-monitor average, and (b) to make a rough estimate of the amount lost by analyzing the distribution of the indicated gains and losses within the field of view. As described in Sec. 9 of this appendix, the latter approach yields the result that perhaps 9 ± 4 g of fuel was lost to the field of view during E6, with equivocal indications that some of that fuel might have returned before the end of the test.

Figure B.3 shows the ratio of the array-average counting rate A to the power-monitor-average counting rate P as a function of time. If there were loss of an appreciable fraction of the fuel, one would expect a drop in A/P . No such drop is seen in Fig. B.3. The scatter of the data and the residual supralinearity are such that loss of fuel corresponding to as much as 0.05 A/P unit might not be evident. Of the average 1.75 A/P units at the time of peak power (9.12 s), ~ 1.0 unit is background. Thus the upper limit to the amount of fuel lost to view is $0.05/(1.75 - 1.0) = 6.5\%$. Since the total amount of test fuel was 450 g, we conclude on this basis that not more than 30 g of fuel moved to the upper region during the test. This is consistent with the other indications, mentioned above, that only 9 g of fuel left the field of view during E6.

Fig. B.3. Time Plot of Ratio of Array-average Counting Rate to Power-monitor-average Counting Rate for Transient E6

In E8, the upward velocity of the initially expelled fuel was about 20 m/s, which means that a spurt originating near the midplane would spend not more than about 10 ms traveling upward through the fuel zone. Even though the data-collection cycle time in E6 was 1.5 ms, a few grams of fuel moving at such a velocity would be difficult to see in the data, because this amount of fuel would tend to be lost in the counting statistics. If the initial break was in fact only 75 mm from the top of the fuel column (as indicated by the post-mortem), the fuel in transit would of course be even harder to detect. Thus we will not be able to be quantitative about the velocity at which the fuel traveled upward in E6.

Redistribution of fuel below the top of the fuel zone will be apparent in the differential hodographs to follow. Loss of fuel from a limited portion of the fuel zone, even if the fuel lost moves out of the field of view, will show up as a region of deficits. There will, of course, be no information as to where such lost fuel went, and the deficits will be balanced (since the data are normalized to the array average) by randomly appearing counting-rate increases in the rest of the field of view. (Although normalizing the data to the power-monitor average P would in principle prevent the small spurious increases from appearing, in reality the statistics in P are so much worse than in A that any advantage is lost. Note that in Fig. B.3 the ratio P/A is constant within the scatter of the data.)

6. Fuel Motion

The differential hodographs in Fig. B.4 help to determine when the first fuel motion to be evident in the hodoscope data occurred. For all three diagrams, the reference time interval is the period between 8.0 and 8.8 s, during which we can assume that there was negligible fuel motion. Averaging over that long an interval, even with the power at or near the plateau level, gives fairly good statistics.

The final, or terminating, intervals of these three differential hodographs cover the range from 8.932 to 9.113 s in consecutive 60-ms steps. The first two show the sort of random scatter of changes that is consistent with the reproducibility of the data, with no indication that any fuel has moved. In the third, however, a pattern of counting-rate decreases begins to emerge, particularly in column 9 near the midplane.

We conclude from Fig. B.4 that fuel motion reached the point where it should be evident in more detailed differential hodographs somewhere between 9.05 and 9.11 s. We proceed to examine the evidence of first fuel motion at somewhat higher time resolution.

a. Fuel Motion from 9.052 to 9.082 s

For the differential hodographs of Fig. B.5, the reference time interval is the period 8.99-9.05 s, which, as we have just seen, is before significant fuel motion. The final data-averaging intervals, specified below each diagram, have durations of 30, 30, 23, and 15 ms.

Fig. B.4. Differential Hodographs for E6 from 8.932 to 9.113 s, Referenced to Preheat Plateau (8.0-8.8 s). The final data-averaging interval is given below each hodograph. The first evidence of fuel motion comes after 9.05 s.

Fig. B.5. Differential Hodographs for E6 from 9.052 to 9.150 s, Referenced to Promotion Time (8.992-9.052 s). For mass scale, see Fig. B.4.

The earliest differential hodograph that shows fuel motion is the first one of Fig. B.5, the chief feature of which is a string of small deficits in column 9, centered approximately at the midplane. The deficits are balanced by higher density in the fuel region than outside it. There are several possible explanations for the pattern in this differential hodograph.

(1) Apparent fuel motion could be due to random variations in the data, unrelated to fuel motion, and in fact this cannot be ruled out. (As the reactor power increases, the statistical noise decreases, but channel-to-channel variations due to imperfect corrections for deadtime and supralinearity tend to increase.) However, earlier hodographs (see Fig. B.4) do not have comparable patterns, and the concentration of deficits in column 9 suggests something nonrandom. Additional confirmation that this is probably the beginning of real fuel motion is given by the succeeding differential hodographs, which indicate a continuing spread of deficits in the fuel zone.

(2) Lateral motion of some fuel pins could account for the string of losses. Although one would then expect to see more consistent gains at the left or right, this explanation cannot be ruled out either. If the gains were spread over a larger area than the losses, many of the former could well be below the minimum (0.4 g) that would show up on the diagram. Again, however, the fact that the succeeding pictures show spreading of the depleted region is strong evidence that lateral motion, although possibly the cause of what is seen in Fig. B.5A, at least is not the main cause of the fuel motion that immediately follows.

(3) Conceivably, fission-gas pressure within the still-unfailed central pin increased in the midregion in such a manner as to cause the central pellets to separate. However, the presence of a central void over most of the length of this preirradiated pin makes such a mechanism hard to visualize. Moreover, to account for the indicated loss of 4 g from this region of the central pin, the top of the fuel column in that pin would have to be levitated by 20 mm, which is approximately the vertical extent of a hodoscope channel (22.5 mm). Thus one would expect to see a counting-rate increase in row 2, column 9, which we do not. However, since single-channel indications are unreliable, this lack by itself is not conclusive.

(4) There could perhaps have been axial flow of liquid fuel within the central pin, which had been irradiated and had a central void. (Calculations indicate that axial melting is beginning at about this time.) The flow could be upward--driven by expanding fission gases--or downward, or both. Again, some 4 g of fuel must leave the central part of the pin, and the failure to see sufficient accumulation at the top or bottom casts doubt on this scenario.

(5) The pattern could be indicative of molten fuel expelled from the axis of the central (since the deficits are central) pin through a break in the cladding. Judging by other transients (such as E8 and H5), such extruded

fuel would have been carried rapidly upward to congeal in the cooler region above the fuel zone, which could account for the failure to see in Fig. B.5A where the displaced fuel went.

(6) Gradual failure of one of the peripheral pins might have begun at 9.07 s, by which time the solidus, as calculated, was approaching the edge of the hottest fresh pellets. Since there was no built-up pressure of fission gas in the fresh pins, the meltthrough of cladding, accompanied by the mild expulsion of perhaps still-solid fuel fragments into the sodium, might lead to smaller perturbations of the flow and pressure than would release of the fission-gas inventory of the central pin. Along with this, we might postulate a coincident, slight, leftward displacement of one or more pins, to account for the central location of the deficits. The postulated displacement is leftward (away from the pump), because that is where the hottest peripheral pins were, and thus where the expulsion of the fuel would occur first. This scenario has a serious problem, however, in that the insertion of even 5 g of hot fuel into the coolant stream should have led to clearly apparent perturbations in flow and pressure, and no such changes above the noise level appear until 9.15 s. This can be seen in Figs. 15 and 16. The evidence, particularly from the flow curves, is convincing that there was negligible gas release to the coolant stream before 9.15 s. Thus we will reject the possibility that there was pin failure at 9.07 s.

(7) The COBRA calculations indicate that most of the fuel in the hotter peripheral pins was molten by this time. Although there were no fission gases in these pins, helium was locked inside the pins when they were welded, and the postmortem revealed that there had been bubbles of gas in the fuel in regions where this fuel had been molten. Thus there is a mechanism--expansion of helium that had penetrated the oxide pellets--for reducing the fuel density near the midregion of the hotter peripheral pins. The possibility is considered more quantitatively in Sec. 10 of this appendix, with the conclusion that the mechanism is indeed a possible one.

If the hodoscope data were considered alone, explanation (5) would seem the most likely one. However, this would be in direct conflict with the failure of the loop flow and pressure sensors to show any perturbations until 110 ms later, before which time--as will be seen--the hodoscope data show small but widespread changes in fuel distribution. We also note that the COBRA calculations show the columnar-grain region of the central pin just reaching the solidus at about the time of Fig. B.5A, which would make it a little early for failure of the central pin.

Based on the lack of confirmation by either loop instruments or calculation that the central pin failed at this time, we will abandon (5), along with (6), as a viable scenario. Of the remaining ones, (2), (4), or (7) would do about equally well in accounting for Fig. B.5A, considered in isolation. But when the subsequent differential hodographs are factored in and the other

loop instruments are taken into account, (7) emerges as the most promising candidate. In the discussion that follows, then, we will for the most part assume that gas expansion within still-intact cladding of peripheral pins was responsible for the early fuel motion depicted in Fig. B.5.

A somewhat different view of the hodoscope data is presented in Fig. 19, where each curve shows, as a function of time, the change in the amount of fuel seen by a row (columns 5-14) of hodoscope detectors. These are "R/P-change" curves, where P in this case is the array-average counting rate. The mass calibration was determined as described in Sec. 3 of this appendix. For each curve, the zero level is the average R/P value for the time between 8.0 and 9.6 s, during which there was negligible fuel motion.

Of particular relevance to the timing of first fuel motion are the curves for rows 9 and 11, which show loss of counting rate beginning at 9.02 s. By 9.1 s, these losses had grown to the point where they could show up on the second differential hodograph of Fig. B.5. (Row 10 might have shown a similar pattern in Fig. 19, if it were not for the anomalous, and possibly spurious, increase in the channel in row 10, column 11, that shows in the first two hodographs of Fig. B.5.)

Considering, then, both Figs. B.5 and 19, we conclude that fuel motion observable to the hodoscope began at 9.06 ± 0.01 s, and that we probably have in E6 a case in which there was appreciable axial motion of molten (fresh) fuel before cladding rupture.

b. Fuel Motion from 9.082 to 9.150 s

The next differential hodograph (Fig. B.5B) shows additional deficits in the fuel region. The compensating increases have a tendency to concentrate in the upper left quadrant of the fuel region, and at the extreme upper and lower left of the viewing area. The latter two groupings are probably random. In the scenario we are adopting, expanding gases near the midregion of the hotter peripheral pins are pushing molten fuel toward the top and bottom of the pins, causing increasing density near the ends of the fuel zone as some of the free space within the (thermally expanding) pins is occupied by fuel.

As is discussed in Sec. 9 of this appendix, there is some evidence that fuel is being lost to the field of view of the hodoscope at this time. Since we cannot say that material expelled from pins is being swept upward by sodium, we fall back on the postulate that the tops of some of the fuel columns are moving upward--that we would have seen counting-rate increases above row 2 if that region had been under observation. The increases we do see in row 2 are somewhat consistent with this picture, but larger increases in that row would be more reassuring.

A notable feature of Fig. B.5B is the string of deficits in the top two-thirds of column 8. This more likely represents a leftward shifting of one or two pins than vertical motion of fuel within a pin.

The deficits in the middle third of the fuel region add up to about 15 g, of which perhaps half has left the field of view.

The averaging interval for the differential hodograph of Fig. B.5C includes the time of peak power (9.12 s). There is evidence of continued fuel loss in the central third of the fuel zone, with indication of small accumulations near the top and bottom. Some of the apparent increases could, as mentioned above, be in compensation for loss of fuel from the field of view. Most, however, seem to represent real accumulation of fuel near the top and bottom of the fuel zone, since otherwise one would expect a more uniform scatter of increases outside the fuel zone. Further, the analysis described in Sec. 7 of this appendix does not indicate that much fuel left the viewing area between B and C, the sensitivity being about ± 5 g.

The accumulated net deficit in the middle third of the fuel region at this time amounts to 12 ± 3 g, or somewhat less than 10% of the 150 g of fuel in that region.

Note that in these hodographs the region of deficits is expanding laterally to the full width of the fuel region, implying that more of the peripheral pins are participating.

Figure B.5D shows a rather uniform pattern of fuel-zone deficits in hodoscope rows 7-11, amounting to about 30 g of fuel. The string of deficits has reappeared in column 8 after partially disappearing in the preceding hodograph. This could be accounted for by pin squirming.

The sum of the indicated increases in Fig. B.5D does not balance the sum of the decreases, even though the data are normalized to result in a true balance. The explanation is (necessarily) that the increases are distributed more evenly over the array than are the deficits, making many of the former too small (less than 0.4 g) to show up on the differential hodograph. This is further indication that some fuel has disappeared from the field of view. The net accumulated fuel-region deficit at this time is 15 g, of which more than half (see Sec. 7 of this appendix) seems to have been lost from the field of view.

c. Fuel Motion from 9.150 to 9.211 s

The four differential hodographs of Fig. B.6 show developments in the 60-ms interval between 9.151 and 9.211 s. Notable in this interval are the growth of the fuel surplus above row 7, principally at the left and right and in the top row, and the gradual growth of deficits (totaling 30-35 g by 9.21 s) below that level.

A. 9.151-9.166 s (15 ms)

B. 9.166-9.181 s (15 ms)

C. 9.181-9.196 s (15 ms)

D. 9.196-9.211 s (15 ms)

Fig. B.6. Differential Hodographs for E6 from 9.151 to 9.211 s, Referenced to Premotion Time (8.922-9.052 s). For mass scale, see Fig. B.4.

During the terminating interval of Fig. B.6A, the loop instruments give their first indications of pin failure. We therefore postulate the following sequence of events for the time spanned by Fig. B.6:

At 9.15 s, the central pin (presumably) and possibly some peripheral pins fail, injecting gram quantities of fuel into the coolant stream, with consequent flow and pressure pulses. This supposition is based entirely on nonhodoscope information. Although the hodoscope gives no indication of sudden fuel motion at this time, the postulate is not in conflict with the hodoscope data.

Once in the coolant stream, the fuel particles are carried rapidly upward (as indicated by results from other transients) to congeal in the cooler superstructure above the fuel region. The small increases that appear at the upper left and right of the fuel region in Fig. B.6C could be, in part, fuel on the way up, or else fuel that has come up and has now stopped.

By 9.20 s (see Fig. B.6D), there are signs of congestion in the top third of the fuel region, with an extra ~8 g of fuel in row 2, and more fuel collecting below it on the left and right. There is no indication that any significant amount of fuel has moved downward. We note the variability in Fig. B.6C of the small indicated surplus below the fuel zone, which suggests that much of that apparent surplus, up to this point, has been due to random fluctuations in the data--consistent with all the data being somewhat biased toward apparent surpluses by the upward loss of fuel.

The total (not net) fuel-region deficit indicated in Fig. B.6D is about 25-30 g, of which about 10 g (see Sec. 9 of this appendix) is missing from the field of view.

d. Fuel Motion from 9.211 to 9.294 s

The first hodograph of Fig. B.7 indicates the situation as of 9.22 s, at which point the reactor power was down to 48% of its peak value. An accumulation of some 40 g of fuel (an increase of 15 g over what was showing in that region in the preceding picture) can be seen above the level of row 7, laterally and vertically distributed rather uniformly. The assumption is that this is hot fuel in the coolant channels, perhaps prevented from going further upward by a blockage above.

There is no indication that the fluted tube has yet been breached to any extent.

The configuration near the top of the fuel zone was unstable, as can be seen by noting the differences between parts A and B of Fig. B.6. In hodograph B, there are more deficits and fewer surpluses at the center and left of the fuel zone, in rows 4-8, while new increases develop at the lower left and upper right.

A. 9.211-9.234 s (23 ms)

B. 9.234-9.294 s (60 ms)

C. 9.234-9.249 s (15 ms)

D. 9.234-9.249 s (15 ms)

Ref.: premotion

Ref.: 9.211-9.234 s (23 ms)

Fig. B.7. Differential Hodographs for E6 from 9.211 to 9.294 s. Parts A-C are referenced to the premotion period 8.992-9.052 s; D is referenced to the terminating interval for A. The terminating intervals for C and D are the same; namely, the first 15 ms of the terminating interval for B. For mass scale, see Fig. B.4.

A more precise indication of the timing of this fuel motion can be obtained by looking at shorter-term differential hodographs. Figure B.7C, while still using premotion time for the reference fuel configuration, has the data integrated over a shorter final interval: 15 ms (9.234-9.249 s) instead of 60 ms (9.234-9.294 s). The statistics for this shorter period are, of course, worse, but the main features of the change have already appeared. The hodograph for the preceding 15-ms period (not shown) is not very different from Fig. B.7A, leading us to conclude that the main part of this fuel motion took place rather rapidly--within a 10-ms period centered at 9.234 ± 0.005 s. (The assigned time is near the front of the averaging interval for Fig. B.7C because the extent of agreement between B and C indicates that most of the change had occurred before much of the time interval in C had passed.)

Figure B.7D shows the short-term change: While the final averaging interval is the same as for the preceding hodograph, the reference interval is the same as the averaging interval for Fig. B.7A. Thus Fig. B.7D is in effect the difference between Figs. B.7A and B.7C. The general loss from near the upper left of the fuel zone is evident, as are increases at other parts of the field of view, particularly in the top row. These increases in the top row may represent fuel that is moving upward, but more likely (both on the basis of E8 and of the upper limit on the amount of fuel that went up) this is fuel accumulating against the bottom of a blockage.

It was found in the postmortem examination that the fluted tube had a 5-cm-high breach at about the elevation of the agglomeration at the right-hand side of rows 4-7 in Fig. B.7B, at about 45° from the direction of the pump. Such an event at that angular position would not show up on the hodoscope as a definite penetration of the fluted tube (unless some of the fuel flowed around, outside the fluted tube, toward the pump), because no fore-and-aft component of fuel motion is ever detectable by the hodoscope. However, the sudden augmentation of this agglomeration at the level of the observed breach suggests that penetration of the fluted tube could well have happened at 9.23 s.

The large fuel loss in the channel at row 6, column 9, is not confirmed by comparable losses in adjacent channels and thus is more likely to have been caused by bad data than by a very highly localized fuel voiding, especially since there is enough overlap between adjacent channels that such a loss of fuel in the field of view of one channel would cause an appreciable reduction in the signal from the adjacent channels.

To be credible, counting-rate changes must be evident in groups of channels. In addition, they must be physically reasonable--which the string of deficits in column 2, for example, is not, since no test fuel is in line with those channels. We therefore conclude that many of the small, scattered gains and losses in the last two differential hodographs of Fig. B.7 are caused by random fluctuations in the data.

The total (not net) of the indicated fuel-region deficits in Fig. B.7B is 45-50 g, which is about 10% of the total amount of test fuel. The analysis in Sec. 9 of this appendix indicates that about 20% (9 g) of this displaced fuel is missing from the field of view. This is down from an estimated 13 g missing from the preceding picture, but the difference is within the experimental error and therefore might or might not indicate the return of fuel from above.

The two flowmeters and the lower pressure sensor (see Figs. 15 and 16) showed a disturbance that began at 9.23 s, correlating closely with the sudden fuel motion depicted in Fig. B.7. Although this occurred when the fluted tube was probably breached, as we have seen, the magnitude of the flow disturbance is more compatible with failure of another fuel pin than with in-flow of gas from the adiabatic holder. Possibly, however, failure of a pin triggered the immediate breach of the fluted tube.

e. Fuel Motion from 9.294 to 9.712 s

The reference time for the two differential hodographs of Fig. B.8 is once more the premotion period 8.99-9.05 s. By the time of the first of these hodographs, the power level was at or below the level of the preheat plateau, and the counting statistics were becoming poor. The figure does indicate, however, that fuel motion was still taking place; there is increased accumulation of fuel at the upper right and some apparent loss of fuel from the lower part of the fuel zone.

Although the terminal averaging interval used for the second hodograph of Fig. B.8 is 246 ms long, the statistics are very poor because the reactor had shut down. Note that the mass calibration for this hodograph has changed, each symbol standing for three times the previous mass change. The noise in the data makes it hard to be definite about the significance of the diagram, but some groupings of increases and decreases might be meaningful. We notice the following:

(1) The accumulation at the right side of the fuel region at rows 4-6 persists (remembering the scale change).

(2) There are equivocal signs that some fuel might have left the fuel region at rows 2 and 3--equivocal because some deficits are also indicated at the extreme right of those rows, where such a change is not physically possible.

(3) The increases toward the left of the fuel region at rows 9 and 10 may be real. If they are, they indicate that the net deficit showing in the preceding hodograph at the same location has been more than compensated, with perhaps 20 g more of fuel at that level than was there originally. The hodoscope, of course, cannot indicate whether this extra fuel was among the pins or at the periphery, possibly outside the fluted tube.

A. 9.294-9.466 s (172 ms)

B. 9.466-9.712 s (246 ms)

Fig. B.8. Differential Hodographs for E6 from 9.294 to 9.712 s, Referenced to Premotion Time (8.992-9.052 s). Reactor power is close to zero, and statistics are poor. Note differences in mass scales.

(4) The lower half of the diagram is not greatly changed from the preceding one, with persisting evidence of a slight net loss of fuel from the bottom half of the fuel zone and scattered increases outside the fuel zone at the lower left.

7. Axial Fuel Profiles

Figure B.9 contains the hodoscope data in the form of axial profiles. Each curve shows the axial distribution of fuel at a particular time. Proceeding upward from the bottom, one can see the accumulation above row 7 becoming evident at about 9.17 s, with a corresponding deficit centered on row 9. Beyond 9.5 s, the statistics are too poor to permit definite interpretations. There are indications, however, that some of the midregion deficit is being replenished.

8. Comparison with Posttest Radiograph

The posttest neutron radiograph (Fig. 21) and the last differential hodograph (Fig. B.8) agree in some respects and not in others. Both the radiograph and the hodographs indicate that the top of the fuel was raised somewhat, and both show a depleted region ~20 mm long, centered ~80 mm below the top of the test fuel zone. The radiograph shows an apparent pin separation in the lower half of the fuel zone, which correlates with the string of deficits in column 9 in Fig. B.8B.

The radiograph has a density bulge at both sides, at the lower level of the bellows (55-85 mm below top of fuel zone). Although there are similar bulges in the hodographs of Fig. B.8, particularly on the pump side, they are ~20 mm higher up than the ones in the radiograph and might or might not be related. We do note that fuel motion probably continued beyond the time of Fig. B.8, so that one would not necessarily expect good agreement between the radiograph and the final hodographs.

In the hodographs there are small increases below the fuel zone. No trace of fuel here can be seen in the radiograph, which suggests that these hodoscope indications are spurious. On the other hand, the radiograph shows debris outside the fluted tube, for 20 mm or so above the bottom of the fuel zone, where nothing shows on the hodographs. We conclude that either the debris did not contain fuel or it fell down there after the time of Fig. B.8.

The surplus indicated near the midplane in Fig. B.8B is not confirmed by the radiograph, but this is to be expected, since the original amount of fuel there was sufficient to make the image black.

The radiograph shows some material scattered about in the superstructure, extending for ~250 mm above the fuel zone. As discussed elsewhere, the hodoscope indications are that there was not more than 10-20 g of fuel in this material.

Fig. B.9. Axial Profiles of Fuel Distribution in E6. Time runs from bottom to top. Data for each row are sums over columns 5-14 with background subtracted. Midpoint and duration of each data-averaging time interval are given. Mass calibration is in grams per hodoscope row and in grams per millimeter of axial distance.

9. Estimate of Fuel Lost to Hodoscope Field

The fact that a large portion of the hodoscope field of view is not exposed to test fuel presents us with the chance to estimate the amount of fuel that is lost to view. Such loss can occur in two ways: (1) Fuel that moves outside the boundaries of the hodoscope field is lost to the hodoscope. (2) As discussed in Sec. 1 of this appendix, fuel that moves into a boron-shielded region can be partially lost to view because the efficiency adjustments probably do not completely compensate for the reduced fission rate. The following discussion applies to both types of loss.

We observe in the differential hodographs that small, random increases and decreases appear in the non-fuel-viewing channels, such as those in columns 2-4. These signals are due to statistical and other random fluctuations in the data. We will assume that the chance of having a one-unit random fluctuation in one of the fuel-viewing channels is the same as in one of the peripheral channels. (If anything, this will lead to an underestimate of the noise in the fuel channels, since the signals there, and hence the statistical fluctuations, are somewhat larger). A "unit," in the case at hand, is the signal that would be produced by a change of 0.8 g of fuel as indicated by the calibrated scale of Fig. B.4.

Consider, first, the deficits. In a differential hodograph whose reference interval precedes fuel motion, there is no physical reality to an indicated deficit outside the original fuel zone, i.e., outside rows 2-18 of columns 6-12. Dividing the field, then, into those two regions, we determine the sum of the deficits in each (for a given differential hodograph), determine the average noise level in a peripheral channel, multiply that level by the number of fuel channels, and subtract that product from the sum of the fuel-channel deficits. The result is an approximation of the total amount of fuel leaving the channels where a decrease is indicated. For brevity, this will be referred to as the "true decrease."

The procedure for the increases is similar, except that as the transient progresses, the number of channels that cannot be exposed to fuel diminishes, so that the peripheral region that can be used for determining the noise level becomes smaller. In analyzing the differential hodographs of Figs. B.5-B.8, we used the following fuel regions:

	<u>Fig.</u>	<u>Rows</u>	<u>Columns</u>	<u>No. of Channels</u>	
				<u>Fuel</u>	<u>Background</u>
Deficits	All	2-18	6-12	119	147
Increases	B.5	2-18	6-12	119	147
	B.6	2-19	6-13	144	122
	B.7, B.8	2-20	5-14	190	76

If the true decreases are assumed to exceed the true increases, the difference between them can be interpreted to be the amount of fuel lost to view. As a sample calculation, consider the differential hodograph of Fig. B.6C, which yields the following data:

Total deficits in fuel region (119 channels):	38	units ± 6.2 units
Total deficits in peripheral region (147 channels):	8	
Calculated fuel-region background:	$8(119/147) = 6.5$	± 2.3
"True decreases":	$38 - 6.5 = 31.5$	± 6.6
Total increases in fuel region (144 channels):	33	± 5.7
Total increases in peripheral region (122 channels):	11	
Calculated fuel-region background:	$11(144/122) = 13.0$	± 3.9
"True increases":	$33 - 13.0 = 20.0$	± 7.0
Fuel lost (units):	$31.5 - 20.0 = 11.5$	± 9.6
Fuel lost (g):	9.2	± 7.7

In the above, the error in the number of units counted in each region is assumed to be the square root of the count. Clearly the precision of this calculation is not high. However, the results from the differential hodographs, given in Table B.1, do show some consistency--except for the last two, which are for a time region when the power level was low and the counting statistics were getting poor, and for which there is a possible explanation (see below).

TABLE B.1. Fuel Lost to Hodoscope Field

Differential Hodograph	Time, s	True Decreases, units	True Increases, units	Fuel Lost	
				units	g
B.5A	9.06	6.5	6.1	0.4	0.3
B.5B	9.10	22.9	14.9	8.0	6.4
B.5C	9.13	21.9	13.5	8.4	6.7
B.5D	9.14	29.3	17.3	12.0	9.6
B.6A	9.16	18.3	16.2	2.1	1.7
B.6B	9.17	21.7	15.6	6.2	5.0
B.6C	9.19	31.5	20.0	11.5	9.2
B.6D	9.20	36.8	26.7	10.1	8.1
B.7A	9.22	44.1	28.0	16.1	12.9
B.7B	9.26	59.0	47.5	11.5	9.2
B.8A	9.47	37.6	58.5	-30.5	-24.0
B.8B	9.59	50.0	125.0	-78.0	-62.0

A different indication of the precision of these calculations can be obtained as follows. Assume for the moment that ~8 g of fuel was lost to view just after the first differential hodograph and that from then on there was no more loss. If now we determine the average loss for all the lines in Table B.1 except the first one and last two, we get 7.64 g, with a standard deviation, as

calculated from the scatter of the data, of ± 1.06 g in the average, or a variance of ± 3.19 g in the individual fuel-loss measurements. The latter number is appreciably smaller than the ± 7.7 g determined in the above sample calculation, which perhaps means that the square-root assumption made in that calculation was not valid.

In view of the uncertainty in the numbers in the last column of Table B.1, detailed conclusions cannot be drawn about the course of fuel loss in E6. The data are compatible with any of the following scenarios:

- a. At about 9.08 s, 8 g of fuel was lost to view and did not return, and no more was lost after that.
- b. Starting at 9.06 s, there was a gradual loss of fuel that peaked at 13 g at 9.22 s, after which time a fraction of that returned.
- c. The amount of fuel lost to view fluctuated during the test, with a peak of 10 g at 9.14 s, a valley of 2 g at 9.16 s, and another peak (13 g) at 9.22 s.

Drawing on our experience with other transients, we present this as the most likely, although by no means the only possible, scenario: Upward transport of fuel began with the first pin failure at 9.06 s, reaching a maximum of 9 ± 4 g at 9.20 s, after which a few grams might have come back down.

As outlined above, the calculation of the fuel loss or gain, whose results are listed in Table B.1, depends upon determining a "background" from the non-fuel-viewing channels. For Fig. B.8, the number of channels available for background for the increases is small (76) compared with the number assigned to the fuel region (190). Looking particularly at Fig. B.8B, we notice that there are about twice as many decreases as increases in the background region. This could indicate an overall gain in fuel, but the calculated 60 g (see Table B.1) is not physically reasonable.

An examination of this calculation reveals that doubling the number of background increases (from 11 to 22) would more than cancel the apparent 62-g gain. In view of the poor counting statistics, such an error does not seem unreasonable and provides a more likely explanation for the apparent net gain in fuel after reactor shutdown.

10. Effect of Boron Flux Shapers on Fuel-motion Detection

In trying to make a quantitative determination of loss of fuel from the hodoscope field of view, the question of hodoscope response to fuel that moves into or out of regions shadowed by flux-shaping collars becomes relevant. This section describes calculations based on E6 data and on the use of efficiency factors that are determined by EFFI on the basis of the uniform-background, uniform-pin model. The results should be typical.

The type of efficiency multiplier mentioned provides full compensation for the effects of axial flux gradients in the reactor and partial compensation for the effects of flux-shaping collars. For this analysis, we assume that the reactor flux has no axial gradient over the central 400 mm or so, which (a) is not a bad assumption and (b) makes no difference to the result of this analysis. (Full "compensation" would mean that a given fuel-mass change would lead to a counting-rate change that is independent of position in the test region.)

Fig. B.10. Fission-product Profiles from Gamma Scans of Central H3 Pin with and without Boron Flux-shaping Collars

We are making the unnecessary, but simplifying, assumption that the only reason for using efficiency multipliers is to correct for the effect of the flux-shaping collars; i.e., we ignore the channel-to-channel efficiency variations.

Figure B.10 shows the effect of boron on the fission rate in a 343-mm central fuel pin (data from A. Rothman), the boron configuration here being the same as in E6. The dashed line in Fig. B.10 represents the EBR-II flux shape, which was the shape the boron was intended to match, if possible. Note the high points at either end, which are due to flux peaking caused by local reflectors.

Near the ends of the fuel region, the fission rate (obtained by gamma-counting the fuel pellets) reaches a minimum of ~85% of the average midplane value and then rises rapidly because of the effect of the local flux peaking. The data do not extend beyond the end of the fuel, but one might expect that small amounts of fuel that moved above the original fuel zone would undergo an enhanced fission rate in spite of the boron.

Consider fuel that moves from near the midplane to the region of minimum fission rate. The method of determining the efficiency multipliers E results in

$$E(S_e + B) = S + B, \quad (1)$$

where B is assumed constant over the field.

In Eq. 1 and subsequent equations, the symbols have the following meaning:

B = background signal;

E = efficiency multiplier near end of fuel (under flux-shaping collar)
(At midplane, efficiency multiplier = 1.);

F = neutron flux;

k = constant;

m = fuel mass in region under consideration;

S = signal from test fuel at midplane, not including background;

S_e = signal from test fuel near end (under flux-shaping collar);

T = total signal from midplane: $T = S + B$;

and

T_e = total signal, efficiency corrected, from near the end of the fuel:
 $T_e = E(S_e + B)$.

From Fig. B.10, we have

$$S_e = 0.85S. \quad (2)$$

If we substitute Eq. 2 in Eq. 1, making use of the E6 datum

$$B = 0.45S, \quad (3)$$

we get

$$E = 1.115, \quad (4)$$

which is to say that the 15% decline in the test-fuel fission rate leads to a 12% increase in E , given the signal-to-background conditions that prevailed in E6.

The signal S at the midplane is proportional to m and to F :

$$S = kmF. \quad (5)$$

Similarly, from Eq. 2,

$$S_e = 0.85kmF. \quad (6)$$

Thus,

$$T = kmF + B \quad (7)$$

and

$$T_e = E(\text{Se} + B) = E(0.85kmF + B). \quad (8)$$

By differentiating Eqs. 7 and 8 with respect to m , we get

$$dT/dm = kF \quad (9)$$

and

$$dT_e/dm = 0.85EkF. \quad (10)$$

The relative effect of a change dm in fuel mass is, then, the ratio of Eq. 10 to Eq. 9, which is $0.85E$. Since $E = 1.115$, we have

$$dT_e/dT = 0.95. \quad (11)$$

Equation 11 says that, in E6, 5% of fuel that moves from the midplane to the region of minimum flux inside the boron will seem to have left the field of view of the hodoscope. This constitutes an upper limit to the amount of fuel that can disappear in this manner. In practice, of course, only about 10 mm of axial distance at each end is in the minimum-flux region. Also, as mentioned above, any fuel that moves above the main mass of fuel is likely to have its fission rate somewhat enhanced. Thus, although the boron definitely adds to the uncertainty in interpreting the hodoscope data, the added uncertainty is not in general large: If 10 g were to move into the minimum-flux zone, ~0.5 g would disappear.

Conversely, fuel that moved down (or up, if it could be seen) from that zone would tend to be augmented slightly as it came out from behind the boron.

In E6, the top of the test fuel was close to the top of the hodoscope field of view, with the flux minimum coming near the boundary between rows 2 and 3 of the hodoscope detectors. Thus apparent accumulations in those rows would tend to be ~4% too small, while fuel that went up a little farther, to the enhanced-flux region, would tend to be above the field of view and thus would truly be lost to view. Had the test region been a little lower in the field, there would have been more possibility of some offsetting of the overall loss by enhanced response in the region of flux peaking.

The hodoscope data from E6 indicate an apparent loss of ~7 g of fuel from the field of view before pin failure, from a total of ~17 g of fuel displaced from the midregion. This is much too high a fraction to be due entirely to the boron, so that most of the missing fuel probably did in fact leave the field of view.

In conclusion, this discussion indicates that the uniform-pin, uniform-background model for determining efficiency multipliers will provide fairly good compensation for the effects of flux-shaping collars, provided that (a) S/B is ~ 2 or greater, and (b) the flux depression under the collar does not amount to more than 15 or 20%.

11. Fabrication Gas as a Cause of Prefailure Fuel Motion in TOP Tests

The postulate that early fuel motion in unfailed, unirradiated pins in E6 was due in part to expansion of gas (mainly helium) left in the pin in the fabrication process can be tested for reasonableness by simple gas-law calculation.

In E6, we need to account for the displacement of ~ 10 g of fuel, between the time when the fuel temperature in the hotter region was ~ 2600 K and the time of pin failure. At a density of 10 g/cm^3 , this would be 1.0 cm^3 of oxide. If the fuel-pellet density was a typical 92% of maximum theoretical, one can assume that $\sim 8\%$ of the volume of fuel was occupied by fabrication gas.

We will calculate the average melt fraction that would be needed in some of the fresh, peripheral pins that would lead to an axial displacement of the indicated amount of fuel by a combination of thermal expansion, phase-change expansion, and expansion of fabrication gas. Certain simplifying assumptions will be used.

<u>Symbol</u>	<u>Value</u>	<u>Definition</u>
Fg	0.08	Fraction of (room-temperature) fuel volume occupied by gas (value based on 92% of maximum theoretical density).
Fs	3.34 N	Downward force exerted by the spring at the top of the pin.
G	9.80 m/s^2	Acceleration due to gravity.
Mi	0.0221 kg	Mass of Inconel spacer + oxide insulator pellet at the top of pin.
Mp	0.0670 kg	Total mass of fuel in one pin.
P1	101.3 kPa	Atmospheric pressure.
S	$2.03 \times 10^{-5} \text{ m}^2$	Cross-sectional area inside cladding.
T1	293 K	Room temperature (initial temperature for calculating gas expansion).

<u>Symbol</u>	<u>Value</u>	<u>Definition</u>
T2	3040 K	Liquidus temperature of oxide fuel.
Vf	$4.5 \times 10^{-5} \text{ m}^3$	Total volume of fuel (seven pins).
Vp	$6.4 \times 10^{-6} \text{ m}^3$	Volume of fuel in one pin.

The following five quantities will vary from test to test and probably will not be accurately known for any test. The values listed are assumed to be reasonable approximations for Test E6.

Et	0.01	Fractional linear thermal expansion of solid fuel during a time interval preceding pin failure. The value given comes from assuming an average fuel temperature in E6 of 2600 K at 9.025 s (the reference point for the differential hodographs, before which there was no discernible fuel motion), and an average fuel temperature of 2900 K at the time of first fuel melting. The results of the calculation will not be very sensitive to changes of a hundred degrees or so in this temperature interval.
Lf	0.5	Of the fabrication gas liberated as the fuel melts, this fraction is assumed to remain in the pin, retained by the solid crust, to cause fuel displacement as it expands. The value is no better than a guess.
Lp	0.75	Fraction of axial length of fuel column assumed to participate in the early axial melting. Axial melting is assumed to extend to the top of the fuel column.
Md	0.01 kg	Mass of fuel displaced before pin failure. The value is consistent with hodoscope indications for E6.
Np	3	Number of pins assumed to participate in the early axial melting. The value 3 is considered a reasonable guess for E6.

Derived Quantities

F_m	Areal melt fraction, averaged over V_t .
P_h	Pressure increment due to weight of Inconel rod, insulator pellet, and head of molten fuel.
P_2	Final pressure on the liberated gas (volume V_2) that is retained within the solid crust.
Q	Factor relating V_2 with molten volume; defined by Eq. 10.
V_d	Volume of displaced fuel (mass M_d).
V_e	Volume of fuel displaced by linear expansion + phase-change expansion.
V_g	Original volume (STP) of liberated gas remaining in fuel to cause displacement.
V_t	Total "participating volume" of fuel, i.e., the volume of fuel in the hot fraction L_p of the N_p pins.
V_2	Final volume of the gas that had initial volume V_g .

In doing the calculations, we will use additional assumptions:

- a. At TREAT time 9.025 s, the mean reference time used by the hodoscope for determining fuel displacement, the mean temperature in the participating volume of the fuel was ~ 2600 K.
- b. At the time of pin failure, the mean fuel temperature in the participating volume was 2900 K, implying a 300° rise during the time interval of interest.
- c. The entire fuel bundle (seven pins) will be assumed to undergo a 300° temperature rise during that time interval, and the value of E_t will be assumed to be constant over the whole bundle.
- d. Only the vertical component of thermal expansion can be detected by the hodoscope.
- e. The fuel displaced by expanding gas moves axially only, being radially constrained by an unmolten shell whose outer diameter does not change during the interval of interest.
- f. The phase-change expansion (increase in specific volume of oxide upon melting) causes axial motion only, for the same reason.
- g. The phase-change expansion amounts to 10% of the original volume of oxide that melts (from Ref. 33).
- h. The inertia of the material above the expanding gas does not pertain, since the situation when acceleration has ceased (pin has failed) is relevant.

a. Formulas for Derived Quantities

$$V_t = N_p \times V_p \times L_p \quad (12)$$

and

$$P_h = (M_i + L_p \times M_p/2)G/S, \quad (13)$$

where the second term in parentheses is the average head of molten fuel.

$$P_2 = F_s/S + P_h + P_1. \quad (14)$$

$$V_d = M_d/(10 \text{ g/cm}^3) = (1E - 4M_d) \text{ m}^3/\text{kg}, \quad (15)$$

where the density of fuel is assumed to be 10 g/cm³.

$$V_g = L_f \times F_g \times F_m \times V_t. \quad (16)$$

$$V_e = E_t \times V_f + 0.1F_m \times V_t. \quad (17)$$

The volume V_2 will be the difference between the total volume V_d of fuel displaced and the sum V_e of the effects of linear expansion and phase-change expansion:

$$V_2 = V_d - V_e. \quad (18)$$

By the gas law,

$$V_2 = V_g \times P_1 \times T_2/(P_2 \times T_1). \quad (19)$$

From Eqs. 19 and 16,

$$\begin{aligned} V_2 &= F_m \times V_t [L_f \times F_g \times P_1 \times T_2/(P_2 \times T_1)] \\ &= F_m \times V_t \times Q, \end{aligned} \quad (20)$$

where, for convenience, Q represents the quantity in brackets:

$$Q = L_f \times F_g \times P_1 \times T_2/(P_2 \times T_1). \quad (21)$$

Combining Eqs. 17-19, we get

$$F_m = (V_d - E_t \times V_f)/[(Q + 0.1)V_t]. \quad (22)$$

b. Results

If the input-constant values given above for E_6 are used in Eqs. 12-15, 21, and 22, one gets

$$F_m = 16\%,$$

which is to say that, under the assumptions used, a total of 10 g of fuel would have been displaced when the average melt fraction over the postulated "participating volume" was 16%. Equations 16 and 20 now give 0.090 and 0.33 cm³, respectively, for V_g and V₂, and the volume of molten fuel would have been $F_m \times V_t = 2.2 \text{ cm}^3$.

Changes in some of the input constants can have a pronounced effect on F_m and V₂. For example, increasing the gas-leakage estimate so that only 10% (instead of 50%) is retained ($L_f = 0.1$) increases F_m to 30%, lowers V₂ to 0.12 cm³, and increases the volume of molten fuel to 4.3 cm³. At the limit of no gas retention, $F_m = 38\%$ and ~5.5 cm³ of fuel would be molten, to cause a displacement of 10 g.

c. Conclusions

Because of the large uncertainty in some of the input quantities (notably L_f and also the product $N_p \times L_p$), the above calculation could not be expected to provide a useful estimate of the melt fraction F_m. The calculation is an order-of-magnitude one to test the hypothesis that expanding fabrication gas could contribute to the observed prefailure axial fuel motion.

The conclusion is that the gas can help move the molten fuel if conditions are right. Under the assumed value of 0.5 for L_f , only a modest melt fraction is required to cause a total displacement of 10 g of fuel, of which ~3 g was due to the retained gas. A melt fraction larger than 16% averaged over the top 75% of three pins can be accommodated by postulating a smaller L_f , although eventually (at $F_m = \sim 38\%$, under the other assumptions used here) oxide expansion by itself will account for the observed displacement.

In any event, expanding fabrication gas can be expected to cause fuel displacement before the melt fraction becomes large, under the following conditions:

(1) The fuel is relatively fresh; i.e., there is no central void or extensive cracking to permit the rapid escape of gas from the fuel pin. (Cracks and a central void could also keep phase-change expansion from causing observable axial displacement.)

(2) Heating is rapid enough that (a) central melting of the pin can extend over an appreciable fraction of the axial length while a thick peripheral crust of solid oxide remains intact, and (b) there is not time for all the liberated gas to leak from the fuel. The former condition (large axial extent of central melting) tends to prevail in a TOP test where there is a rapid ramp rate and the outside of the pin is cooled by flowing sodium. The latter is made more likely if (and perhaps required that) most of the pellets in the region of axial melting are (or become) fused together. If the hot pellets have expanded to a tight friction fit in the cladding, their axial displacement will be hindered, helping to prevent radial leakage of the gas from the molten center.

(3) The constraint against upward flow of molten fuel must not be too great; i.e., $P2$ must not be too large.

Note that the assumption made in connection with the definition of L_p , that axial melting extends to the top of the pin, is not strictly necessary. What is sufficient is that the pellets be fused together over an appreciable axial distance. Any fuel pellets above the region of axial melting that are displaced upward can be regarded as adding to the weight of the insulator pellet in the above analysis.

Failure to see, in many of the other transients, signs of prefailure motion such as occurred in E6 is not remarkable. Irradiated fuel (with cracks and a central void), for instance, would not be expected to show it. Nor would an LOF test in which the cladding failed early and heating was relatively slow, giving time and opportunity for the expanding gases and molten fuel to escape from the pins. Indications of the phenomenon were, however, discovered in the analysis of the fresh-fuel TOP Tests E1 (Ref. 34) and H2 (Ref. 10), where conditions were favorable. In the postmortem examination of the E6 peripheral pins, small voids postulated to have been caused by expanding fabrication gas were observed.

APPENDIX C

Thermal-Hydraulic Calculations

Results from LIFE-3 for the steady-state irradiation of the central pin were used directly in COBRA input as a weighting function for fresh-pin data. The results are given in Sec. IV.B. Details of the additional input parameters to COBRA are given in this appendix.

1. Flow-channel Geometry

Assume the space wires and the peripheral pins are in contact with the fluted tube, and the irradiated pin is centered in the cluster. The geometry for this case is illustrated in Fig. C.1.

Fig. C.1. Geometry Used in Computing Channel Flow Areas,
Heated and Wetted Surfaces, and Duct-wall Lengths

Dimensions given in the design specifications or postfabrication measurements are:

$$r_1 = \text{radius of central pin} = 0.115 \text{ in.} = 0.2921 \text{ cm,}$$

$$r_2 = \text{radius of spacer wire on central pin} = 0.020 \text{ in.} = 0.0508 \text{ cm,}$$

$$r_3 = \text{radius of edge pins} = 0.115 \text{ in.} = 0.2921 \text{ cm,}$$

$$r_4 = \text{radius of spacer wire on edge pin} = 0.028 \text{ in.} = 0.07112 \text{ cm,}$$

$$r_5 = \text{flute radius} = 0.115 \text{ in.} = 0.2921 \text{ cm,}$$

$$\overline{OE} = \text{flute centers} = 0.495 \text{ in.} = 1.2573 \text{ cm,}$$

and

$$\overline{OC} = \text{ID of fluted tube} = 0.460 \text{ in.} = 1.1697 \text{ cm.}$$

From these definitions,

$$\overline{OA} = \overline{OC} - 2r_4 - r_3 = 0.7341 \text{ cm.}$$

Assume that spacer wires are heat sinks and are homogenized into the cladding OD:

$$r_1' = \sqrt{r_1^2 + r_2^2} = 0.2965 \text{ cm}; \quad r_2' = 0,$$

$$r_3' = \sqrt{r_3^2 + r_4^2} = 0.3006 \text{ cm}; \quad r_4' = 0.$$

The coordinates of A are $X_A = \overline{OA} \cos(\pi/6) = 0.6357 \text{ cm}$ and $Y_A = \overline{OA} \sin(\pi/6) = 0.3670 \text{ cm}$. The coordinates of D are intersections of circles:

$$X^2 + Y^2 = \overline{OC}^2$$

and

$$(\overline{OE} - X)^2 + Y^2 = r_5^2,$$

or

$$X_D = \frac{\overline{OC}^2 + \overline{OE}^2 - r_5^2}{2\overline{OE}} = 1.1376 \text{ cm}$$

and

$$Y_D = \sqrt{\overline{OC}^2 - X_D^2} = 0.2665 \text{ cm}.$$

From the geometry of Fig. C.1,

$$\alpha = \tan^{-1}(Y_D/X_D) = 0.2301 \text{ radian},$$

$$\beta = \pi/6 - \alpha = 0.2935 \text{ radian},$$

$$\delta = \tan^{-1}(Y_A/\overline{BE}) = 0.5333 \text{ radian},$$

$$\gamma = \tan^{-1}[Y_D/(\overline{OE} - X_D)] - \delta = 0.6153 \text{ radian},$$

$$\angle OAB = \pi/3 = 1.0472 \text{ radians},$$

$$\angle BAE = \pi/2 - \delta = 1.0375 \text{ radians},$$

and

$$\angle CAE = \pi - \pi/3 - (\pi/2 - \delta) = \pi/6 + \delta = 1.0567 \text{ radians}.$$

Flow areas in channels are given by

$$F_A = \Delta AOB - (\pi/12)(r_1^2 + r_2^2) - (\pi/6)(r_3^2 - r_4^2) = 0.04637 \text{ cm}^2,$$

$$F_B = \Delta AEB - \delta r_3^2/2 - \frac{1}{2}\angle BAE(r_3^2 + r_4^2) = 0.04447 \text{ cm}^2,$$

and

$$F_C = \text{Total} - \text{Ch A} - \text{Ch B} = 0.06346 \text{ cm}^2,$$

where

$$\text{Total} = \beta \overline{OC}^2/2 + \Delta ODE - r_5^2(\gamma + \delta)/2 - \pi(r_3^2 + r_4^2)/2 - \pi(r_1^2 + r_2^2)/12 = 0.1543 \text{ cm}^2$$

and

$$\Delta AOB = \frac{1}{2} X_A Y_A = 0.1167 \text{ cm}^2,$$

$$\Delta AEB = \frac{1}{2} (\overline{OE} - X_A) Y_A = 0.1141 \text{ cm}^2,$$

and

$$\Delta ODE = \frac{1}{2} \overline{OE} Y_D = 0.1675 \text{ cm}^2.$$

The heated surfaces by channel are

$$H_A = \pi r_1/6 + \pi r_3/3 = 0.470 \text{ cm},$$

$$H_B = \angle BAE r_3 = 0.312 \text{ cm},$$

and

$$H_C = \angle CAE r_3 = 0.138 \text{ cm}.$$

The duct wall lengths by channel are

$$D_A = 0,$$

$$D_B = \delta r_3 = 0.156 \text{ cm},$$

and

$$D_C = \beta \overline{OC} + \gamma r_3 = 0.499 \text{ cm}.$$

The wetted surfaces by channel are

$$W_A = H_A + \frac{\pi}{6} r_2 + \frac{\pi}{3} r_4 = 0.470 \text{ cm},$$

$$W_B = H_B + D_B + \angle BAE r_4 = 0.468 \text{ cm},$$

and

$$W_C = H_C + D_C + \angle CAE r_4 = 0.817 \text{ cm}.$$

The geometry used in the COBRA calculation is that shown in Fig. 7, where channels 7 and 8 are twice those shown here for channel A. The same is true for channels 2 and 5.

2. Thermal Conductivity

Fuel thermal conductivity depends on both the porosity and the oxygen-to-metal (O/M) ratio.³³ Relative to its value at 100% theoretical density (TD), the thermal conductivity is given as

$$k(P) = k_{TD}(1 - 2.5P) \text{ for porosities } P \leq 0.1$$

and by

$$k(P) = k_{TD} \frac{1 - P}{1 + 2P} \text{ for } P > 0.1.$$

Relative to the O/M ratio for 95% TD ($P = 0.05$) fuel,³³

$$k = (4.2 + 350X + 0.0271T)^{-1} + (6.9 - 35X)10^{-13}T^3 \text{ W/cm}\cdot\text{K},$$

where T is the temperature in degrees Kelvin and $X = 2.00 - (O/M)$.

The central pin in Test E6 had $O/M = 1.97 \pm 0.02$ (see Table I) and an average porosity of 0.122. Accordingly, the thermal conductivity was 70% of the value for TD fuel or 80% of the value calculated for 95% TD fuel.

The fresh edge pins had $O/M = 1.96$ and a porosity of 0.08. Thermal conductivity for this fuel is 91% of that calculated for 95% TD fuel with $X = 0.04$. Results are tabulated in Table C.1, where k_f is the thermal conductivity for

TABLE C.1. Calculated Values of Thermal Conductivity for
Fresh PNL-17 Pins (k_f) and Preirradiated HEDL-NF Pin (k_I)
(in W/cm·K) Used in Test E6

T, °F ^a	k_f	k_I	T, °F ^a	k_f	k_I
500	0.028724	0.028377	2100	0.016751	0.015506
600	0.026516	0.025941	2200	0.017023	0.015748
700	0.024654	0.023921	2300	0.01739	0.01608
800	0.023075	0.02223	2400	0.017851	0.016502
900	0.021731	0.020807	2500	0.018408	0.017015
1000	0.020589	0.019607	2600	0.019061	0.01762
1100	0.019621	0.018596	2700	0.019811	0.018316
1200	0.018807	0.017751	2800	0.02066	0.019106
1300	0.018131	0.017051	2900	0.021608	0.019989
1400	0.017583	0.016482	3000	0.022659	0.020969
1500	0.017152	0.016033	3100	0.023814	0.022047
1600	0.016832	0.015696	3200	0.025074	0.023223
1700	0.016618	0.015464	3300	0.026441	0.024501
1800	0.016505	0.015332	3400	0.027919	0.025882
1900	0.016491	0.015296	3500	0.029508	0.027368
2000	0.016573	0.015355			

^aConversion factor: °C = (°F - 32)/1.8.

the fresh PNL-17 pins and k_I is for the irradiated HEDL-NF pin. Since COBRA accepts only one tabular listing for fuel thermal conductivity, the values for k_I were used.

Reference 33 gives the thermal conductivity for the cladding (Type 316 stainless steel) as

$$k_{316SS} = 0.09248 + 1.571 \times 10^{-4}T \text{ W/cm}\cdot\text{K}$$

and for the duct wall (of Type 304 stainless steel) as

$$k_{304SS} = 0.08116 + 1.618 \times 10^{-4}T \text{ W/cm}\cdot\text{K}.$$

3. Heat Capacity

Heat capacity for $(U_{0.75}Pu_{0.25})O_{1.98}$ is given in Ref. 33 as

$$C_p = 12.54 + 0.017T - 0.117 \times 10^{-4}T^2 + 0.307 \times 10^{-8}T^3 \text{ cal/mole}\cdot\text{K},$$

where 1 cal = 4.184 J and 1 mole of fuel = 268.222 g. (Reference 33 has a typographical error in the coefficient of the T^2 term, printed as 0.0117×10^{-4} .) Results are tabulated in Table C.2.

TABLE C.2. Calculated Values of Heat Capacity for $(U_{0.75}Pu_{0.25})O_{1.98}$

T, K	C_p , J/g·K	T, K	C_p , J/g·K
500	0.28856	1800	0.3609
600	0.29936	1900	0.36907
700	0.30824	2000	0.37906
800	0.31547	2100	0.39113
900	0.32136	2200	0.4056
1000	0.32618	2300	0.42273
1100	0.33022	2400	0.44282
1200	0.33377	2500	0.46616
1300	0.33712	2600	0.49303
1400	0.34056	2700	0.52372
1500	0.34437	2800	0.55852
1600	0.34884	2900	0.59771
1700	0.35425	3000	0.64159

Similarly, the heat capacity for cladding and duct wall are given in Ref. 33 as

$$C_{p304SS} = 6.213 + 1.784 \times 10^{-3}T \text{ cal/mole}\cdot\text{K}$$

and

$$C_{p316SS} = 6.181 + 1.788 \times 10^{-3}T \text{ cal/mole}\cdot\text{K}.$$

Both materials are assumed to have a gram molecular weight of 56.34 g/mole.

4. Thermal Expansion

Reference 33 gives the mean thermal-expansion coefficient for $(U_{0.75}Pu_{0.25})O_2$ up to the melting temperature (2998 K) as

$$\frac{\Delta L}{L_0} = 6.8 \times 10^{-6}(T - 273) + 2.9 \times 10^{-9}(T - 273)^2 \text{ cm/cm.}$$

COBRA calculates the outer radius of the fuel pellet from

$$r(T) = r_0[1 + (A + BT)(T - T_0)],$$

where A and B are input constants:

$$A = 6.0083 \times 10^{-6} \text{ and } B = 2.9 \times 10^{-9}.$$

Expansion coefficients for steel are given as

$$\left(\frac{L}{L_0}\right)_{304SS} = 1.263 \times 10^{-5} + 4.854 \times 10^{-9}T + 7.238 \times 10^{-13}T^2 \text{ cm/cm}$$

and

$$\left(\frac{L}{L_0}\right)_{316SS} = 1.789 \times 10^{-5} + 2.398 \times 10^{-9}T + 3.269 \times 10^{-13}T^2 \text{ cm/cm,}$$

where L_0 is the length at 298.15 K.

A reference temperature of 293 K is used in COBRA. Neglecting terms in T^2 and higher gives

$$A_{304SS} = 1.285 \times 10^{-5}; \quad B_{304SS} = 4.939 \times 10^{-9}$$

and

$$A_{316SS} = 1.820 \times 10^{-5}; \quad B_{316SS} = 2.440 \times 10^{-9}.$$

5. Gap Conductance

Gap conductance will vary from a minimum value at room temperatures to a maximum value when the gap is closed. Both limiting values are calculated by the LIFE-3 code and are used as input to COBRA for the irradiated pin. After cooldown, the LIFE-3 code also gives the residual gap due to fuel swelling. For the fresh pins in COBRA, the as-fabricated gap is used and its conductance is determined from the thermal conductivity of helium. A value of $0.493 \text{ W/cm}^2\cdot\text{K}$ was calculated at room temperature. When the gap

is closed, the contact conductance becomes large and depends on the contact pressure, the interface roughness, and the cladding yield strength. Since the cladding yield strength changes by more than a factor of 2 between 850 and 1150 K, the contact gap conductance will vary from approximately 2 to 4 W/cm²·K for a contact pressure of 0.1 MPa (1000 atm). As a compromise, a value of 3 W/cm²·K was used as the maximum gap conductance in the COBRA calculation for fresh fuel. Values for the gap parameters used in the E6 calculations are listed below.

	<u>Central Pin</u>	<u>Edge Pin</u>
Room-temperature gap, mm	0.0418	0.0762
Minimum gap conductance, W/cm ² ·K	0.297	0.493
Maximum gap conductance, W/cm ² ·K	2.178	3.0

6. Miscellaneous COBRA Input Constants

All thermodynamic properties for sodium were taken from Ref. 33 and entered into COBRA in tabular form. The Lyon-Martinelli correlation for constant wall heat flux was used for the film coefficients:

$$\text{Nu} = 6.3 + 0.03\text{Pe}^{0.8},$$

where Nu is the Nusselt number and Pe the Peclet number. Friction factors used in calculating pressure drops were based on the Darey-Weisback correlations (four times the Fanning factors):

$$f = 0.3164\text{Re}^{-0.25}.$$

Interchannel thermal mixing was used (thermal-conduction factor = 1.0), and turbulent momentum mixing was set to 0.7 times the interchannel mass mixing.

APPENDIX D

Digital-test Data

Test signals from the loop and reactor instrumentation were recorded on 14-channel analog tape having a bandwidth of 20 kHz. Data from the tape were digitized at a 20-kHz rate, summed into 1-ms time bins, corrected for zero shift in the read-and-write amplifiers, and multiplied by constants to convert ADC output to millivolts and millivolts to engineering units. Constants for the zero shift and the first conversion were determined from calibration signals recorded on the tape.

Flow signals over selected ranges were least-squares fit to a trend plus a 60-Hz sine and cosine term of the form

$$X(t_i) = \beta_0 + \beta_1 t_i + \beta_2 t_i^2 + \beta_3 t_i^3 + \beta_4 \sin(\omega_0 t_i) + \beta_5 \cos(\omega_0 t_i) + \epsilon_i.$$

The square residuals $\sum [X(t_i) - \epsilon_i]^2$ were minimized. The 60-Hz signals were then removed from the flow data over a range that included the fitting range:

$$y(t_i) = x(t_i) - \beta_4 \sin(\omega_0 t_i) - \beta_5 \cos(\omega_0 t_i).$$

Problems associated with normalizing the outlet flow to that at the inlet during steady flow conditions were noted in Sec. IV.A. The test data in 50-ms increments are tabulated in Table D.1. Outlet-flow data in this table have been normalized to the inlet flow during the 50-ms interval from 9.00 to 9.05 s in order to produce a zero void at 9.05 s. Flow rates, their integrals and temperatures, and the indicated void are shown in millisecond time increments in Table D.2.

TABLE D.1. E6 Test Data Listed in 50-ms Time Increments.

Outlet flow has been normalized to inlet flow rate during the interval 9.00-9.05 s.

TIME	TC1	TC2	TC3	TC4	TC5	TC6	TC7	UF	LF	UP	LP	SAF1	INT1
SEC	DEGK	DEGK	DEGK	DEGK	DEGK	DEGK	DEGK	CC/S	CC/S	PSI	PSI	W	HJ
9.025	668.	671.	673.	671.	669.	670.	584.	788.9	697.6	33.1	-6.3	7.	7.
9.075	668.	672.	675.	672.	670.	671.	584.	784.9	694.1	40.6	-3.5	13.	9.
9.125	668.	671.	675.	672.	670.	670.	585.	799.4	704.3	47.9	-0.8	18.	10.
9.175	668.	670.	675.	671.	669.	670.	584.	787.9	697.6	55.4	0.3	19.	9.
9.225	668.	671.	674.	671.	669.	670.	584.	790.1	706.4	66.4	3.4	22.	10.
9.275	668.	670.	675.	672.	670.	671.	584.	820.7	720.0	77.8	8.1	27.	12.
9.325	669.	671.	675.	672.	669.	671.	585.	840.6	738.5	90.7	12.4	30.	14.
9.375	668.	671.	674.	672.	670.	670.	584.	826.5	731.8	102.2	16.1	34.	14.
9.425	668.	671.	674.	672.	669.	670.	584.	806.6	715.7	114.3	21.3	45.	15.
9.475	668.	671.	675.	672.	670.	671.	585.	818.4	725.8	127.2	28.5	40.	19.
9.525	669.	672.	675.	672.	670.	671.	585.	817.9	725.9	135.3	36.5	77.	22.
9.575	668.	671.	675.	672.	670.	670.	584.	816.4	713.9	137.0	43.8	96.	26.
9.625	668.	672.	675.	673.	670.	670.	584.	830.2	735.2	133.6	52.3	123.	32.
9.675	669.	672.	676.	673.	671.	671.	585.	818.5	719.3	125.1	58.8	148.	37.
9.725	669.	673.	676.	674.	671.	671.	585.	831.4	732.5	118.0	62.0	177.	46.
9.775	669.	672.	676.	674.	671.	671.	584.	839.8	746.9	114.3	62.6	179.	55.
9.825	668.	672.	676.	674.	671.	671.	584.	840.9	761.4	115.1	63.0	178.	64.
9.875	669.	674.	678.	676.	672.	671.	585.	861.9	769.3	119.3	64.4	169.	74.
9.925	670.	675.	679.	677.	673.	671.	585.	859.4	773.9	117.7	65.4	146.	82.
9.975	670.	674.	679.	678.	673.	671.	584.	830.6	748.2	117.1	65.4	171.	89.
10.025	669.	675.	680.	679.	673.	671.	584.	811.4	711.5	110.4	66.7	176.	98.
10.075	670.	677.	681.	681.	674.	678.	585.	809.3	720.4	113.2	68.0	169.	107.
10.125	670.	677.	684.	683.	676.	678.	585.	824.1	727.2	112.8	70.0	167.	116.
10.175	670.	679.	684.	685.	677.	671.	585.	816.5	723.1	107.6	69.5	172.	123.
10.225	670.	679.	686.	688.	678.	671.	585.	808.5	709.6	106.3	71.2	175.	132.
10.275	671.	680.	687.	690.	681.	672.	585.	813.7	709.8	108.0	71.8	171.	141.
10.325	671.	683.	689.	692.	682.	672.	586.	809.9	703.1	108.0	74.4	170.	150.
10.375	671.	683.	692.	694.	684.	671.	585.	778.7	693.7	102.2	74.0	172.	157.
10.425	670.	686.	693.	696.	685.	671.	585.	791.0	694.5	101.9	75.6	175.	166.
10.475	671.	687.	696.	698.	687.	678.	586.	812.8	697.0	104.7	76.9	169.	175.
10.525	672.	688.	698.	701.	689.	678.	586.	799.0	698.2	101.0	78.0	172.	183.
10.575	671.	688.	698.	703.	690.	671.	585.	800.7	689.5	96.3	78.0	173.	191.
10.625	671.	689.	700.	706.	690.	671.	585.	786.0	685.9	97.0	78.4	171.	200.
10.675	672.	691.	702.	708.	690.	678.	586.	783.0	683.7	97.1	80.3	171.	209.
10.725	672.	694.	707.	710.	693.	678.	586.	782.0	683.7	93.5	81.4	173.	218.
10.775	672.	696.	707.	711.	694.	671.	585.	779.1	674.9	92.0	81.4	176.	226.
10.825	672.	696.	710.	713.	698.	671.	585.	776.8	671.9	93.1	81.8	171.	234.
10.875	673.	699.	713.	715.	700.	678.	586.	782.0	669.0	90.9	83.4	172.	244.
10.925	674.	700.	715.	718.	704.	678.	586.	767.2	661.0	88.8	84.0	180.	252.
10.975	673.	702.	717.	722.	705.	678.	586.	762.4	659.3	86.7	83.7	171.	260.
11.025	673.	703.	720.	735.	704.	671.	586.	764.2	656.2	86.4	84.4	170.	269.
11.075	674.	706.	723.	726.	705.	678.	586.	743.2	664.6	84.1	86.2	175.	278.
11.125	675.	707.	725.	729.	708.	678.	587.	749.3	664.7	83.0	87.2	175.	287.
11.175	674.	708.	727.	732.	710.	672.	586.	732.4	655.6	82.4	86.7	171.	294.
11.225	674.	709.	728.	733.	710.	678.	586.	707.4	650.2	79.4	86.6	171.	303.
11.275	675.	712.	731.	735.	715.	672.	587.	724.2	654.6	78.1	88.8	174.	313.
11.325	676.	713.	733.	738.	718.	678.	587.	712.6	647.1	78.2	90.8	174.	322.
11.375	676.	713.	734.	739.	719.	678.	586.	718.3	640.9	76.6	89.4	178.	329.
11.425	676.	716.	737.	742.	720.	672.	586.	735.8	649.6	73.6	90.4	173.	338.
11.475	677.	717.	740.	745.	725.	672.	587.	717.2	657.5	73.3	92.4	173.	347.

TABLE D.1 (Contd.)

TIME SEC	TC1 DEGK	TC2 DEGK	TC3 DEGK	TC4 DEGK	TC5 DEGK	TC6 DEGK	TC7 DEGK	UF CC/S	LF CC/S	UP PSI	LP PSI	SAF1 MW	INT1 MJ
7.525	678.	717.	740.	747.	729.	672.	587.	719.1	645.1	72.9	93.6	173.	356.
7.575	677.	716.	740.	749.	731.	672.	586.	716.1	645.6	69.4	93.1	172.	364.
7.625	678.	717.	741.	751.	732.	673.	586.	682.9	637.3	67.2	94.7	174.	373.
7.675	679.	720.	744.	752.	733.	673.	587.	684.7	639.9	68.0	97.2	176.	382.
7.725	679.	722.	745.	753.	734.	673.	587.	650.7	648.9	66.9	98.0	174.	391.
7.775	680.	722.	747.	754.	734.	673.	587.	657.9	635.1	62.9	97.5	175.	399.
7.825	680.	722.	748.	755.	734.	673.	587.	691.6	637.6	61.7	99.1	174.	407.
7.875	681.	724.	750.	758.	739.	674.	587.	691.5	641.3	62.3	100.6	174.	417.
7.925	682.	725.	752.	759.	740.	674.	588.	685.8	640.6	60.5	101.8	174.	426.
7.975	682.	726.	751.	761.	741.	674.	587.	664.1	635.3	56.7	101.5	176.	434.
8.025	682.	726.	754.	762.	743.	674.	587.	668.3	636.2	55.0	101.6	172.	442.
8.075	684.	729.	756.	763.	745.	674.	588.	660.8	624.4	55.4	103.3	175.	452.
8.125	685.	731.	758.	766.	747.	674.	588.	672.1	628.9	53.5	103.7	175.	461.
8.175	685.	732.	760.	768.	746.	674.	587.	646.2	628.4	50.6	102.9	174.	469.
8.225	685.	733.	764.	770.	743.	674.	587.	645.9	621.4	48.1	103.8	173.	477.
8.275	686.	735.	763.	771.	748.	675.	588.	674.5	623.2	48.3	106.1	173.	487.
8.325	688.	736.	765.	775.	750.	675.	588.	647.6	623.4	47.5	106.8	176.	496.
8.375	688.	735.	764.	777.	750.	675.	588.	600.8	614.3	43.3	106.2	173.	504.
8.425	688.	737.	766.	777.	750.	675.	588.	615.2	613.6	42.9	106.7	175.	512.
8.475	689.	739.	769.	779.	753.	676.	588.	625.8	624.1	42.1	108.5	176.	521.
8.525	691.	740.	769.	782.	755.	676.	589.	613.3	621.9	41.5	109.2	173.	531.
8.575	691.	740.	770.	796.	757.	676.	588.	584.2	610.7	36.3	108.6	176.	538.
8.625	691.	740.	771.	785.	758.	677.	588.	573.1	610.4	18.4	108.0	201.	548.
8.675	693.	742.	773.	785.	759.	678.	589.	589.9	608.1	-17.0	102.6	255.	560.
8.725	694.	742.	774.	785.	761.	678.	589.	624.0	614.1	-65.5	92.5	330.	574.
8.775	694.	744.	774.	786.	761.	678.	588.	592.4	606.8	-120.1	77.6	427.	592.
8.825	695.	744.	775.	787.	766.	679.	588.	580.6	601.1	-173.2	61.8	546.	616.
8.875	697.	747.	777.	790.	769.	680.	589.	574.7	614.2	-222.7	49.6	727.	648.
8.925	698.	748.	779.	792.	768.	681.	590.	608.3	618.3	-263.6	35.0	955.	689.
8.975	699.	749.	781.	793.	776.	682.	590.	588.8	595.6	-295.2	23.4	1252.	742.
9.025	700.	753.	785.	797.	778.	685.	590.	602.3	597.5	-318.7	18.8	1622.	812.
9.075	703.	757.	790.	800.	781.	692.	591.	625.9	596.3	-335.2	16.8	2018.	902.
9.125	706.	759.	793.	801.	782.	712.	592.	641.3	574.8	-342.1	18.5	2241.	1007.
9.175	706.	765.	795.	810.	785.	722.	593.	1332.1	-23.8	-352.4	32.3	1917.	1110.
9.225	707.	767.	800.	831.	803.	766.	594.	769.0	-236.4	-334.8	49.5	1113.	1184.
9.275	707.	773.	799.	848.	816.	800.	646.	799.7	46.2	-247.7	78.1	453.	1222.
9.325	710.	776.	806.	860.	833.	818.	713.	203.9	281.0	-149.3	115.2	148.	1235.
9.375	1179.	777.	807.	891.	837.	804.	710.	50.8	-43.5	-120.5	151.3	40.	1241.
9.425	1337.	775.	809.	892.	817.	805.	695.	0.3	-177.6	-118.6	169.8	40.	1244.
9.475	1407.	777.	802.	868.	799.	807.	702.	153.8	119.0	-136.8	187.3	15.	1247.
9.525	1542.	771.	795.	856.	784.	807.	694.	234.1	224.3	-144.4	195.8	4.	1247.
9.575	524.	740.	783.	843.	785.	805.	677.	234.1	-23.3	-147.5	200.5	5.	1247.
9.625	1338.	761.	779.	838.	782.	805.	678.	133.0	-67.8	-149.0	197.7	2.	1247.
9.675	1341.	766.	781.	836.	784.	806.	680.	205.9	189.9	-149.5	196.7	6.	1248.
9.725	1372.	767.	782.	844.	772.	800.	674.	170.6	125.1	-153.0	201.1	3.	1249.
9.775	1421.	768.	792.	848.	759.	787.	669.	88.2	-88.8	-154.2	201.4	1.	1248.
9.825	1493.	766.	788.	849.	759.	757.	669.	232.9	94.5	-154.4	194.6	-1.	1248.
9.875	1567.	764.	781.	845.	757.	754.	661.	283.1	178.0	-154.5	197.7	4.	1249.
9.925	1648.	763.	781.	835.	751.	742.	643.	271.6	-9.7	-155.0	197.9	2.	1250.
9.975	1990.	763.	783.	830.	750.	737.	630.	274.1	25.2	-154.0	191.4	0.	1249.

TABLE D.1 (Contd.)

TIME	TC1	TC2	TC3	TC4	TC5	TC6	TC7	UP	LP	UP	LP	SAFI	INT1
SEC	DEGK	DEGK	DEGK	DEGK	DEGK	DEGK	DEGK	CC/S	CC/S	PSI	PSI	MW	MJ
10.025	1003.	765.	780.	824.	752.	739.	622.	289.1	161.3	-156.8	190.1	1.	1249.
10.075	427.	763.	782.	820.	754.	738.	619.	238.2	63.5	-156.5	192.7	2.	1250.
10.125	653.	761.	778.	813.	762.	730.	617.	154.5	5.4	-156.7	189.7	2.	1250.
10.175	2070.	761.	776.	807.	762.	732.	616.	246.0	140.1	-156.8	184.2	-0.	1249.
10.225	2289.	759.	773.	812.	758.	730.	616.	278.3	115.8	-156.8	185.6	0.	1250.
10.275	1614.	760.	774.	813.	757.	723.	617.	291.4	41.5	-154.5	184.3	2.	1251.
10.325	1030.	758.	774.	811.	751.	727.	616.	285.3	89.2	-155.3	181.0	2.	1251.
10.375	1117.	756.	772.	814.	749.	728.	616.	545.1	137.1	-156.8	178.2	-1.	1250.
10.425	1210.	755.	779.	827.	747.	722.	616.	260.1	84.6	-156.3	177.7	0.	1250.
10.475	1320.	756.	774.	829.	741.	721.	617.	174.9	58.2	-154.0	175.8	1.	1251.
10.525	1486.	756.	776.	830.	741.	723.	617.	194.5	107.4	-154.0	172.9	2.	1252.
10.575	1793.	755.	778.	825.	737.	729.	617.	200.1	147.3	-154.9	170.5	-1.	1251.
10.625	1579.	754.	782.	833.	736.	723.	617.	179.9	94.6	-155.5	168.8	-1.	1251.
10.675	1668.	754.	780.	839.	738.	719.	617.	213.9	47.5	-152.5	169.2	0.	1252.
10.725	1771.	753.	778.	831.	734.	728.	618.	298.2	96.1	-152.4	165.8	1.	1252.
10.775	1839.	754.	781.	850.	735.	728.	617.	263.5	146.4	-153.1	163.4	-1.	1251.
10.825	1868.	759.	788.	861.	734.	724.	618.	259.7	97.3	-152.4	162.7	-1.	1251.
10.875	1899.	761.	794.	853.	735.	723.	618.	279.3	81.1	-149.9	161.7	1.	1252.
10.925	1956.	760.	795.	840.	741.	722.	618.	300.8	125.1	-151.4	159.3	0.	1253.
10.975	1962.	758.	794.	834.	740.	722.	618.	218.8	134.2	-150.8	157.1	-1.	1252.
11.025	1944.	759.	795.	845.	733.	723.	618.	175.8	91.8	-151.2	155.6	-1.	1252.
11.075	1945.	761.	800.	873.	730.	718.	619.	314.6	85.6	-149.7	155.4	0.	1253.
11.125	1938.	757.	811.	875.	733.	716.	619.	482.2	125.6	-148.5	152.9	1.	1253.
11.175	1905.	764.	817.	888.	736.	718.	618.	369.2	142.5	-149.5	150.1	-2.	1252.
11.225	1867.	765.	818.	878.	737.	696.	618.	229.2	115.7	-150.4	148.6	-1.	1252.
11.275	1852.	769.	812.	868.	732.	689.	619.	216.4	70.6	-147.0	148.9	0.	1253.
11.325	1855.	766.	810.	867.	732.	688.	619.	158.2	120.4	-147.6	146.5	0.	1254.
11.375	1849.	770.	810.	865.	732.	691.	619.	-68.3	173.9	-148.1	143.7	-2.	1253.
11.425	1813.	778.	826.	915.	731.	694.	619.	-323.4	142.0	-147.6	142.7	-1.	1253.
11.475	1785.	777.	826.	895.	731.	690.	619.	-542.0	69.9	-146.3	143.8	-0.	1254.
11.525	1783.	776.	824.	880.	728.	698.	620.	-708.4	85.3	-146.3	141.2	1.	1254.
11.575	1756.	778.	827.	894.	722.	689.	619.	-822.3	143.8	-147.0	138.0	-3.	1253.
11.625	1724.	780.	831.	890.	721.	688.	619.	-718.1	150.0	-146.0	137.1	-2.	1253.
11.675	1708.	777.	827.	898.	729.	686.	620.	-728.4	89.8	-144.8	137.4	-0.	1254.
11.725	1697.	784.	834.	911.	734.	687.	620.	-700.1	84.7	-145.6	136.1	-1.	1254.
11.775	1685.	792.	845.	916.	729.	691.	619.	-465.6	139.8	-144.6	132.9	-2.	1254.
11.825	1669.	800.	856.	916.	729.	689.	619.	-282.9	163.2	-145.3	132.7	-2.	1254.
11.875	1656.	800.	861.	926.	734.	688.	620.	-50.8	109.7	-144.7	132.0	-1.	1254.
11.925	1637.	800.	860.	912.	735.	683.	620.	219.3	84.9	-143.4	129.9	-1.	1255.
11.975	1619.	801.	858.	913.	740.	678.	619.	139.7	135.4	-143.8	127.3	-3.	1254.
12.025	1598.	804.	865.	918.	760.	677.	619.	6.5	171.6	-143.4	126.2	-2.	1254.
12.075	1583.	797.	861.	902.	764.	676.	620.	99.6	127.4	-141.6	126.4	-1.	1255.
12.125	1560.	795.	883.	902.	754.	676.	620.	102.1	96.9	-141.1	125.5	-1.	1255.
12.175	1533.	794.	874.	917.	746.	676.	619.	49.4	138.4	-141.1	123.4	-3.	1254.
12.225	1499.	792.	866.	915.	766.	672.	619.	-29.2	165.5	-140.7	121.1	-2.	1254.
12.275	1409.	792.	848.	918.	788.	671.	620.	-37.7	139.7	-140.5	121.2	-0.	1255.
12.325	1388.	793.	851.	912.	779.	669.	620.	118.0	108.6	-138.5	120.2	-1.	1255.
12.375	1306.	792.	851.	917.	768.	668.	619.	448.3	121.0	-140.4	117.1	-3.	1255.
12.425	1303.	790.	847.	941.	757.	667.	619.	624.9	149.1	-140.3	116.0	-3.	1255.
12.475	1303.	793.	850.	954.	762.	668.	620.	802.7	136.1	-139.1	117.0	-1.	1255.

TABLE D.1 (Contd.)

TIME	TC1	TC2	TC3	TC4	TC5	TC6	TC7	UF	LF	UP	LP	SAF1	INT1
SEC	DEGK	DEGK	DEGK	DEGK	DEGK	DEGK	DEGK	CC/S	CC/S	PSI	PSI	WV	MJ
12.525	1304.	796.	851.	948.	761.	668.	620.	845.8	117.2	-138.8	115.3	-1.	1256.
12.575	1302.	801.	859.	947.	752.	667.	619.	731.8	121.6	-138.0	112.4	-3.	1255.
12.625	1301.	800.	861.	944.	753.	665.	619.	658.4	156.7	-138.3	111.0	-2.	1255.
12.675	1301.	803.	863.	935.	760.	664.	620.	682.8	164.9	-136.8	110.9	-1.	1256.
12.725	1302.	800.	862.	943.	771.	663.	620.	630.6	162.8	-138.1	110.4	-1.	1256.
12.775	1301.	803.	863.	942.	786.	664.	619.	590.9	143.1	-137.8	107.7	-3.	1255.
12.825	1301.	804.	866.	953.	780.	667.	619.	581.7	224.2	-138.0	105.7	-3.	1255.
12.875	1301.	806.	867.	956.	782.	668.	620.	595.7	181.8	-135.3	106.5	-1.	1256.
12.925	1301.	806.	869.	956.	789.	667.	620.	610.2	160.9	-134.8	105.7	-1.	1256.
12.975	1299.	810.	873.	950.	792.	670.	619.	577.7	161.1	-135.4	103.7	-3.	1256.
13.025	1298.	811.	886.	964.	779.	676.	619.	422.7	162.3	-134.9	101.9	-3.	1256.
13.075	1299.	811.	881.	960.	766.	677.	620.	319.3	165.1	-134.3	102.5	-1.	1256.
13.125	1299.	812.	878.	952.	765.	672.	620.	236.5	157.2	-134.3	101.0	-1.	1257.
13.175	1298.	812.	879.	960.	760.	676.	619.	114.5	144.1	-134.2	98.5	-3.	1256.
13.225	1297.	814.	882.	954.	754.	675.	619.	111.6	146.4	-135.0	97.6	-2.	1256.
13.275	1298.	812.	883.	944.	753.	676.	620.	125.4	157.5	-132.0	97.4	-1.	1256.
13.325	1297.	809.	878.	940.	759.	677.	620.	-29.5	167.5	-133.3	96.6	-2.	1257.
13.375	1295.	808.	875.	946.	762.	677.	619.	-188.4	168.1	-133.4	94.4	-4.	1256.
13.425	1293.	806.	870.	947.	763.	677.	619.	-212.7	174.9	-133.0	92.2	-3.	1256.
13.475	1293.	807.	868.	953.	760.	678.	619.	-155.9	184.3	-130.7	93.4	-2.	1257.
13.525	1292.	807.	871.	947.	758.	681.	620.	-167.0	195.6	-132.0	91.8	-2.	1257.
13.575	1290.	807.	868.	945.	755.	688.	619.	-200.1	197.9	-131.3	90.0	-3.	1256.
13.625	1288.	808.	871.	944.	754.	682.	619.	-356.4	192.5	-130.2	88.0	-2.	1256.
13.675	1287.	812.	874.	943.	761.	684.	619.	-528.8	197.4	-130.5	88.8	-1.	1257.
13.725	1288.	814.	876.	946.	776.	680.	619.	-522.4	188.0	-129.7	86.8	-1.	1257.
13.775	1283.	811.	875.	951.	788.	676.	619.	-496.8	177.2	-130.7	85.6	-3.	1256.
13.825	1279.	807.	870.	954.	754.	678.	619.	-493.5	174.8	-130.1	84.6	-3.	1256.
13.875	1279.	807.	869.	960.	780.	678.	619.	-399.8	180.6	-129.1	84.6	-1.	1257.
13.925	1277.	807.	866.	972.	781.	679.	619.	-331.6	178.8	-129.2	84.7	-1.	1257.
13.975	1273.	813.	872.	966.	783.	677.	619.	-341.7	184.5	-128.7	82.2	-3.	1257.
14.025	1271.	824.	879.	977.	792.	678.	618.	-343.3	185.7	-127.9	80.9	-4.	1026.
14.075	1273.	817.	882.	970.	793.	688.	619.	-336.5	186.5	-128.0	80.3	-1.	244.
14.125	1268.	811.	871.	972.	813.	692.	619.	-386.1	193.5	-126.8	79.8	-2.	68.
14.175	1268.	809.	867.	958.	836.	708.	618.	-524.3	192.9	-126.6	78.1	-2.	22.
14.225	1267.	803.	865.	968.	846.	702.	618.	-622.5	206.2	-127.5	75.8	-3.	11.
14.275	1261.	812.	865.	965.	844.	697.	619.	-584.7	213.2	-125.6	76.5	-1.	8.
14.325	1259.	807.	863.	950.	830.	698.	619.	-600.6	212.2	-125.1	75.9	-2.	8.
14.375	1257.	816.	865.	986.	814.	692.	619.	-741.3	209.9	-126.4	73.4	-3.	6.
14.425	1253.	815.	876.	1001.	819.	692.	618.	-675.3	214.5	-126.2	72.6	-3.	6.
14.475	1250.	811.	860.	1008.	851.	692.	619.	-583.9	232.7	-125.0	72.5	-1.	7.
14.525	1246.	826.	879.	1016.	862.	691.	619.	-926.9	242.7	-124.5	71.6	-2.	7.
14.575	1241.	838.	906.	1011.	859.	690.	618.	-1013.2	210.7	-124.7	69.3	-3.	6.
14.625	1237.	837.	931.	1005.	858.	689.	618.	-1082.7	186.0	-125.1	68.5	-3.	6.
14.675	1235.	839.	901.	1019.	852.	687.	619.	-1208.7	187.5	-123.3	68.3	-2.	7.
14.725	1230.	842.	905.	1032.	867.	686.	619.	-1289.6	191.3	-123.2	67.4	-2.	7.
14.775	1223.	842.	912.	1032.	883.	686.	618.	-1346.9	184.8	-123.6	65.2	-3.	6.
14.825	1215.	843.	905.	1043.	897.	691.	618.	-1397.8	190.5	-123.7	64.2	-4.	6.
14.875	1209.	852.	916.	1003.	912.	708.	619.	-1483.3	193.6	-121.8	64.1	-2.	7.
14.925	1205.	855.	926.	1004.	911.	718.	619.	-1659.4	180.4	-120.6	63.6	-2.	7.
14.975	1199.	849.	917.	996.	906.	708.	618.	-1732.2	155.5	-122.2	60.5	-4.	6.

TABLE D.2. Inlet and Outlet Flow Data with Integrals since 9.000 s, Temperatures, and Indicated Void

TIME SEC	LF CC/S	TC1 DEGR	ILF CC	UF CC/S	TC4 DEGR	IUF CC	VUID CC
9.000	603.3	700.	0.6	559.9	792.	0.6	=0.0
9.001	579.8	698.	1.2	587.9	792.	1.1	=0.0
9.002	588.1	698.	1.8	548.7	793.	1.7	=0.1
9.003	579.9	696.	2.4	565.9	793.	2.3	=0.1
9.004	593.0	698.	2.9	578.6	793.	2.8	=0.1
9.005	596.1	700.	3.5	593.6	794.	3.4	=0.1
9.006	601.6	698.	4.1	576.8	795.	4.0	=0.1
9.007	603.1	700.	4.7	561.6	795.	4.6	=0.2
9.008	602.5	700.	5.3	554.2	795.	5.1	=0.2
9.009	590.6	700.	5.9	546.9	795.	5.7	=0.3
9.010	592.7	702.	6.5	572.9	795.	6.2	=0.3
9.011	579.8	702.	7.1	583.7	795.	6.8	=0.3
9.012	591.8	700.	7.7	571.8	795.	7.4	=0.3
9.013	586.6	700.	8.3	557.5	794.	8.0	=0.3
9.014	598.8	702.	8.9	575.1	794.	8.5	=0.4
9.015	607.8	700.	9.5	583.9	793.	9.1	=0.4
9.016	600.2	700.	10.1	584.7	795.	9.7	=0.4
9.017	593.1	698.	10.7	605.6	794.	10.3	=0.4
9.018	607.5	698.	11.3	586.0	795.	10.9	=0.4
9.019	579.5	698.	11.9	581.5	794.	11.5	=0.4
9.020	581.1	700.	12.5	592.6	797.	12.1	=0.4
9.021	603.7	700.	13.1	606.1	796.	12.7	=0.4
9.022	612.7	700.	13.7	601.4	796.	13.3	=0.4
9.023	612.8	700.	14.3	578.4	796.	13.9	=0.4
9.024	613.3	700.	14.9	597.8	796.	14.5	=0.4
9.025	604.8	700.	15.5	611.0	798.	15.1	=0.4
9.026	562.5	700.	16.1	603.5	797.	15.7	=0.4
9.027	585.2	700.	16.7	635.9	797.	16.3	=0.3
9.028	593.4	702.	17.2	611.8	797.	16.9	=0.3
9.029	588.1	702.	17.8	592.4	797.	17.5	=0.3
9.030	584.9	702.	18.4	604.6	798.	18.1	=0.3
9.031	602.7	702.	19.0	614.6	799.	18.7	=0.3
9.032	593.4	700.	19.6	602.5	797.	19.3	=0.3
9.033	597.9	700.	20.2	616.7	796.	19.9	=0.3
9.034	594.3	700.	20.8	603.5	798.	20.5	=0.3
9.035	596.1	698.	21.4	598.0	798.	21.1	=0.3
9.036	574.2	698.	22.0	600.9	798.	21.7	=0.2
9.037	566.1	700.	22.5	612.8	798.	22.4	=0.2
9.038	602.2	700.	23.1	627.0	798.	23.0	=0.2
9.039	601.6	700.	23.7	623.1	799.	23.6	=0.1
9.040	592.6	700.	24.3	614.3	799.	24.2	=0.1
9.041	596.3	700.	24.9	606.7	800.	24.8	=0.1
9.042	595.7	702.	25.5	620.0	800.	25.5	=0.1
9.043	608.4	702.	26.1	612.2	801.	26.1	=0.1
9.044	597.7	702.	26.7	616.7	800.	26.7	=0.1
9.045	615.5	702.	27.4	598.8	800.	27.3	=0.1
9.046	596.7	704.	27.9	605.8	801.	27.9	=0.1
9.047	591.6	702.	28.5	610.4	799.	28.5	=0.0
9.048	607.0	704.	29.1	619.8	800.	29.1	=0.0
9.049	618.0	702.	29.8	648.2	799.	29.8	=0.0

TABLE D.2 (Contd.)

TIME SEC	LF CC/S	TC1 DEGK	ILF CC	UF CC/S	TC4 DEGK	IMF CC	VOID CC
9.050	618.7	702.	30.4	635.0	800.	30.4	0.0
9.051	587.6	702.	31.0	635.7	798.	31.0	0.1
9.052	603.5	702.	31.6	610.1	799.	31.6	0.1
9.053	587.6	700.	32.2	600.0	799.	32.2	0.1
9.054	600.7	700.	32.8	612.7	800.	32.9	0.1
9.055	600.0	700.	33.4	655.1	800.	33.5	0.1
9.056	597.7	702.	34.0	645.0	800.	34.2	0.2
9.057	599.2	700.	34.6	623.1	800.	34.8	0.2
9.058	602.5	702.	35.2	602.0	799.	35.4	0.2
9.059	582.8	702.	35.7	628.8	800.	36.0	0.3
9.060	596.6	704.	36.3	607.1	801.	36.6	0.3
9.061	591.4	704.	36.9	617.8	801.	37.2	0.3
9.062	603.4	704.	37.5	612.8	800.	37.8	0.3
9.063	602.1	704.	38.1	612.2	800.	38.5	0.3
9.064	602.7	704.	38.7	602.4	799.	39.1	0.3
9.065	607.8	702.	39.3	624.9	800.	39.7	0.3
9.066	607.9	704.	40.0	605.2	799.	40.3	0.3
9.067	589.2	700.	40.5	598.8	797.	40.9	0.3
9.068	607.5	700.	41.2	613.3	800.	41.5	0.4
9.069	598.8	700.	41.8	595.2	801.	42.1	0.3
9.070	592.7	702.	42.3	626.7	799.	42.7	0.4
9.071	603.7	704.	42.9	592.4	799.	43.3	0.4
9.072	604.9	700.	43.6	615.1	800.	43.9	0.4
9.073	612.8	702.	44.2	605.7	801.	44.5	0.4
9.074	597.9	704.	44.8	604.6	803.	45.1	0.4
9.075	601.0	702.	45.4	611.0	802.	45.8	0.4
9.076	589.6	704.	46.0	610.3	800.	46.4	0.4
9.077	593.0	704.	46.5	635.9	802.	47.0	0.5
9.078	608.9	704.	47.2	652.8	801.	47.7	0.5
9.079	599.7	704.	47.8	647.0	801.	48.3	0.5
9.080	592.7	704.	48.3	611.4	801.	48.9	0.6
9.081	591.1	704.	48.9	607.8	799.	49.5	0.6
9.082	601.2	702.	49.5	595.6	798.	50.1	0.6
9.083	594.0	700.	50.1	637.2	798.	50.8	0.6
9.084	594.3	704.	50.7	644.5	800.	51.4	0.7
9.085	611.6	704.	51.3	625.3	800.	52.0	0.7
9.086	589.7	702.	51.9	621.4	800.	52.6	0.7
9.087	589.3	700.	52.5	633.2	800.	53.3	0.8
9.088	602.2	700.	53.1	640.7	799.	53.9	0.8
9.089	605.4	706.	53.7	643.6	799.	54.6	0.8
9.090	592.6	702.	54.3	621.1	800.	55.2	0.9
9.091	604.1	704.	54.9	640.8	801.	55.8	0.9
9.092	576.3	704.	55.5	647.3	799.	56.5	1.0
9.093	596.7	704.	56.1	646.3	801.	57.1	1.0
9.094	601.5	706.	56.7	637.2	800.	57.8	1.1
9.095	611.6	706.	57.3	653.4	800.	58.4	1.1
9.096	596.7	704.	57.9	639.9	801.	59.0	1.1
9.097	587.7	704.	58.5	630.9	800.	59.7	1.2
9.098	603.1	702.	59.1	647.1	801.	60.3	1.2
9.099	598.7	704.	59.7	675.5	800.	61.0	1.3

TABLE D.2 (Contd.)

TIME SEC	LF CC/S	TC1 DEGK	ILF CC	UF CC/S	TC4 DEGK	IUF C6	VGIN CC
9.100	611.0	702.	60.3	655.5	800.	61.7	1.3
9.101	583.7	704.	60.9	642.5	800.	62.3	1.4
9.102	584.2	704.	61.5	637.4	800.	62.9	1.5
9.103	564.4	702.	62.0	634.2	801.	63.6	1.5
9.104	581.3	704.	62.6	640.0	800.	64.2	1.6
9.105	592.2	704.	63.2	641.4	800.	64.9	1.6
9.106	597.7	704.	63.8	651.9	802.	65.5	1.7
9.107	595.3	704.	64.4	636.7	802.	66.1	1.7
9.108	587.0	706.	65.0	643.0	802.	66.8	1.8
9.109	582.8	706.	65.6	642.5	802.	67.4	1.9
9.110	592.7	706.	66.2	641.2	802.	68.1	1.9
9.111	595.2	706.	66.8	645.1	801.	68.7	1.9
9.112	607.2	706.	67.4	633.2	801.	69.3	2.0
9.113	609.8	708.	68.0	619.0	800.	70.0	2.0
9.114	602.7	704.	68.6	636.5	800.	70.6	2.0
9.115	607.8	706.	69.2	638.9	800.	71.2	2.0
9.116	623.4	706.	69.8	625.7	800.	71.9	2.1
9.117	577.6	706.	70.4	632.9	800.	72.5	2.1
9.118	599.8	704.	71.0	627.0	800.	73.1	2.1
9.119	610.4	704.	71.6	642.9	800.	73.8	2.2
9.120	600.4	704.	72.2	619.9	799.	74.4	2.2
9.121	607.6	702.	72.8	640.2	799.	75.0	2.2
9.122	597.2	704.	73.4	649.2	800.	75.7	2.3
9.123	589.6	704.	74.0	653.5	801.	76.3	2.3
9.124	594.0	706.	74.6	652.4	801.	77.0	2.4
9.125	597.1	708.	75.2	645.1	800.	77.6	2.4
9.126	581.9	706.	75.8	658.1	801.	78.3	2.5
9.127	577.5	706.	76.3	649.5	801.	78.9	2.6
9.128	585.7	708.	76.9	659.6	800.	79.6	2.7
9.129	576.5	706.	77.5	660.6	801.	80.3	2.7
9.130	584.9	706.	78.1	659.2	800.	80.9	2.8
9.131	579.4	706.	78.7	648.8	801.	81.6	2.9
9.132	597.3	708.	79.3	677.6	800.	82.2	3.0
9.133	601.7	704.	79.9	671.3	800.	82.9	3.0
9.134	555.6	704.	80.4	644.5	800.	83.6	3.1
9.135	580.6	704.	81.0	645.8	800.	84.2	3.2
9.136	554.9	704.	81.6	635.0	802.	84.8	3.3
9.137	546.7	704.	82.1	646.9	802.	85.5	3.4
9.138	563.5	704.	82.7	647.5	802.	86.1	3.5
9.139	559.0	706.	83.2	630.0	801.	86.8	3.5
9.140	561.6	706.	83.8	655.3	801.	87.4	3.6
9.141	573.1	708.	84.4	634.0	802.	88.1	3.7
9.142	564.7	708.	84.9	647.3	803.	88.7	3.8
9.143	581.3	708.	85.5	646.3	802.	89.3	3.8
9.144	582.2	708.	86.1	657.7	802.	90.0	3.9
9.145	584.5	706.	86.7	626.1	801.	90.6	3.9
9.146	569.6	706.	87.3	633.1	802.	91.3	4.0
9.147	537.4	706.	87.8	637.7	803.	91.9	4.1
9.148	421.2	708.	88.2	722.2	802.	92.6	4.4
9.149	409.1	706.	88.6	832.5	800.	93.5	4.8

TABLE D.2 (Contd.)

TIME	LF	TC1	ILF	UF	TC4	IUF	VOID
SEC	CC/S	DEGK	CC	CC/S	DEGK	CC	CC
9.150	425.3	706.	89.0	901.2	801.	94.4	5.3
9.151	397.9	706.	89.4	956.5	802.	95.3	5.9
9.152	398.5	702.	89.8	999.2	800.	96.3	6.5
9.153	42.0	704.	89.9	1071.0	802.	97.4	7.5
9.154	-409.3	704.	89.5	1698.1	804.	99.1	9.6
9.155	-123.6	706.	89.4	2040.8	802.	101.1	11.8
9.156	-91.1	706.	89.3	2215.1	804.	103.3	14.1
9.157	-4.4	706.	89.3	2213.6	805.	105.6	16.3
9.158	76.3	706.	89.3	2288.1	805.	107.8	18.5
9.159	10.2	706.	89.3	2137.4	805.	110.0	20.6
9.160	89.6	708.	89.4	1931.3	805.	111.9	22.5
9.161	107.7	708.	89.5	1778.3	805.	113.7	24.1
9.162	104.2	708.	89.6	1677.7	807.	115.4	25.7
9.163	60.4	708.	89.7	1595.1	806.	117.0	27.3
9.164	45.5	706.	89.7	1455.7	806.	118.4	28.7
9.165	31.2	706.	89.8	1273.4	807.	119.7	29.9
9.166	39.1	706.	89.8	1212.7	808.	120.9	31.1
9.167	55.2	708.	89.9	1083.4	809.	122.0	32.1
9.168	85.1	706.	90.0	913.7	806.	122.9	32.9
9.169	111.3	702.	90.1	806.8	808.	123.7	33.6
9.170	93.5	704.	90.2	797.4	808.	124.5	34.3
9.171	58.1	706.	90.2	947.4	809.	125.5	35.2
9.172	67.1	706.	90.3	1065.6	811.	126.5	36.2
9.173	105.8	706.	90.4	1090.4	812.	127.6	37.2
9.174	129.6	706.	90.5	1178.0	812.	128.8	38.3
9.175	36.0	706.	90.6	1266.3	812.	130.1	39.5
9.176	-849.9	706.	89.7	1313.4	812.	131.4	41.7
9.177	-440.2	706.	89.3	1298.0	812.	132.7	43.4
9.178	-339.1	706.	88.9	1164.8	812.	133.8	44.9
9.179	-170.3	708.	88.8	1083.8	811.	134.9	46.1
9.180	-142.5	708.	88.6	1150.7	810.	136.1	47.4
9.181	-148.0	708.	88.5	1338.2	812.	137.4	48.9
9.182	-168.9	706.	88.3	1394.3	812.	138.8	50.5
9.183	-145.1	704.	88.2	1353.9	811.	140.1	52.0
9.184	-121.5	704.	88.0	1477.3	812.	141.6	53.6
9.185	-115.9	704.	87.9	1533.2	811.	143.2	55.2
9.186	-145.5	704.	87.8	1501.9	814.	144.7	56.9
9.187	-157.5	706.	87.6	1466.0	811.	146.1	58.5
9.188	-148.5	706.	87.5	1439.4	814.	147.6	60.1
9.189	-125.9	706.	87.3	1387.7	816.	149.0	61.6
9.190	-111.7	708.	87.2	1351.5	815.	150.3	63.1
9.191	-115.7	706.	87.1	1337.1	816.	151.6	64.5
9.192	-120.2	708.	87.0	1309.4	817.	153.0	66.0
9.193	-92.0	706.	86.9	1240.2	817.	154.2	67.3
9.194	-91.1	708.	86.8	1142.3	819.	155.3	68.5
9.195	-19.1	710.	86.8	1069.8	820.	156.4	69.6
9.196	31.7	710.	86.8	1001.7	819.	157.4	70.6
9.197	76.9	708.	86.9	958.6	819.	158.4	71.5
9.198	107.8	706.	87.0	933.8	818.	159.3	72.3
9.199	142.1	708.	87.2	900.8	818.	160.2	73.0

TABLE D.2 (Contd.)

TIME SEC	LF CC/S	TC1 DEGK	ILF CC	UF CC/S	TC4 DEGK	IUF CC	VOID CC
9.200	169.9	706.	87.3	839.8	821.	161.0	73.7
9.201	158.0	704.	87.5	792.7	824.	161.8	74.4
9.202	181.8	704.	87.7	692.0	822.	162.5	74.9
9.203	173.6	704.	87.8	600.0	824.	163.1	75.3
9.204	178.9	706.	88.0	571.7	823.	163.7	75.7
9.205	178.2	706.	88.2	518.5	824.	164.2	76.0
9.206	168.2	706.	88.4	453.9	826.	164.7	76.3
9.207	138.7	706.	88.5	384.1	827.	165.1	76.6
9.208	107.2	706.	88.6	363.1	827.	165.4	76.8
9.209	52.7	708.	88.7	273.9	828.	165.7	77.0
9.210	62.6	708.	88.7	265.8	828.	166.0	77.2
9.211	57.4	708.	88.8	228.7	829.	166.2	77.4
9.212	61.6	708.	88.8	216.9	828.	166.4	77.6
9.213	68.1	708.	88.9	209.4	828.	166.6	77.7
9.214	64.8	708.	89.0	206.5	826.	166.8	77.8
9.215	58.3	708.	89.0	215.3	828.	167.0	78.0
9.216	35.2	706.	89.1	222.9	828.	167.3	78.2
9.217	28.1	706.	89.1	216.5	830.	167.5	78.4
9.218	38.7	704.	89.1	203.8	828.	167.7	78.5
9.219	18.4	704.	89.2	226.5	828.	167.9	78.7
9.220	20.0	704.	89.2	258.1	827.	168.2	79.0
9.221	0.0	704.	89.2	298.9	830.	168.5	79.3
9.222	-14.2	704.	89.2	294.3	829.	168.8	79.6
9.223	-37.3	708.	89.1	298.5	828.	169.0	79.9
9.224	-79.3	706.	89.0	331.6	831.	169.4	80.3
9.225	-114.9	708.	88.9	358.4	831.	169.7	80.8
9.226	-164.9	708.	88.8	426.0	832.	170.2	81.4
9.227	-204.2	708.	88.6	513.0	832.	170.7	82.1
9.228	-625.5	708.	87.9	584.5	832.	171.3	83.3
9.229	-688.9	706.	87.2	660.6	832.	171.9	84.7
9.230	-618.5	708.	86.6	809.4	834.	172.7	86.1
9.231	-639.5	708.	86.0	969.6	834.	173.7	87.7
9.232	-521.0	708.	85.5	1080.3	834.	174.8	89.3
9.233	-454.7	706.	85.0	1176.4	831.	176.0	91.0
9.234	-504.6	706.	84.5	1238.4	831.	177.2	92.7
9.235	-526.1	704.	84.0	1267.0	834.	178.5	94.5
9.236	-536.4	704.	83.4	1331.3	832.	179.8	96.4
9.237	-540.6	704.	82.9	1377.3	834.	181.2	98.3
9.238	-562.6	704.	82.3	1459.8	834.	182.6	100.3
9.239	-601.9	706.	81.7	1462.8	835.	184.1	102.4
9.240	-676.6	706.	81.1	1447.1	838.	185.5	104.5
9.241	-730.9	706.	80.3	1405.4	837.	186.9	106.6
9.242	-739.3	708.	79.6	1384.5	838.	188.3	108.7
9.243	-722.8	706.	78.9	1356.2	838.	189.7	110.8
9.244	-718.0	708.	78.1	1347.1	836.	191.0	112.9
9.245	-677.0	708.	77.5	1356.5	838.	192.4	114.9
9.246	-645.4	708.	76.8	1384.0	838.	193.8	117.0
9.247	-588.6	708.	76.2	1429.6	837.	195.2	119.0
9.248	-522.9	708.	75.7	1479.9	839.	196.7	121.0
9.249	-504.1	710.	75.2	1549.3	840.	198.2	123.0

TABLE D.2 (Contd.)

TIME SEC	LF CC/S	TC1 DEGK	ILF CC	UP CC/S	TC4 DEGK	IUF CC	VNID CC
9.250	=480.2	706.	74.7	1583.9	840.	199.8	125.1
9.251	=480.4	706.	74.2	1598.2	840.	201.4	127.2
9.252	=433.5	704.	73.8	1606.7	842.	203.0	129.2
9.253	=403.0	704.	73.4	1603.5	842.	204.6	131.2
9.254	=378.3	706.	73.0	1636.6	843.	206.3	133.2
9.255	=367.4	706.	72.7	1603.9	841.	207.9	135.2
9.256	=358.1	706.	72.3	1539.3	844.	209.4	137.1
9.257	=317.9	708.	72.0	1449.0	845.	210.9	138.9
9.258	=279.7	704.	71.7	1346.1	844.	212.2	140.5
9.259	=276.2	710.	71.4	1256.9	845.	213.5	142.0
9.260	=239.3	708.	71.2	1173.6	845.	214.6	143.4
9.261	=198.0	710.	71.0	1136.6	844.	215.8	144.8
9.262	=158.9	708.	70.8	1022.3	846.	216.8	146.0
9.263	=106.0	710.	70.7	967.1	845.	217.8	147.0
9.264	=74.5	710.	70.7	950.5	846.	218.7	148.1
9.265	=34.6	706.	70.6	904.7	846.	219.6	149.0
9.266	=22.8	706.	70.6	864.6	845.	220.5	149.9
9.267	1.0	708.	70.6	830.8	846.	221.3	150.7
9.268	31.0	704.	70.6	790.8	847.	222.1	151.5
9.269	53.2	706.	70.7	745.3	846.	222.8	152.2
9.270	74.1	704.	70.8	701.8	847.	223.5	152.8
9.271	89.0	704.	70.8	701.6	847.	224.2	153.4
9.272	117.4	706.	71.0	683.4	848.	224.9	154.0
9.273	129.1	706.	71.1	667.1	850.	225.6	154.5
9.274	152.9	708.	71.2	645.6	850.	226.2	155.0
9.275	167.6	708.	71.4	624.7	852.	226.9	155.5
9.276	156.2	706.	71.6	603.5	849.	227.5	155.9
9.277	186.7	708.	71.8	588.1	850.	228.1	156.3
9.278	214.2	708.	72.0	591.4	851.	228.7	156.7
9.279	232.1	708.	72.2	578.7	850.	229.2	157.0
9.280	240.5	708.	72.4	556.8	850.	229.8	157.3
9.281	242.8	708.	72.7	546.4	848.	230.3	157.6
9.282	241.3	708.	72.9	520.6	847.	230.9	157.9
9.283	257.3	706.	73.2	507.5	850.	231.4	158.2
9.284	253.8	706.	73.4	501.1	849.	231.9	158.4
9.285	274.9	706.	73.7	468.3	849.	232.3	158.6
9.286	256.9	704.	74.0	457.5	849.	232.8	158.8
9.287	264.2	706.	74.2	462.6	850.	233.3	159.0
9.288	273.2	706.	74.5	442.7	850.	233.7	159.2
9.289	272.7	706.	74.8	418.3	852.	234.1	159.3
9.290	255.9	706.	75.0	409.5	852.	234.5	159.5
9.291	255.8	706.	75.3	381.4	854.	234.9	159.6
9.292	255.2	708.	75.5	387.9	853.	235.3	159.7
9.293	271.7	710.	75.8	393.8	854.	235.7	159.9
9.294	280.4	708.	76.1	377.8	855.	236.1	160.0
9.295	286.6	710.	76.4	400.8	856.	236.5	160.1
9.296	271.7	710.	76.7	394.2	855.	236.9	160.2
9.297	270.4	708.	76.9	351.0	852.	237.2	160.3
9.298	270.3	706.	77.2	340.0	853.	237.6	160.3
9.299	269.8	706.	77.5	347.9	854.	237.9	160.4

TABLE D.2 (Contd.)

TIME SEC	LF CC/S	TC1 DEGK	ILF CC	UF CC/S	TC4 DEGK	IUF CG	VOID CC
9.300	270.5	704.	77.7	327.8	853.	238.2	160.5
9.301	239.3	706.	78.0	314.8	855.	238.5	160.6
9.302	255.3	706.	78.2	309.8	855.	238.9	160.6
9.303	235.5	706.	78.5	306.5	857.	239.2	160.7
9.304	244.7	704.	78.7	285.0	856.	239.4	160.7
9.305	255.6	706.	79.0	279.6	858.	239.7	160.8
9.306	245.6	708.	79.2	269.6	857.	240.0	160.8
9.307	243.2	706.	79.5	261.3	859.	240.3	160.8
9.308	231.0	708.	79.7	260.7	858.	240.5	160.8
9.309	223.0	708.	79.9	260.2	859.	240.8	160.9
9.310	236.7	708.	80.2	265.8	858.	241.0	160.9
9.311	243.1	708.	80.4	262.9	859.	241.3	160.9
9.312	247.4	708.	80.6	244.2	857.	241.5	160.9
9.313	253.8	708.	80.9	243.5	858.	241.8	160.9
9.314	254.4	706.	81.1	254.3	859.	242.0	160.9
9.315	255.7	706.	81.4	249.4	857.	242.3	160.9
9.316	248.0	708.	81.7	236.6	856.	242.5	160.9
9.317	306.7	698.	82.0	434.9	854.	243.0	161.0
9.318	243.8	706.	82.2	237.9	858.	243.2	161.0
9.319	246.7	704.	82.5	226.5	857.	243.4	161.0
9.320	263.7	704.	82.7	203.5	857.	243.6	160.9
9.321	259.3	706.	83.0	210.2	858.	243.8	160.9
9.322	252.8	706.	83.2	205.5	857.	244.0	160.8
9.323	256.8	706.	83.5	209.8	858.	244.3	160.8
9.324	257.3	706.	83.7	201.9	858.	244.5	160.7
9.325	252.7	706.	84.0	174.1	858.	244.6	160.6
9.326	253.0	708.	84.2	193.9	859.	244.8	160.6
9.327	279.5	708.	84.5	205.8	860.	245.0	160.5
9.328	295.5	706.	84.8	195.4	860.	245.2	160.4
9.329	309.5	708.	85.1	189.6	860.	245.4	160.3
9.330	310.2	708.	85.4	195.0	860.	245.6	160.2
9.331	312.4	710.	85.8	191.4	860.	245.8	160.1
9.332	314.8	710.	86.1	186.1	861.	246.0	159.9
9.333	315.4	712.	86.4	186.6	860.	246.2	159.8
9.334	311.9	712.	86.7	180.3	860.	246.4	159.7
9.335	325.2	712.	87.0	147.5	860.	246.5	159.5
9.336	318.8	712.	87.3	170.8	862.	246.7	159.3
9.337	333.9	716.	87.7	182.7	862.	246.9	159.2
9.338	342.9	722.	88.0	183.3	863.	247.0	159.0
9.339	353.9	726.	88.4	165.8	863.	247.2	158.8
9.340	352.7	728.	88.7	150.1	864.	247.4	158.6
9.341	348.7	726.	89.1	142.5	864.	247.5	158.4
9.342	324.8	724.	89.4	155.8	865.	247.7	158.3
9.343	353.0	724.	89.7	141.2	865.	247.8	158.0
9.344	346.2	718.	90.1	145.7	866.	247.9	157.8
9.345	356.2	716.	90.5	148.3	866.	248.1	157.6
9.346	345.2	714.	90.8	114.3	866.	248.2	157.4
9.347	328.5	710.	91.1	125.8	865.	248.3	157.2
9.348	328.4	708.	91.5	121.5	867.	248.5	157.0
9.349	327.8	704.	91.8	109.0	866.	248.6	156.8

TABLE D.2 (Contd.)

TIME SEC	LF CC/S	TC1 DEGK	ILF CC	UF CC/S	TC4 DEGK	IUF CG	VOID CC
9.350	313.1	700.	92.1	82.1	866.	248.6	156.6
9.351	266.4	696.	92.4	123.7	868.	248.8	156.4
9.352	294.0	766.	92.7	98.2	868.	248.9	156.2
9.353	289.7	840.	92.9	94.9	870.	249.0	156.0
9.354	275.7	912.	93.2	100.7	872.	249.1	155.8
9.355	263.3	956.	93.5	102.1	873.	249.2	155.7
9.356	261.1	1076.	93.7	92.1	876.	249.3	155.5
9.357	243.2	1093.	94.0	104.3	878.	249.4	155.4
9.358	223.3	1112.	94.2	96.9	880.	249.5	155.2
9.359	188.2	1126.	94.4	69.1	881.	249.5	155.1
9.360	182.5	1139.	94.6	88.3	882.	249.6	155.0
9.361	161.8	1141.	94.7	78.5	882.	249.7	155.0
9.362	154.5	1143.	94.9	66.7	883.	249.8	154.9
9.363	133.9	1149.	95.0	72.9	886.	249.8	154.8
9.364	99.6	1160.	95.1	70.0	887.	249.9	154.8
9.365	81.5	1166.	95.2	24.2	887.	249.9	154.7
9.366	66.2	1170.	95.3	65.9	888.	250.0	154.7
9.367	12.7	1181.	95.3	66.3	887.	250.1	154.8
9.368	23.2	1193.	95.3	46.8	888.	250.1	154.8
9.369	-0.9	1206.	95.3	35.4	890.	250.1	154.8
9.370	-18.7	1213.	95.3	39.7	890.	250.2	154.9
9.371	-42.5	1215.	95.3	66.8	891.	250.2	155.0
9.372	-49.0	1219.	95.2	55.3	891.	250.3	155.1
9.373	-83.8	1223.	95.1	45.9	894.	250.3	155.2
9.374	-90.9	1249.	95.0	44.9	894.	250.4	155.4
9.375	-107.1	1245.	94.9	30.8	896.	250.4	155.5
9.376	-153.3	1249.	94.8	23.3	896.	250.4	155.7
9.377	-157.7	1251.	94.6	42.0	897.	250.5	155.9
9.378	-168.9	1253.	94.4	58.9	896.	250.5	156.1
9.379	-178.1	1258.	94.3	32.6	896.	250.6	156.3
9.380	-189.0	1262.	94.1	17.5	895.	250.6	156.5
9.381	-198.3	1262.	93.9	41.2	898.	250.6	156.8
9.382	-203.7	1264.	93.7	22.2	897.	250.7	157.0
9.383	-218.6	1266.	93.5	16.0	899.	250.7	157.2
9.384	-253.1	1268.	93.2	16.5	899.	250.7	157.5
9.385	-239.7	1268.	93.0	38.2	900.	250.7	157.8
9.386	-261.6	1273.	92.7	34.3	901.	250.8	158.1
9.387	-258.2	1279.	92.4	46.2	901.	250.8	158.4
9.388	-256.9	1279.	92.2	46.8	902.	250.9	158.7
9.389	-265.2	1284.	91.9	15.6	902.	250.9	159.0
9.390	-274.2	1286.	91.6	34.1	904.	250.9	159.3
9.391	-270.4	1286.	91.4	6.0	905.	250.9	159.5
9.392	-309.8	1288.	91.1	-14.9	905.	250.9	159.8
9.393	-285.5	1290.	90.8	-2.2	904.	250.9	160.1
9.394	-292.3	1295.	90.5	16.0	902.	250.9	160.4
9.395	-266.8	1297.	90.2	4.9	904.	250.9	160.7
9.396	-289.4	1297.	89.9	11.9	904.	250.9	161.0
9.397	-279.1	1301.	89.7	-3.9	903.	250.9	161.3
9.398	-267.5	1303.	89.4	-28.7	901.	250.9	161.5
9.399	-260.4	1303.	89.1	-20.7	902.	250.9	161.8

ACKNOWLEDGMENTS

We are pleased to acknowledge the contributions of C. E. Dickerman, manager of the Fuel Dynamics Section, for his contributions to the planning and continued support and guidance of the experiment; to R. Schultz, R. T. Purviance, K. J. Schmidt, G. Maslowitz, J. Burkhardt, and J. Emerson for the engineering, assembly, and testing of the loop and test train; to J. Cook and D. Mitchell at HFEF for pre- and posttest handling of the loop and fuel; to J. F. Boland and L. J. Harrison for their support and cooperation at TREAT; to A. B. Rothman and A. K. Agrawal for their early work on fresh-fuel calibrations; to D. A. Donahue, W. Kettman, J. C. Florek, F. E. Savoie, and J. J. Puro of MSD for their contributions to the disassembly and post-test examination; to L. W. Deitrich and M. E. Stephenson for their early support in data interpretation; and to P. H. Froehle for the generation of computer plots of the test data and some of the data-handling programs.

REFERENCES

1. R. C. Doerner et al., *Irradiated Fuel Failure Experiment in a Fast Reactor Reactivity Accident (Test E6)*, Trans. Am. Nucl. Soc. 17, 294 (Nov 1973).
2. *Reactor Development Program Progress Report: February 1972*, ANL-RDP-2, p. 8.18 (Mar 29, 1972).
3. *Ibid.*: June 1972, ANL-RDP-6, p. 8.19 (July 31, 1972).
4. *Ibid.*: August 1972, ANL-RDP-8, p. 9.21 (Oct 10, 1972).
5. *Ibid.*: December 1972, ANL-RDP-12, p. 9.12 (Feb 1, 1973).
6. *Ibid.*: January 1973, ANL-RDP-13, p. 9.9 (Feb 28, 1973).
7. *Ibid.*: February 1973, ANL-RDP-14, p. 9.16 (Mar 22, 1973).
8. *Ibid.*: July 1973, ANL-RDP-18, p. 7.22 (Aug 29, 1973).
9. *Ibid.*: November 1973, ANL-RDP-22, p. 7.14 (Jan 8, 1973).
10. R. C. Doerner et al., *Final Summary Report of Fuel-dynamics Tests H2 and E4*, ANL-76-16 (Feb 1976).
11. R. C. Doerner et al., *Final Report of Fuel Dynamics Test E7*, ANL-77-25 (Apr 1977).
12. L. W. Deitrich et al., *Test E3 on High-energy Transient Meltdown of Irradiated UO₂ in a TREAT Mark-II Loop*, ANL-77-94 (Dec 1977).
13. F. E. Dunn et al., *The SAS2A LMFBR Accident-analysis Computer Code*, ANL-8138 (Oct 1974).
14. A. E. Waltar et al., *MELT-III - A Neutronics, Thermal Hydraulic Computer Program for Fast Reactor Safety Analysis*, HEDL-TME 74-47 (Dec 1974).
15. A. E. Waltar et al., *An Analysis of the Unprotected Transient Overpower Accident in FTR*, HEDL-TME-75-50 (June 1975).
16. *Reactor System Engineering Parameters*, SDD31 (Sept 1974).
17. D. Stahl and T. J. Patrician, "Fission-gas Behavior Studies," *Reactor Development Program Progress Report: April-May 1973*, ANL-RDP-16, pp. 6.43-6.45 (July 9, 1973).
18. C. E. Dickerman, "Kinetics of the Transient Reactor Test Facility (TREAT)," *Reactor Kinetics and Control*, AEC Symp. Series 419, USAEC, Oak Ridge (1964).
19. A. DeVolpi and C. H. Freese, *Fast Neutron Transient Detection Hodoscope for Reactor Fuel Meltdown Studies*, IEEE Trans. Nucl. Sci., NSI, NS-13(1), 623-629 (Feb 1966).
20. A. DeVolpi, C. E. Dickerman, and J. F. Boland, *Preliminary Performance Data from Fast Neutron Hodoscope at TREAT*, Trans. Am. Nucl. Soc. 12(2), 868 (1969).
21. A. DeVolpi et al., *Fast-neutron Hodoscope at TREAT: Development and Operations*, Nucl. Tech. 27, 449 (1975).
22. L. E. Robinson, R. T. Purviance, and K. J. Schmidt, *The Mark-II Integral Sodium TREAT Loop*, Trans. Am. Nucl. Soc. 13(1), 354 (1970).

23. L. E. Robinson and R. Carlson, *The Development of Pumps for Use in Fast-reactor-safety Integral-loop Experiments*, ANL-7369 (Apr 1968).
24. A. K. Agrawal and P. Royal, private communication (Nov 1972).
25. A. E. Wright et al., *Final Report for the H3 Transient Overpower Failure Threshold Experiment*, ANL-75-32 (June 1975).
26. W. W. Marr and R. M. Crawford, *Thermal-Hydraulic Analysis of Multipin In-Pile Experiments*, Trans. Am. Nucl. Soc. 15, 880 (1972).
27. L. W. Deitrich et al., *Summary and Evaluation of Fuel Dynamics Transient-Overpower Experiments: Status 1974*, ANL-77-44 (June 1977).
28. M. G. Stevenson, private communication (Sept 1974).
29. W. Bohl, private communication (Apr 28, 1977).
30. J. H. Scott et al., *Microstructure Dependence of Failure Threshold in Mixed Oxide LMFBR Fuel Pins*, HEDL-TME 75-9 (Oct 1975).
31. R. E. Baars et al., *HEDL Empirical Correlation of Fuel Pin TOP Failure*, HEDL-SA-861 (Sept 1976).
32. R. E. Baars and A. Padilla, Jr., *Fuel Pin Post-Failure Transient Behavior*, HEDL-TME 75-110 (Nov 1976).
33. L. Leibowitz et al., *Properties for LMFBR Safety Analysis*, ANL-CEN-RSD-76-1 (Apr 1976).
34. C. E. Dickerman et al., *Initial TREAT Loop Experiments on LMFBR Fuel Behavior during a Power Excursion (Tests E1 and E2)*, ANL-8099 (May 1974).

Distribution of ANL-78-73Internal:

J. A. Kyger	L. Baker	R. Simms
R. Avery	P. A. Lottes	G. S. Stanford (7)
L. Burris	W. C. Lipinski	R. C. Doerner (7)
D. W. Cissel	D. H. Cho	J. P. Tylka
S. A. Davis	L. W. Deitrich	H. U. Wider
B. R. T. Frost	A. E. Klickman	A. E. Wright
D. C. Rardin	R. A. Noland	O. R. McNary
R. J. Teunis	B. A. Korelc (3)	T. H. Bauer
C. E. Till	R. O. Brittan	M. Kurtz (6)
R. S. Zeno	J. P. Burelbach	R. E. Henry
C. E. Dickerman	N. J. Carson	D. H. Lennox
H. K. Fauske	A. DeVolpi	D. R. Pedersen
S. Fistedis	C. L. Fink	J. H. Tessier
B. D. LaMar	P. H. Froehle	T. T. Anderson
J. F. Marchaterre	R. N. Koopman	D. Stahl
H. O. Monson	R. K. Lo	L. A. Neimark
R. Sevy	R. J. Page	W. F. Murphy (7)
A. J. Goldman	R. G. Palm	L. J. Harrison
D. Rose	L. W. Person	A. B. Krisciunas
I. Bornstein	E. A. Rhodes	ANL Record File
T. C. Chawla	A. B. Rothman	ANL Libraries (5)
D. R. Ferguson	L. A. Semenza	TIS Files (6)

External:

DOE-TIC, for distribution per UC-79p (257)
 Manager, Chicago Operations Office
 Chief, Office of Patent Counsel, CH
 Director, Reactor Programs Div., CH
 Director, CH-INEL
 Director, DOE-RRT (2)
 President, Argonne Universities Association
 Reactor Analysis and Safety Division Review Committee:
 S. Baron, Burns and Roe, Inc.
 J. R. Dietrich, Combustion Engineering, Inc.
 W. Kerr, U. Michigan
 M. Levenson, Electric Power Research Inst.
 S. Levy, S. Levy, Inc.
 D. Okrent, U. California, Los Angeles
 N. C. Rasmussen, Massachusetts Inst. Technology
 Materials Science Division Review Committee:
 E. A. Aitken, General Electric Co., Sunnyvale
 G. S. Ansell, Rensselaer Polytechnic Inst.
 R. W. Balluffi, Massachusetts Inst. Technology

R. J. Birgeneau, Massachusetts Inst. Technology
S. L. Cooper, U. Wisconsin
C. Laird, U. Pennsylvania
M. T. Simnad, General Atomic
C. T. Tomizuka, U. Arizona
A. R. C. Westwood, Martin Marietta Labs.