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MASTER

SOUTHWEST EXPERIMENTAL FAST OXIDE REACTOR DEVELOPMENT PROGRAM

**THIRTY-FIRST AND FINAL REPORT
NOVEMBER 1971-JANUARY 1972**

U.S. ATOMIC ENERGY COMMISSION
CONTRACT AT(04-3)-540

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**SOUTHWEST EXPERIMENTAL FAST OXIDE
REACTOR DEVELOPMENT PROGRAM**

**Thirty-First and Final Quarterly Report
November 1971-January 1972**

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TABLE OF CONTENTS

	Page
Abstract	ix
1 Introduction	1-1
2 Summary	2-1
2.1 Completed Tasks	2-1
2.2 Task 6 – Reactivity Controls Required for Experimentation	2-1
2.3 Task 9 – Fuel Fabrication	2-1
2.4 Task 12 – Core I Super-Prompt Transients	2-1
2.5 Task 13 – Core II Test Program	2-1
2.6 SEFOR Safety Audit and Licensing	2-2
2.7 SEFOR Support	2-3
2.8 SEFOR Facility	2-3
3 Task 6 – Reactivity Controls Required for Experimentation	3-1
3.1 Task 6.1 – Fast Reactivity Excursion Device (FRED)	3-1
3.1.1 Purpose	3-1
3.1.2 Past Accomplishments	3-1
3.1.3 Current Results	3-1
4 Task 9 – Fuel Fabrication	4-1
4.1 Purpose	4-1
4.2 Past Accomplishments	4-1
4.3 Current Results	4-1
5 Task 12 – Core I Super-Prompt Transients	5-1
5.1 Test Description	5-1
5.2 Past Performance	5-1
5.3 Current Results	5-1
5.3.1 Influence of Core Arrangement on Reactivity	5-1
5.3.2 Static Test Measurements During Core I Transients Program	5-1
6 Task 13 – Core II Test Program	6-1
6.1 Past Performance	6-1
6.2 Current Results	6-1
6.2.1 Core II Reflector Calibration	6-1
6.2.2 Calculation of Reactivity Coefficients	6-1
6.2.3 Core II Temperature Coefficient Measurements	6-10
6.2.4 Core II Flow and Pressure Coefficients of Reactivity	6-22
6.2.5 Oscillator Rod Worth Measurements in Core II	6-24
6.2.6 Core II Zero Power Oscillator Tests	6-24
6.2.7 Similar Core I and Core II Arrangements	6-32
6.2.8 SEFOR Fuel Temperature Calculations	6-32
6.2.9 Static Test Doppler Measurements	6-47
6.2.10 Sub-Prompt Critical Transient Analysis	6-60
6.2.11 Core II Super-Prompt Critical Transients	6-68
6.2.12 Static FRED Slug Worth Measurements in Core II	6-72
6.2.13 Subcriticality and λ/β Measurements	6-74
6.2.14 Conventional Oscillator Tests	6-78
6.2.15 Core II IFA and IFR Measurements	8-88
6.2.16 Core II Calculations	6-88
6.2.17 Fuel Examinations	6-104

TABLE OF CONTENTS (Continued)

	Page
7 SEFOR Safety Audit and Licensing	7-1
7.1 Objectives	7-1
7.2 Current Results	7-1
8 SEFOR Support	8-1
9 SEFOR Facility	9-1
9.1 Experimental Program	9-1
9.1.1 Reflector Calibrations	9-1
9.1.2 I-C3 - Isothermal Temperature Coefficient	9-1
9.1.3 I-C4 - Flow Coefficient	9-1
9.1.4 I-D1 - Pressure Coefficient	9-1
9.1.5 I-C1 - Oscillator Poison Rod Calibration	9-1
9.1.6 I-C2 - Zero Power Transfer Function	9-1
9.1.7 II-4 - Power Ascension and Static Tests	9-1
9.1.8 II-9 - Flow Rate Oscillation Tests	9-2
9.1.9 II-2 - Conventional Oscillator Tests	9-2
9.1.10 I-B-7 - Activation Measurements	9-2
9.1.11 Sub-Prompt Slug (E. P. No. 6332) Calibration	9-2
9.1.12 Transient Detector Calibration	9-3
9.1.13 Sub-Prompt Transient Tests, Core II	9-3
9.1.14 Super-Prompt Transients	9-3
9.1.15 Fuel Surveillance	9-4
9.1.16 Installation of Instrumented Fuel Rods	9-4
9.1.17 Reactivity Adjustments	9-4
9.1.18 Reflector Position Program	9-5
9.2 Follow-On Program Preparations	9-6
9.2.1 Inverse Kinetics Rod Drop Reactivity Measurements	9-6
9.2.2 Source Multiplication and Neutron Noise Analysis	9-6
9.2.3 Tightener Rod Removal and Storage	9-6
9.3 Decommissioning Work	9-6
9.4 Operation and Maintenance	9-6
References	R-1
Contributors	C-1
Distribution	D-1

LIST OF ILLUSTRATIONS

Figure	Title	Page
4-1	IFR Assembly	4-3
4-2	As Received IFR Pt/Mo Thermocouple Assembly	4-5
4-3	Pt/Mo Fuel Thermocouple	4-6
4-4	IFR's During Assembly	4-7
4-5	Orbital Arc Welder	4-7
5-1	Core Loading for Assembly I-I	5-2
5-2	Core Loading for Assembly I-M	5-3
5-3	Core Loading for Assembly I-L	5-9
5-4	Core I Power Dependent Reactivity Feedback	5-12
6-1	Core Loading for Assembly II-C	6-2
6-2	Core Loading for Assembly II-E	6-6
6-3	Core Loading for Assembly II-F	6-7
6-4	Time Dependence of Temperature (10/14/71 - 10/15/71)	6-12
6-5	Time Dependence of Temperature (10/15/71)	6-12
6-6	Time Dependence of Temperature (10/26/71)	6-13
6-7	Time Dependence of Temperature (10/27/71 - 10/28/71)	6-13
6-8	Time Dependence of Temperature (10/28/71)	6-14
6-9	Temperature Dependent Reactivity Feedback	6-14
6-10	Flow Reactivity Measurements	6-23
6-11	Pressure Reactivity Measurements	6-24
6-12	Oscillator Rod Reactivity Worth	6-26
6-13	Flux Oscillations at Frequency of 0.984 Rad/sec	6-28
6-14	Flux Oscillations at Frequency of 0.227 Rad/sec	6-28
6-15	Flux Oscillations at Frequency of 0.0490 Rad/sec	6-29
6-16	Flux Oscillations at Frequency of 0.0113 Rad/sec	6-29
6-17	Oscillator Rod Oscillations at Frequency of 0.227 Rad/sec	6-30
6-18	Oscillator Rod Oscillations at Frequency of 0.0113 Rad/sec	6-30
6-19	Amplitude of Zero Power Transfer Function for Channel 27	6-34
6-20	Phase of Zero Power Transfer Function for Channel 27	6-34
6-21	Amplitude of Zero Power Transfer Function for Channel 28	6-35
6-22	Phase of Zero Power Transfer Function for Channel 28	6-35
6-23	Core Loading for Assembly I-N	6-37
6-24	Fuel Pellet Model	6-39
6-25	Peak Fuel Rod Temperatures in SEFOR	6-41
6-26	Linear Power and Integral Conductivity vs SEFOR Peak Fuel Rod Temperature	6-45
6-27	Comparison of Peak Fuel Rod Temperatures Before and After Operation at 150 w/cm ³	6-46
6-28	Core I and Core II Doppler Feedback versus Power	6-60
6-29	Reactivity versus Energy Measurements for Core II, Sub-Prompt Transient 4	6-61
6-30	Time Dependent Power for Sub-Prompt Transient 1	6-61
6-31	Time Dependent Power for Sub-Prompt Transient 2	6-63
6-32	Time Dependent Power for Sub-Prompt Transient 4A	6-63
6-33	Time Dependent Power for Sub-Prompt Transient 4	6-64
6-34	Time Dependent Power for Sub-Prompt Transient 6	6-64
6-35	Time Dependent Power for Sub-Prompt Transient 7	6-65
6-36	Time Dependent Power for Sub-Prompt Transient 8	6-65
6-37	FRED and Net Reactivity for Sub-Prompt Test 8, Channel A	6-67
6-38	Overshooting of FRED-Reactivity	6-67
6-39	Time Dependent Power for Super-Prompt Transient 1	6-68
6-40	Time Dependent Power for Super-Prompt Transient 3	6-69
6-41	Time Dependent Power for Super-Prompt Transient 4	6-69

LIST OF ILLUSTRATIONS (Continued)

Figure	Title	Page
6-42	Time Dependent Power for Super-Prompt Transient 4	6-70
6-43	Time Dependent Power for Super-Prompt Transient 6	6-70
6-44	Core Loading for Assembly II-D	6-73
6-45	Comparison of Sub-Prompt FRED Calibration in Core I and Core II	6-74
6-46	Core II Super-Prompt FRED Reactivity Worth	6-77
6-47	Phase of Core II Power Reactivity Transfer Functions	6-87
6-48	Amplitude of Core II Power Reactivity Transfer Functions	6-87
6-49	Instrumented Fuel Rod Fuel Thermocouple Temperature Measurements to 20 MW (December 1971)	6-98
6-50	Core II – Super-Prompt Transient Tests, Transient Fuel Temperature Rise, Instrumented Fuel Rods (IFR), Measured Temperature Rise versus Transient Energy Release	6-102
6-51	Radial Power Distribution	6-103
6-52	Axial Power Distribution	6-103
6-53	Fuel Material Worth – Core II	6-105
6-54	UO ₂ Material Worth – Core II	6-106
6-55	B ₄ C Material Worth – Core II	6-107
6-56	Guinea Pig Fuel Rod Metallography Rod A16 Maximum Linear Power – 21 kW/ft	6-109
6-57	Guinea Pig Fuel Rod Metallography Rod A02 Maximum Linear Power – 21 kW/ft	6-110
6-58	Guinea Pig Fuel Rod Metallography Rod A18 Maximum Linear Power – 21 kW/ft	6-111

LIST OF TABLES

Table	Title	Page
5-1	Reflector Swap Measurements at Zero Power	5-4
5-2	Super-Prompt Slug Calibration With Reflector 3	5-5
5-3	Averaged Slug Worth versus Position	5-6
5-4	FRED Worth Measurements for Both Fine Reflectors	5-7
5-5	Comparison of Averaged FRED Worth versus Position	5-7
5-6	Heat Balance Data	5-8
5-7	Low Power (0.06 MW) Critical Points (Core I-L) (8/12/71 – 8/14/71)	5-10
5-8	Low Power (0.06 MW) Critical Points (Core I-M) (8/16/71 – 8/30/71)	5-10
5-9	Power Reactivity Data	5-11
6-1	Calibration of Reflector 3 Assembly II-C at 550°F	6-3
6-2	Calibration of Reflector 8 Assembly II-C at 550°F	6-3
6-3	Calibration of Reflector 3 Assembly II-C at 750°F	6-4
6-4	Calibration of Reflector 8 Assembly II-C at 750°F	6-4
6-5	Worth of Reflector 8 in Assembly II-C	6-5
6-6	Worth of Reflector 3 in Assembly II-C	6-5
6-7	Calibration of Reflector 3 Assembly II-E at 750°F	6-8
6-8	Calibration of Reflector 8 Assembly II-E at 750°F	6-8
6-9	Calibration of Reflector 3 Assembly II-F at 750°F	6-9
6-10	Calibration of Reflector 8 Assembly II-F at 750°F	6-9
6-11	Core II Doppler Calculations	6-10
6-12	Expansion Reactivity Coefficients for SEFOR	6-11
6-13	Core II Uniform Temperature Coefficient of Reactivity at Zero Power	6-11
6-14	Core II Zero Power Temperature Reactivity Measurements	6-15
6-15	Flow Reactivity Measurements	6-22
6-16	Pressure Reactivity Measurements	6-23
6-17	Core II Oscillator Poison Rod Calibration	6-25
6-18	Frequencies of Oscillation	6-26
6-19	Core II Zero Power Oscillator Data	6-27
6-20	Calculated Core II Transfer Function	6-31
6-21	Core II Zero Power Transfer Function	6-33
6-22	Critical Configurations for Assemblies I-N and II-E	6-36
6-23	Comparison of Core Loadings for Assemblies I-N and II-E	6-36
6-24	Fuel Rod Temperatures for SEFOR	6-42
6-25	Calculated Fuel Rod Temperatures Subsequent to Initial Operation	6-47
6-26	Heat Balance Data	6-48
6-27	Heat Balance Data	6-49
6-28	Heat Balance Data (Assembly II-F)	6-50
6-29	Power Reactivity Data (Assembly II-C)	6-51
6-30	Coolant Temperature Reactivity Data at 10 MW (Assembly II-C)	6-52
6-31	Power Reactivity Data (Assembly II-E)	6-53
6-32	Power Reactivity Data (Assembly II-F)	6-54
6-33	Zero Power Critical Reflector Configurations for Assembly II-C	6-55
6-34	Zero Power Critical Reflector Configurations for Assembly II-E	6-55
6-35	Zero Power Critical Reflector Configurations for Assembly II-F	6-56
6-36	Core II Static Doppler Reactivity Feedback	6-58
6-37	Core I Static Doppler Reactivity Feedback	6-59
6-38	Core II Sub Prompt Critical Test Results	6-62
6-39	Initial Slug Positions Before FRED-Firing in Sub-Prompt Transient	6-66

LIST OF TABLES (Continued)

Table	Title	Page
6-40	Core II Super Prompt Transient Energy Coefficient	6-71
6-41	Initial Core II Transient Test Results	6-72
6-42	FRED Worth Using Period Measurements (Assembly II-D)	6-73
6-43	FRED Worths Using Reflectors Assembly II-D	6-75
6-44	Core II Sub-Prompt FRED Rod Calibration Assembly II-E (Reflector 8)	6-75
6-45	Super-Prompt Critical FRED Calibration by Reflector Swap (Assembly II-F)	6-76
6-46	Super-Prompt Critical FRED Calibration by Asymptotic Period (Assembly II-F)	6-77
6-47	Flux Readings and Reflector Positions in Assembly I-P	6-79
6-48	Flux Readings and Reflector Positions in Assembly II-A	6-80
6-49	Flux Readings and Reflector Positions in Assembly II-C	6-81
6-50	Summary of ORNL Experimental Results in SEFOR Core I Assembly I-P	6-82
6-51	Summary of ORNL Experimental Results in SEFOR Core II Assembly II-A	6-83
6-52	Summary of ORNL Experimental Results in SEFOR Core II Assembly II-B	6-84
6-53	Comparison of Noise Analysis and Inverse Kinetics Results from ORNL Subcriticality Experiment on SEFOR	6-85
6-54	Core II Power Reactivity Transfer Function at 2 MW	6-85
6-55	Core II Power Reactivity Transfer Function at 5 MW	6-86
6-56	Core II Power Reactivity Transfer Function at 10 MW	6-86
6-57	Fuel Temperature Rise Above Coolant Temperature ($\sim 760^{\circ}\text{F}$)	6-89
6-58	IFA Coolant Temperatures and Flow	6-95
6-59	Core II Super-Prompt Transient Tests Measured Fuel Transient Temperature in IFA	6-99
6-60	Thermocouple Response Time to 90% Maximum Temperature Core II Super-Prompt Transient Tests	6-101
6-61	Core II Calculated Fraction of Fission by Isotope	6-104
6-62	Core II Calculated Power Distribution	6-104

ABSTRACT

This report summarizes the work performed on the Research and Development Program for the Southwest Experimental Fast Oxide Reactor during the period from November 1, 1971 through January 31, 1972. The work was performed under contract AT(04-3)-540 with the United States Atomic Energy Commission.

1. INTRODUCTION

Southwest Experimental Fast Oxide Reactor (SEFOR) is a 20 MW, sodium-cooled fast reactor with characteristics similar to the large, soft spectrum fast breeder reactors fueled with mixed PuO_2 - U-238 O_2 , for which studies indicate the potential for producing low cost power. SEFOR will be used to obtain physics and engineering data at fuel compositions, temperatures, and crystalline states characteristic of power reactor operating conditions. SEFOR is particularly designed for the systematic determination of the Doppler coefficient of reactivity at temperatures up to the vicinity of fuel melting.

The SEFOR project consists of two major parts: the design and construction of the reactor facility and the related research and development program. Funds for the design and construction of the facility were provided by the Southwest Atomic Energy Associates (a group of 17 investor-owned utility companies located in the south and southwest of the United States), together with the Karlsruhe Laboratory of The Federal Republic of Germany, Euratom, and the General Electric Company.

The United States Atomic Energy Commission is supporting the research and development program. The R and D program consists of two phases:

Phase I—Preoperational research and development,

Phase II—The reactor test program after the start of reactor operation.

Phase I consists of 10 major tasks divided into 28 subtasks. This report summarizes the tasks scheduled for activity at this time, and is the final report of the quarterly progress report series. The reactor is currently being decommissioned, after successful completion of the experimental program.

The following periodic reports have been issued in partial fulfillment of United States Atomic Energy Commission Contract AT(04-3)-540.

1. "Southwest Experimental Fast Oxide Reactor Development Program, First Quarterly Report, April—June 1964," GEAP-4594 (July 1964).
2. "Southwest Experimental Fast Oxide Reactor Development Program, Second Quarterly Report, July—September 1964," GEAP-4742 (October 1964).
3. "Southwest Experimental Fast Oxide Reactor Development Program, Third Quarterly Report, October 1964—January 1965," GEAP-4799 (February 1965).
4. "Southwest Experimental Fast Oxide Reactor Development Program, Fourth Quarterly Report, February—April 1965," GEAP-4864 (May 1965).
5. "Southwest Experimental Fast Oxide Reactor Development Program, Fifth Quarterly Report, May—July 1965," GEAP-4934 (August 1965).
6. "Southwest Experimental Fast Oxide Reactor Development Program, Sixth Quarterly Report, August—October 1965," GEAP-4994 (November 1965).
7. "Southwest Experimental Fast Oxide Reactor Development Program, Seventh Quarterly Report, November 1965—January 1966," GEAP-5108 (February 1966).
8. "Southwest Experimental Fast Oxide Reactor Development Program, Eighth Quarterly Report, February—April 1966," GEAP-5160 (May 1966).
9. "Southwest Experimental Fast Oxide Reactor Development Program, Ninth Quarterly Report, May—July 1966," GEAP-5208 (August 1966).
10. "Southwest Experimental Fast Oxide Reactor Development Program, Tenth Quarterly Report, August—October 1966," GEAP-5301 (November 1967).

GEAP-10010-31

11. "Southwest Experimental Fast Oxide Reactor Development Program, Eleventh Quarterly Report, November 1966—January 1967," GEAP-5442 (February 1967).
12. "Southwest Experimental Fast Oxide Reactor Development Program Twelfth Quarterly Report, February—April 1967," GEAP-5498 (May 1967).
13. "Southwest Experimental Fast Oxide Reactor Development Program, Thirteenth Quarterly Report, May—July 1967," GEAP-5533 (August 1967).
14. "Southwest Experimental Fast Oxide Reactor Development Program, Fourteenth Quarterly Report, August—October 1967," GEAP-5561 (November 1967).
15. "Southwest Experimental Fast Oxide Reactor Development Program, Fifteenth Quarterly Report, November 1967—January 1968," GEAP-5595 (February 1968).
16. "Southwest Experimental Fast Oxide Reactor Development Program, Sixteenth Quarterly Report, February—April 1968," GEAP-5629 (May 1968).
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18. "Southwest Experimental Fast Oxide Reactor Development Program, Eighteenth Quarterly Report, August—October 1968," GEAP-5705 (November 1968).
19. "Southwest Experimental Fast Oxide Reactor Development Program, Nineteenth Quarterly Report, November 1968—January 1969," GEAP-5754.
20. "Southwest Experimental Fast Oxide Reactor Development Program, Twentieth Quarterly Report, February—April 1969," GEAP-10010 (May 1969).
21. "Southwest Experimental Fast Oxide Reactor Development Program, Twenty-First Quarterly Report, May—July 1969," GEAP-10010-21 (August 1969).
22. "Southwest Experimental Fast Oxide Reactor Development Program, Twenty-Second Quarterly Report, August—October 1969," GEAP-10010-22 (November 1969).
23. "Southwest Experimental Fast Oxide Reactor Development Program, Twenty-Third Quarterly Report, November 1969—January 1970," GEAP-10010-23 (February 1970).
24. "Southwest Experimental Fast Oxide Reactor Development Program, Twenty-Fourth Quarterly Report, February—April 1970," GEAP-10010-24 (May 1970).
25. "Southwest Experimental Fast Oxide Reactor Development Program, Twenty-Fifth Quarterly Report, May—July 1970," GEAP-10010-25 (August 1970).
26. "Southwest Experimental Fast Oxide Reactor Development Program, Twenty-Sixth Quarterly Report, August—October 1970," GEAP-10010-26 (November 1970).
27. "Southwest Experimental Fast Oxide Reactor Development Program, Twenty-Seventh Quarterly Report, November 1970—January 1971," GEAP-10010-27 (February 1971).

GEAP-10010-31

28. "Southwest Experimental Fast Oxide Reactor Development Program, Twenty-Eighth Quarterly Report, February–April 1971," GEAP-10010-28 (May 1971).
29. "Southwest Experimental Fast Oxide Reactor Development Program, Twenty-Ninth Quarterly Report, May–July 1971," GEAP-10010-29 (August 1971).
30. "Southwest Experimental Fast Oxide Reactor Development Program, Thirtieth Quarterly Report, August–October 1971," GEAP-10010-30 (November 1971).

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1. Novak, P. E., and Asamoto, R. R., "A Survey for a High Temperature Sensor for SEFOR," GEAP-4903 (July 1965).
2. Quinn, E. P., "Vibration of SEFOR Fuel Rods in Parallel Flow," GEAP-4966 (September 1965).
3. Johnson, M. L., "A Description of Fuel and Other Core Materials Procured for SEFOR Critical Experiments in ZPR-III," GEAP-5133 (December 1965).
4. Protsik, R., "Epithermal Capture and Fission Distribution in a Fuel Rod—The Computer Code REAX," GEAP-4973 (April 1966).
5. Novak, P. E., and Asamoto, R. R., "An Out-of-Pile Evaluation of W-Re Thermocouple Systems for Use to 4700°F in Mixed Oxide," GEAP-5166 (May 1966).
6. Pflasterer, G. R., "SEFOR Experimental Program Planning, Vols. I and II," GEAP-5092 (August 1966).
7. Morrell, R. P., "SEFOR β/ℓ Measurements by Noise Analysis Techniques," IDO-17210 (August 1966).
8. Williams, R. F., and Polomik, E. E., "Pressure Drop and Dye Tests with Water on the SEFOR Prototype Fuel Bundle," GEAP-5129 (February 1966).
9. Craig, C. N., Ryer, C. M., and Thompson, M. L., "Plutonium-Uranium Mixed Oxide Fuel Pellet Fabrication Development for the Southwest Experimental Fast Oxide Reactor," GEAP-5285 (October 1966).
10. Polomik, E. E., and Williams, R. F., "Coolant Surface Turbulence Study, SEFOR Reactor Vessel," GEAP-5099 (December 1966).
11. Wilkinson, L., "Use of Neutron Filters for Fast Reactor Fuel Irradiations in a Thermal Core," GEAP-5035 (April 1967).
12. Wilkinson, L., et al., "Devices for Cyclic and Transient Power Control in a Steady-State Neutron Flux Gradient," GEAP-5036 (May 1967).
13. Reynolds, A. B., and Stewart, S. L., "Analysis of the SEFOR Mockup Critical Experiments in ZPR-3," GEAP-5294 (March 1967).
14. Wilkinson, D., "Weighted Doppler Analysis Code—WEDOP," GEAP-5513 (October 1967).
15. Craig, E. R., Fulton, R. H., Damon, J. J., "Design and Testing of Solenoid and Instrument Lead Connector for Use in SEFOR Reactor Vessel," GEAP-5307 (March 1967).
16. Asamoto, R. R., Perry, K. J., and Zebroski, E. L., "The Effective and Diametral Thermal Expansion of UO_2 Under a Radial Temperature Gradient," GEAP-5284 (October 1966).
17. McVean, R. L., Weitzberg, A., Kremser, J. A., Leridon, A. M., and Long, J. K., "Critical Studies of the Southwest Experimental Fast Oxide Reactor (SEFOR) in ZPR-3," ANL-7348.

18. Polomik, E., "Fluid Flow and Vibration Tests, 1/2-Scale Model of SEFOR Reactor Vessel," GEAP-5440 (April 1967).
19. Field, J. H., Johnson, M. L., and Novak, P. E., "An Evaluation of the Effect of Design and Operating Variables on SEFOR Fuel and Fuel Cladding," GEAP-5309 December 1967).
20. Noble, L. D., "Final Specifications for the SEFOR Experimental Program," GEAP-5576 (April 1968).
21. Russell, C. E., "Flow Distribution Measurements in a 3-Scale Model of the SEFOR Fuel Bundle," GEAP-5184 (May 1968).
22. Cochran, J., "SEFOR Core Clamping Model Tests, One-Sixth Segment," GEAP-5465 (May 1968).
23. Asamoto, R. R., and Novak, P. E., "An In-Pile Evaluation of W-Re Thermocouple Systems for Use to 4700°F in SEFOR Fuel," GEAP-5466 (October 1968).
24. Cochran, J. T., "SEFOR Fuel Assembly Sodium Flow Tests," GEAP-5466 (September 1968).
25. Cochran, J. T., "SEFOR Fuel Rod Sodium Thermal Shock Tests," GEAP-5467 (August 1968).
26. Craig, E. R., "SEFOR Instrumented Fuel Assembly Design and Development," GEAP-5615 (April 1968).
27. Steamer, A. G., Brynsvold, G. V., and Franckx, L. C., "Fuel Handling and Other Tests in the SEFOR Refueling Cell Mockup," GEAP-5701 (March 1969).
28. Johnson, M. L., Becker, R. A., Haar, J. M., "SEFOR Fuel Handling," GEAP-13565 (December 1969).
29. Noble, L. D., et al., "Results of SEFOR Zero Power Experiments," GEAP-13588 (March 1970).
30. Ikeuye, D. T., and Young, F. E., "Fabrication of Non-Fuel Core Components for SEFOR," GEAP-13595 (February 1970).
31. Meyer, R. A., Stewart, S. L., Craig, E. R., Reynolds, A. B., and Johnson, M. L., "Design and Analysis of SEFOR Core I," GEAP-13598 (April 1970).
32. McKeehan, E. R., "Design and Testing of the SEFOR Fast Reactivity Excursion Device (FRED)," GEAP-13649 (October 1970).
33. Noble, L. D., et al., "SEFOR Core I Test Results to 20 MW," GEAP-13702 (April 1971).

The following reports are scheduled to be issued concerning Phase I work:

Farwell, B. E., and Eggert, W. K., "SEFOR Fuel Rod Fabrication 1970-1971," GEAP-13745 (to be published).

Johnson, M. L., Lannin, T. E., Pflasterer, G. R., and Wallace, R. E., "SEFOR Fuel Rod Fabrication 1967-1968," GEAP-13760 (to be published).

Craig, E., Hall, W., Kubik, B., Gregg, J., and Mine, W., "IFA Fabrication Report," GEAP-13713 (to be published).

Allen, D. C., et al., "Design and Fabrication of Instrumented Fuel Rods for SEFOR Core II," GEAP-13807 (to be published).

Wittry, W. B., VonDamm, C. A., Neissel, J. P., "SEFOR Transient Flux Detection System," GEAP-13762 (to be published).

McKeehan, E. R., and Margetanski, W., "Design, Development and Testing of the SEFOR Reactivity Oscillator System," EAP-13761 (to be published).

Tentative titles of reports planned to be issued describing and evaluating the SEFOR test results obtained under Phase II are:

Integral Capture-to-Fission and Fission Ratio Measurements in SEFOR Cores I and II.

Description and Analysis of SEFOR Flow Oscillation and Balanced Oscillator Tests in Core I.

Results and Doppler Evaluation for SEFOR Sub-Prompt Transient Tests in Core I.

Results and Doppler Evaluation for SEFOR Super-Prompt Transient Tests in Core I.

Results and Doppler Evaluation for SEFOR Core II Experiments—Zero Power, Approach to Full Power, Oscillations, Sub-Prompt and Super-Prompt Transient Tests.

Results of SEFOR Fuel Examination (Non-Destructive and Destructive).

Evaluation of Doppler Effect from SEFOR Core I and Core II Test Program and Application to LMFBR Design.

Summary of SEFOR Plant Operating Experience.

These reports will complete the series of topical reports on the SEFOR R&D Program.

2. SUMMARY

2.1 COMPLETED TASKS

Experimental and/or analytical work has been completed on the tasks listed below, although in some cases work on topical reports is continuing:

TASK	TITLE
1.1	Specifications for the Reactor and Experimental Program
1.2	Final Specifications of the Experimental Program
2.0	Experimental Program in ZPR-III
3.0	Fuel Development
4.0	Special Instrumentation
5.0	Steady-State and Transient Characteristics of the Core Assembly
6.0	Reactivity Controls Required for Experimentation
7.0	Fuel Handling
8.0	Core Design
9.0	Fuel Fabrication
10.0	Core I Startup Testing
11.0	Core I Transient Tests
12.0	Core I Prompt Excursion Tests

2.2 TASK 6 – REACTIVITY CONTROLS REQUIRED FOR EXPERIMENTATION

Fabrication of the Phase IV (125 cents) neutron absorber rod for the Core II super-prompt transient tests was completed.

2.3 TASK 9 – FUEL FABRICATION

Three Instrumented Fuel Rods (IFR) were fabricated (plus one spare IFR), installed in SEFOR, and irradiated during the Core II super-prompt transient tests. The IFR's performed satisfactorily during the transient tests.

2.4 TASK 12 – CORE I SUPER-PROMPT TRANSIENTS

Static test measurements performed during the calibration of the FRED rod used for the Core I super-prompt critical transients illustrated that reactivity worths of individual reflectors, and thus apparent worths of materials such as the FRED rod, are dependent on the core loading and on the reflector configuration. The measurements reaffirmed the previously estimated $\pm 4\%$ in reactivity measurements that were observed during earlier zero power tests.

Comparison of Core I pre-transient and post-transient static reactivity measurements shows that the power dependent reactivity feedback was unaltered by the Core I transient testing. This implies that if any changes in fuel or structure occurred as a result of transient shocks they were small, since they had an insignificant effect on a very sensitive indicator (the reactivity) of such changes.

2.5 TASK 13 – CORE II TEST PROGRAM

Additional fine reflector calibrations were performed on Assembly II-C and also on Assembly II-E, and Assembly II-F. Comparison of these and earlier measurements redemonstrated the previously observed results that reflector worths are more dependent on neighboring reflector configurations than on temperature or non-neighboring reflector positions.

The uniform temperature coefficient of reactivity was measured in Core II at temperatures between 350°F and 750°F. The measured reactivity effects indicated a Doppler $T dk/dT$ of -0.0060 and a non-Doppler coefficient of -0.38¢F . These correspond to the calculated values of -0.0063 and -0.38¢F respectively.

The flow and pressure coefficients of reactivity were measured in SEFOR Core II. The data indicates that any reactivity effects resulting from flow or pressure changes are of the same order of magnitude as the estimated standard deviation ($\pm 0.5\text{¢}$) in zero power measurements. The flow and pressure coefficients of reactivity may thus be considered equal to zero, in agreement with predictions and Core I measurements.

Conventional oscillator tests were performed at low (zero) power in SEFOR Core II to provide measurements for evaluation of the theoretical model that is used for later determination of reactivity feedback during oscillatory experiments at higher power levels. The measurements were in excellent agreement with the theoretical model for the zero power transfer function throughout the frequency range (0.25 Hz to 0.0018 Hz) of interest; thus authenticating the model and substantiating the appropriateness of its use in predictions of SEFOR dynamic behavior.

Fuel temperature calculations have been performed for SEFOR fuel rods at linear powers up to 27 kW/ft. The calculational model accounted for central void formation and fuel densification, but neglected plutonium migration, and any axial movement of molten fuel. The calculations used thermal conductivity, and fuel to cladding heat transfer coefficients which have given agreement with measured SEFOR fuel temperatures. The thermal conductivity of molten fuel was taken equal to that of the solid at the melting point. In addition, the calculational model was extended to investigate the fuel temperature behavior at low power levels subsequent to operation at high temperatures. The calculations indicate that for the nominal condition the peak temperature in a standard rod at the core center (at a linear power of 18.5 kW/ft) is 4600°F. The standard deviation in the high temperature calculations is estimated to be $\pm 10\%$. The calculations also indicate that at low power levels marked reductions in fuel temperatures may occur as a result of intervening operation at high power. Such trends are in the direction to account for previously observed reductions in power reactivity feedback. An effective thermal conductivity for use in calculating SEFOR fuel temperatures, and Doppler effects, with a simpler model was also calculated.

Based on analysis of the Core II static power versus reactivity data, and comparison with the corresponding Core I data, the ratio of the Core II to Core I Doppler coefficients (in units of dollars) is 0.782 ± 0.011 . For a Core I Doppler $T dk/dT$ in absolute units of -0.0081 ± 0.0008 , the Core II value in absolute units is -0.0060 ± 0.0006 .

Analysis of the Core II subprompt critical transient test data gives a value of -0.0060 for the Doppler $T dk/dT$ in agreement with the static test results. Preliminary analysis of the superprompt transient data also shows reasonable agreement with the calculations, however the measured energy coefficient decreases less rapidly with increasing energy than does the calculated value. Analysis is continuing and the influence on Core I transients of a slightly different conductivity and heat capacity used for the Core II analysis will be considered at a later date.

The difference of the order of 4% between the "static" and "dynamic" worth of the FRED rod that occurred in Core I has apparently been eliminated in Core II by recalibrating the reflectors (the "static" reactivity yardstick) after each change in core loading, and by basing "static" measurements on the as-calculated inhour equation, rather than on one that was adjusted to fit zero power oscillator data as in Core I.

The ratio (λ/β^*) of the prompt neutron lifetime to the delayed neutron fraction was measured in both Core I and Core II. The measured ratio was the same (131 μsec) for both cores under similar partially reflected configurations but a larger value (143 μsec) was obtained for a more completely reflected Core II configuration.

Conventional oscillator tests were performed in Core II to demonstrate reactor stability and to obtain information concerning reactivity feedback and fuel frequency response parameters. As with previous results in Core I, preliminary analysis indicates the theoretical model fits the data better when the reactivity effects of coolant oscillations are included, but the power coefficients are in better agreement with static test results when the coolant oscillation was treated as zero.

2.6 SEFOR SAFETY AUDIT AND LICENSING

The Eighth Meeting of the SEFOR Safety Review Committee was held in Sunnyvale.

An audit trip was made to the site to review problems with mercury-wetted relays, and an engineering review of this problem was conducted. Four safety evaluations were completed and five letter reports and the vessel main flange stress report were sent to the AEC.

Three changes to the Technical Specifications were approved by the DRL. The reactor operating license was extended for a period of 18 months.

2.7 SEFOR SUPPORT

Engineering work was completed on design modifications to the reactor protective system, reactor vessel head seal and the half-ton hoist grapple.

2.8 SEFOR FACILITY

All of the Core II experimental program was completed, including all Core II transient tests, the power ascension to 20 MW and irradiation of the plutonium capture/fission ratio foil holder rod. Major plant modifications accomplished during this time included installation of a redesigned cover gas backup seal and installation of three instrumented fuel rods in the reactor at the thruhead port locations.

With the completion of the Core II experimental program the reactor was shutdown and cooled down to 350°F. Some rod drop experiments were performed to establish the feasibility of performing subcriticality monitoring by inverse kinetic measurements based on the response of the intermediate range monitors. These experiments were terminated and the reactor secured. Planning and procedures toward plant decommissioning were initiated.

3. TASK 6 – REACTIVITY CONTROLS REQUIRED FOR EXPERIMENTATION

3.1 TASK 6.1 – FAST REACTIVITY EXCURSION DEVICE (FRED)

3.1.1 Purpose

The purpose of the FRED tests is to initiate reactor power excursions under controlled conditions. The device developed and fabricated under this task is used in SEFOR to carry out the planned excursions during the experimental program.

3.1.2 Past Accomplishments

The FRED design, fabrication, and testing have been completed and a topical report on the design and testing has been issued.

The three different worth neutron absorber rods required for the FRED tests in the Core I experimental program were fabricated and then used to complete the Core I testing.

3.1.3 Current Results

Fabrication of the neutron absorber rod required for the Core II super-prompt FRED tests was completed. It was designed to enable reactivity worth adjustment and remote assembly and disassembly from the extension shaft. Evaluation of subsequent Core II reactivity worth measurements indicated that the neutron absorber rods available from Core I were adequate to complete the Core II testing. For this reason, the Phase IV rod (fabricated for Core II) was not used.

4. TASK 9 – FUEL FABRICATION

4.1 PURPOSE

The purpose of Task 9 is to procure fuel rods and associated core components for SEFOR. Fabrication of the hexagonal fuel channel and all of its internal components are part of this task, as well as the instrumented fuel assembly fabrication.

4.2 PAST ACCOMPLISHMENTS

The complete core component and fuel rod order has been received at SEFOR in previous quarters. The stainless steel tightener rods for Core II were received. Six instrumented fuel assemblies were shipped to the SEFOR site. Fabrication was completed on 102 additional fuel rods. Design of SEFOR Core II instrumented fuel rods was completed. The design includes three rods located at three separate through-head ports. Each rod contains one fuel thermocouple. Fabrication specifications were prepared and initial IFR assembly operations were begun.

4.3 CURRENT RESULTS

Four Instrumented Fuel Rods (IFR) were provided for SEFOR Core II superprompt critical transient tests to determine the fuel temperature. A single high temperature fuel thermocouple was contained in each IFR. To satisfy the operational objectives, the thermocouples were specially designed for fast response to the transient test requirements.

Four Instrumented Fuel Rods (IFR) were fabricated, released by QA, and shipped, and 3 of these units were installed in SEFOR. A safety evaluation was completed for the use of IFR's in Core II. The IFR's performed satisfactorily during the Core II superprompt transient tests. Each IFR contained one Platinum/Molybdenum fuel thermocouple. After the transient tests, IFR fuel centerline temperature measurements to 20 MW were compared to fuel center temperature calculations. These data showed agreement within 10%. The resulting close agreement between calculated and experimental values demonstrated the good status of the IFR thermocouple during the superprompt transient testing.

The IFR's were assembled as shown in Figure 4-1 and shipped to SEFOR. The mini stainless steel rod was pinned in place at SEFOR before installation into the reactor. Assembly of the IFR's was begun with the fuel thermocouple.

A coupling was attached to the thermocouple to produce the assembly shown in Figure 4-2. Figure 4-3 shows a close-up of the thermocouple junction. The reduced diameter grounded junction was required for fast response to temperature changes during transient tests. Seven stranded-bare wire (w/3% Re versus w/25% Re thermocouple assemblies) were fabricated as possible backup thermocouples to the Platinum/Molybdenum. The coupling served as the upper end closure for the fuel chamber and as the transition between the fuel cladding and extension rod. Figure 4-4 shows IFR's numbers 1 and 2 during assembly at the coupling welds and the thermocouple leadout penetration through the rod. An orbital arc welder shown in Figure 4-3 was used to make both of the coupling welds.

Subsequent assembly steps included loading of the (Pu, U) O₂ fuel, welding of bottom and closure, attachment of the seal plate assembly, and assembly of the thermocouple penetration connector. After assembly was completed, several checkout tests were performed. A Time Domain Reflectometer (TDR) signature was obtained on each IFR fuel thermocouple before shipment to SEFOR.

The IFR's were installed into SEFOR in three steps. First the IFR assembly was completed by pinning on the mini stainless steel rods and loading them into a special handling container. The IFR's which were tiered in the handling container were then placed vertically into a floor well inside the refueling cell. From the floor well the IFR's were remotely installed into their respective positions in the "through" head ports. A manned entry was made to connect the thermocouple penetration leads and to give final radially alignment before bolting the domes in place.

Before committing the Platinum 20% Rhodium sheathed Pt/Mo thermocouples to the IFR, a material compatibility test was performed. A swaged assembly of Pt/Mo thermocouple materials (1/16 diameter x 4 inches long) was exposed to a temperature gradient from 2300°F to 1300°F for 70 hours. The thermocouple test specimen was placed in the center of (Pu, U) O₂ SEFOR fuel pellets and contained in a molybdenum cylindrical container. The hotter portion of the thermocouple appeared as clean if not cleaner (brighter) than when they were first assembled into the container. There was some discoloration (dark gray) along the cooler half.

The main concern with the T/C assembly after the test was embrittlement of the Pt/RH sheath or Pt/Mo wires. The specimens were cut open at four points along the length. The sheath and wires were bent and flexed at each opening. The material was still ductile indicating there was no significant embrittlement of the materials. The metalurgy samples showed chemical compatibility between the thermocouple and fuel materials for the times and temperatures of the test. Based mainly on these test results, the Pt/Mo thermocouple was determined to be satisfactory for use in the IFR for the SEFOR Core II superprompt transient tests.

Figure 4-1 IFR Assembly

Figure 4-2 As Received IFR Pt/Mo Thermocouple Assembly

(a)

(b)

Figure 4-3 Pt/Mo Fuel Thermocouple

Figure 4-4 IFR's During Assembly

Figure 4-5 Orbital Arc Welder

5. TASK 12 – CORE I SUPER-PROMPT TRANSIENTS

5.1 TEST DESCRIPTION

There are eight super-prompt critical transients in the Core I experimental program. The transients are initiated by rapid insertion of a positive reactivity (produced by ejecting a B_4C slug from a central channel in a time interval of ~ 0.1 sec) in excess of $\$1.0$. The tests are terminated by introduction of large negative reactivities (reactor scram) within ~ 0.3 sec of transient initiation. These transients result in peak power levels that are more than 3 orders of magnitude larger than the initial values, and the prompt behavior of the inherent Doppler feedback reactivity is demonstrated by the prompt turn-around of the transient power.

5.2 PAST PERFORMANCE

The Core I transient tests were analyzed and compared with predicted results. Agreement between predicted and actual test results was very good, and the Doppler coefficient $T dk/dT = -0.0081$ that was determined from the transient analyses agreed exactly with the value obtained from earlier power ascension tests. These compared favorably with the predicted value of -0.0085 . Fuel temperature measured during both static and transient tests showed agreement with expected results.

5.3 CURRENT RESULTS

5.3.1 Influence of Core Arrangement on Reactivity

Prior to transient tests in SEFOR, the reactivity worth of the B_4C rod used to initiate the transients is measured as a function of position. When combined with position versus time measurements, this affords a prediction of the time dependent transient reactivity. The Fast Reactivity Excursion Device (FRED) worth as a function of position is determined at a zero power critical configuration by moving a previously calibrated fine reflector to compensate reactivity changes introduced as the FRED is moved by increments in the core.

The two fine reflector segments (No. 3 and 8) were previously calibrated in Assembly I-I at a sodium temperature of $\sim 760^\circ F$. This core loading is illustrated in Figure 5-1. The worth of the FRED rod for the super-prompt critical transients was also measured at $\sim 760^\circ F$, but in Assembly I-M that is illustrated in Figure 5-2. The loading for Assembly I-M was obtained from Assembly I-I by inserting 4 Instrumented Fuel Assemblies (as illustrated) by replacing a B_4C rod at location W3.0-S2.0E with a fuel rod, and by replacing a B_4C rod at location W0.0-N4.0A with a stainless steel rod. These changes, which are on the side of the core toward reflector No. 3, might be expected to increase the worth of No. 3 relative to that of No. 8. The results in Table 5-1 indicate that this occurred, and that the worth of No. 3 is higher, relative to No. 8 in Assembly I-M than in Assembly I-I.

Measurements were performed using both of the calibrated fine reflectors (3 and 8) during calibration of the Core I super-prompt critical FRED rod. Results from initial measurements with reflector 3 are tabulated in Tables 5-2 and 5-3. Additional measurements with reflector 3, and those with reflector 8, are tabulated in Table 5-4. The averaged values from reflectors 3 and 8 are compared in Table 5-5.

The results in Table 5-5 illustrate that the FRED rod worth appears to vary depending on which fine reflector is used to determine its worth. In fact, the differences occur because the reflectors were calibrated with core loadings and reflector configurations other than those for which the FRED rod measurement was performed. This is clearly illustrated by arranging the tabulated measurements in Table 5-4 into the order given in Table 5-1. For the measurements at any given FRED position in this table, such as 6.0 inches, reactor criticality is maintained as one reflector is lowered and the other is raised. The loss in reactivity that occurs when one reflector is lowered is exactly offset by the gain in reactivity as the other is raised. Thus, the sum of the changes in reactivity is equal to zero, and the values in the last column of Table 5-1 should be zero. That they are not demonstrates that the apparent reflector worths, as determined from the earlier calibrations, are not exact. It also demonstrates that uncertainties of the order of those previously¹ estimated ($\pm 4\%$) can result from use of these calibrations in determining reactivity worths for the core in which the FRED rod worth was measured.

5.3.2 Static Test Measurements During Core I Transients Program

SEFOR was operated at power levels up to 9 MW subsequent to the Core I subprompt critical tests, but just prior to initiation of the Core I super-prompt critical transient tests. Measurements of power level, coolant temperatures, etc. obtained during this period are listed in Table 5-6, along with the corresponding data at power levels up to 8 MW that were obtained just prior to lowering of the B_4C rod into the core for each transient test.

625 STANDARD FUEL RODS

4 IFA FUEL RODS

106 STANDARD TIGHTENER RODS

2 IFA TIGHTENER RODS

12 B_4C RODS

7 GUINEA PIG RODS

● - B_4C ROD
○ - GUINEA PIG ROD
○○○ - INSTRUMENTED FUEL ASSEMBLY

Figure 5-1 Core Loading for Assembly I-I

618 STANDARD FUEL RODS
 12 IFA FUEL RODS
 103 STANDARD B&O TIGHTENER RODS
 6 IFA B&O TIGHTENER RODS
 10 B&C RODS
 7 GUINEA PIG RODS
 1 STAINLESS STEEL ROD

● B&C ROD
 ⊕ STAINLESS STEEL ROD
 ○ GUINEA PIG ROD
 ○ ○ ○ INSTRUMENTED FUEL ASSEMBLY

Figure 5-2 Core Loading for Assembly I-M

The static test measurements were performed on two slightly different core loadings, Assemblies I-L and I-M, which are illustrated in Figures 5-2 and 5-3. The change in loading was made on August 16, 1971, prior to the second super-prompt critical transient, to provide additional reactivity to compensate both the B₄C rod reactivity and the feedback between zero and eight megawatts. As Figures 5-2 and 5-3 indicate, Assembly I-M was obtained from I-L by replacing a B₄C rod at W0.ON4.0A with a stainless steel rod. Comparison of the zero power test data for these cores (Tables 5-7 and 5-8) shows that in the critical configuration the fine reflectors were at a lower, less reflective, position in Assembly I-M than in I-L and that the B₄C to stainless steel exchange resulted in a reactivity increase of 38.7¢.

The reflector configurations for the at-power measurements on Assemblies I-L and I-M between 8/12/71 and 8/30/71 are listed in Table 5-9. These data were combined with the values in Tables 5-7 and 5-8 to obtain the negative reactivity feedback due to power changes at a constant average coolant temperature, as listed in the last column of Table 5-9.

The power reactivity data of Table 5-9 are plotted in Figure 5-4 where they are compared with earlier data¹ obtained during the power ascension phase of the experimental program. As the figure illustrates, the earlier data, as well as all of the data obtained just prior to and during the super-prompt critical transient phase of the Core I program lie within the previously¹ estimated standard deviation for power reactivity measurements of $\pm 2\sigma$, or $\pm 4\%$, whichever is larger.* This indicates that no change in the reactivity feedback characteristics have occurred as a result of the transient testing on Core I.

Table 5-1

REFLECTOR SWAP MEASUREMENTS AT ZERO POWER

FRED Position (in)	Reflector 3		Reflector 8		Coolant Temperature (°F)	Apparent Change in Reactivity		
	Position (cm)	Worth (¢)	Position (cm)	Worth (¢)		Reflector 3 (¢)	Reflector 8 (¢)	Sum ^(a)
6.0	0.29	-0.53	65.8	101.3	750	Base	Base	-
6.0	20.20	20.85	52.8	79.3	750	+21.4	-22.0	-0.6
6.0	51.85	77.82	20.2	20.9	750	+78.4	-80.4	-2.0
6.0	63.84	98.40	1.0	0.0	750	+98.9	-101.3	-2.4
1.4	6.50	4.46	95.0	129.5	751	Base	Base	-
1.4	22.00	23.58	71.1	109.1	751	+19.1	-20.4	-1.3
1.4	69.30	106.80	22.0	23.6	751	+102.3	-105.9	-3.6
1.4	95.20	129.22	1.8	0.6	751	+124.8	-128.9	-4.1
0.05	14.38	12.94	95.0	129.5	751	Base	Base	-
0.05	95.19	129.21	11.0	9.1	751	+116.3	-120.4	-4.1

(a) At a given FRED position, there is no change in reactivity as the reflectors are swapped, and the sum should thus be zero.

*The $\sim 5\%$ uncertainty in absolute power level does not apply to these comparative measurements.

Table 5-2

SUPER-PROMPT SLUG CALIBRATION WITH REFLECTOR 3

FRED Positioner (in)	Reflector 3		Core Temperature (°F)	Relative ^(a) FRED Worth (¢)
Position (cm)	Worth (¢)			
29.69	0.13	- .64	758.7	0.00
25.00	0.13	- .64	758.5	0.11
20.00	6.85	4.79	759.5	5.00
18.00	11.69	9.77	759.5	9.98
16.00	17.43	16.91	759.0	17.39
14.00	23.65	26.20	760.0	26.98
12.00	30.41	37.83	759.0	38.31
10.00	37.25	50.45	759.0	50.93
8.00	44.37	63.84	758.5	64.59
6.00	51.78	77.69	759.5	77.90
4.00	59.81	91.66	759.0	92.14
2.00	69.00	106.39	758.0	107.41
1.00	74.09	112.84	759.0	113.32
0.05	79.44	118.87	759.5	119.08
1.00	74.08	112.83	759.0	113.31
3.00	64.34	99.22	760.0	99.16
5.00	55.90	84.95	760.0	84.89
7.00	48.34	71.31	760.0	71.25
9.00	40.91	56.36	760.0	56.30
11.00	33.96	44.28	760.0	44.22
13.00	27.21	32.20	749.0	32.68
15.00	20.70	21.60	758.9	22.13
17.00	14.64	13.27	758.9	13.80
19.00	9.57	7.47	758.9	8.00
21.00	4.66	2.83	758.9	3.36
25.00	0.32	- .51	758.9	.02

(a) Temperature corrections were made with temperature coefficient of $-0.54\text{¢}^{\circ}\text{F}$.

Table 5-3

AVERAGED SLUG WORTH VERSUS POSITION
(Reflector 3)

FRED Position (in.)	Averaged Measured Worth (¢)
0.05	0
1.0	5.76
2.0	11.67
3.0	19.92
4.0	26.94
5.0	34.19
6.0	41.18
7.0	47.83
8.0	54.49
9.0	62.78
10.0	68.15
11.0	74.86
12.0	80.77
13.0	86.40
14.0	92.10
15.0	96.95
16.0	101.69
17.0	105.28
18.0	109.10
19.0	111.08
20.0	114.08
21.0	115.72
25.0	119.02
29.7	119.08

Table 5-4

FRED WORTH MEASUREMENTS FOR BOTH FINE REFLECTORS

FRED Position (in.)	Reflector 3		Reflector 8		Coolant Temperature (°F)	Relative FRED Worth	
	Position (cm)	Worth (¢)	Position (cm)	Worth (¢)		Reflector 3 (¢)	Reflector 8 (¢)
29.7	0.29	-0.53	19.8	20.3	749	0.0(a)	0.0(a)
29.7	0.29	-0.53	20.2	20.9	750		
6.0	51.85	77.82	20.2	20.9	750	78.3	—
6.0	0.29	-0.53	65.8	101.3	750	—	80.4
1.4	69.30	106.80	22.0	23.6	751	109.4	—
1.4	6.50	4.46	95.0	129.5	751	—	113.0
29.7	19.61	19.99	1.0	0.0	749	0.0(a)	0.0(a)
29.7	19.43	19.72	1.0	0.0	751		
6.0	63.84	98.40	1.0	0.0	750	78.6	—
6.0	20.20	20.85	52.8	79.3	750	—	80.3
1.4	95.20	129.22	1.8	0.6	751	109.4	—
1.4	22.00	23.58	71.1	109.1	751	—	112.3
29.7	12.33	10.50	11.0	9.1	751	0.0	0.0
0.05	95.19	129.21	11.0	9.1	751	118.7	—
0.05	14.38	12.94	95.0	129.5	751	—	122.8

(a) Average of two readings

Table 5-5

COMPARISON OF AVERAGED FRED WORTH VERSUS POSITION

FRED Position (in)	Averaged FRED Worth	
	Reflector 3	Reflector 8
29.7	0.0	0.0
6.0	78.3	80.4
1.4	109.4	112.7
0.05	118.9	122.8

Table 5-6

HEAT BALANCE DATA

Super-Prompt Transient Test	Date (1971)	Main Primary System			Auxiliary Primary System			Thermal Power (MW)	Average Coolant Temperature (°F)
		Inlet ^(a) Temperature (°F)	Outlet Temperature (°F)	Flow (gpm)	Inlet ^(a) Temperature (°F)	Outlet Temperature (°F)	Flow (gpm)		
-	8/12	737.8	748.9	4350	734.1	747.7	227	1.96	743.2
-	8/13	731.5	754.1	4360	732.4	752.1	229	3.94	742.8
-	8/13	727.9	756.6	4366	730.4	753.7	231	4.99	742.2
-	8/13	720.2	760.4	4392	725.2	757.4	232	7.03	740.4
-	8/13	715.1	767.0	4370	721.2	761.4	228	9.01	741.1
1B ^(b)	8/14	751.4	758.3	4908	758.4	759.2	225	1.30	755.0
1	8/14	753.4	764.4	4847	761.4	764.1	227	2.06	759.1
2	8/17	757.2	767.8	4802	752.6	767.5	232	2.08	762.4
3	8/19	757.3	768.1	4875	753.7	767.5	235	2.14	762.6
4	8/21	749.7	776.4	4906	750.1	774.1	237	5.22	763.0
5	8/23	749.6	777.1	4802	754.6	775.6	231	5.23	763.4
6	8/26	739.9	782.1	4832	746.7	779.1	240	8.09	761.1
7	8/28	742.5	784.4	4797	746.5	780.4	234	7.98	763.5
8	8/30	742.5	784.0	4823	744.1	780.1	225	7.96	763.2

(a) To account for observed temperature differences at zero power, the main primary inlet temperature was decreased 0.5°F and the auxiliary primary inlet temperature was increased 2.5°F.

(b) Sub-prompt transient

- 618 STANDARD FUEL RODS
- 12 IFA FUEL RODS
- 102 STANDARD BeO TIGHTENER RODS
- 6 IFA BeO TIGHTENER RODS
- 11 B₄C RODS
- 7 GUINEA PIG RODS

- INSTRUMENTED FUEL ASSEMBLY (IFA)
- GUINEA PIG ROD
- B₄C ROD

Figure 5-3 Core Loading for Assembly I-L

Table 5-7

LOW POWER (0.06 MW) CRITICAL POINTS (CORE I-L)
(8/12/71-8/14/71)

Date	Reflector 3		Reflector 8		Reactor Coolant Temperature (°F)	Relative Reactivity ^(b) at 760°F and Zero Power (¢)
	Position (cm)	Worth (¢)	Position (cm)	Worth (¢)		
8/12/71 ^(a)	39.20	54.13	0.4	-0.44	741	63.94
8/13/71	0.26	-0.55	45.0	64.58	757	64.69
						Average = 64.32

(a) At 0.0006 MW

(b) Reactivity corrections for temperature changes were made with a coefficient of $-0.54¢/°F$, and corrections from the indicated power level to zero power were made with a power coefficient of $-16¢/MW$.

Table 5-8

LOW POWER (0.06 MW) CRITICAL POINTS (CORE I-M)
(8/16/71 - 8/30/71)

Date	Reflector 3		Reflector 8		Reactor Coolant Temperature (°F)	Relative Reactivity ^(b) at 760°F and Zero Power (¢)
	Position (cm)	Worth (¢)	Position (cm)	Worth (¢)		
8/16/71 ^(a)	19.61	19.99	0.4	-0.44	749	25.48
8/16/71 ^(a)	0.26	-0.55	19.80	20.30	749	25.18
8/17/71	0.26	-0.55	24.80	27.91	758	27.48
8/23/71	0.12	-0.64	22.60	24.48	756	25.04
8/26/71	22.80	24.84	0.4	-0.44	759	23.98
8/28/71	0.15	-0.62	19.20	19.43	745	25.95
8/30/71	24.43	27.48	0.4	-0.44	760	26.08
						Average = 25.60

(a) At 0.0006 MW

(b) Reactivity corrections for temperature changes were made with a coefficient of $-0.54¢/°F$, and corrections from the indicated power level to zero power were made with a power coefficient of $-16¢/MW$.

Table 5-9

POWER REACTIVITY DATA

Super-Prompt Transient Test	Date (1971)	Reflector 3		Reflector 8		Average Core Coolant Temperature (°F)	Thermal Power (MW)	Neutron Instrumentation (MW)	Reactivity change ^(a) at 760° F Average Coolant Temperature (¢)
		Position (cm)	Worth (¢)	Position (cm)	Worth (¢)				
-	8/12-8/14	-	-	-	-	760.0	0.0	0.0	0.0 ^(b)
-	8/12	40.00	55.63	24.90	28.06	743.2	1.96	1.93	28.0
-	8/13	40.00	55.63	39.56	54.11	742.8	3.94	3.89	54.2
-	8/13	40.00	55.63	46.60	67.64	742.2	4.99	5.01	67.9
-	8/13	40.00	55.63	58.76	89.86	740.4	7.03	6.92	90.8
-	8/13	42.18	59.72	70.00	107.54	741.1	9.01	9.09	111.6
1B ^(c)	8/14	40.00	55.63	22.64	24.54	755.0	1.30	1.11	18.5
1	8/14	0.26	-0.55	62.00	95.29	759.1	2.06	2.00	30.9
-	8/16-8/30	-	-	-	-	760.0	0.0	0.0	0.0 ^(b)
2	8/17	0.26	-0.55	41.80	58.42	762.4	2.08	1.95	31.0
3	8/19	0.26	-0.55	41.00	56.88	762.6	2.14	2.00	29.4
4	8/21	0.26	-0.55	63.00	96.91	763.0	5.22	5.02	69.3
5	8/23	0.24	-0.56	63.50	97.72	763.4	5.23	5.08	69.9
6	8/26	80.00	119.43	7.80	5.74	761.1	8.09	7.99	99.0
7	8/28	87.30	125.40	1.00	-0.01	763.5	7.98	7.95	98.1
8	8/30	86.49	124.86	0.70	-0.23	763.2	7.96	7.83	97.5

(a) Reactivity corrections for temperature changes were made with a coefficient of $[-0.35 - \frac{0.19(1220)}{1220+65P}]$ ¢/°F at power level P in MW.

(b) Average values obtained from Tables 5-7 and 5-8.

(c) Sub-prompt transient.

Figure 5-4 Core I Power Dependent Reactivity Feedback

6. TASK 13 – CORE II TEST PROGRAM

6.1 PAST PERFORMANCE

Measurements indicated the reactivity loss associated with the conversion from SEFOR Core I to Core II (replacement of 102 BeO tightener rods with stainless steel tightener rods) was $-2.52\% \pm 0.10\%$. This compares with the expected loss, based on earlier worth measurements in Core I, of -2.7% . When combined with earlier measurements in Core I, these results indicate that the minimum critical size for Core II would be 536 ± 5 standard fuel rods (for fuel having zero burnup and as-specified fuel) and 89 stainless steel tightener rods.

The reactivity worths of reflector segments were measured in Core II. Compared to similar measurements in Core I, the reflectors have increased (because of the harder spectrum) approximately 8% in worth.

The reactivity worths of fuel, B_4C , UO_2 and guinea pig rods (1/3 more Pu than a standard rod) were measured at different locations in the initial Core II configuration. The measurements indicate that the reactivity worth of Pu is of the order of 14% larger in Core II than in Core I, while other material reactivity worths are unchanged. Preliminary calculations of fuel reactivity worth in Core II indicated that the trend and order of magnitude of the change are reasonable. More detailed calculations for all Core II material worths were initiated.

The delayed neutron parameters for SEFOR Core II were calculated. These parameters are nearly the same as those calculated for Core I, and there is essentially no difference in the relation (the inhour equation) between period and reactivity for the two cores. The calculated value of the total effective delayed neutron fraction for Core II is 0.00310.

6.2 CURRENT RESULTS

6.2.1 Core II Reflector Calibration

The values of most reactivity changes in SEFOR are determined from observed changes in positions of the two fine reflectors. These reflectors are calibrated, using the asymptotic period technique described in reference 2, to provide a means of expressing the reactivity effects in units of dollars (cents) rather than merely in units of length of reflector movement.

Earlier¹ reflector worth measurements demonstrated that the worth of a fine reflector is particularly dependent on the configuration of immediately adjacent reflectors, and that it is slightly influenced by the position of a neighbor which is only two reflectors removed (such as the influence of reflector 10 on the worth of reflector 8 — see below). The measurements also indicated that the reflector worths are influenced by changes in core loading and may be somewhat influenced by non-neighboring reflector configurations.

To provide data for the different coarse reflector configurations expected during operation on Assembly II-C, the fine reflectors, No. 3 and 8, (see Figure 6-1) were calibrated at nominal core coolant temperatures of 350°F, 550°F, and 750°F. The calibrations at 350°F were reported in reference 2. The calibrations at 550°F and 750°F are listed in Tables 6-1 through 6-4. The conversion from measured doubling time (the period multiplied by $\ln 2$) to reactivity was made using the inhour equation in reference 2.

The effect of the positions of coarse reflectors upon the worths of the fine reflectors can be seen from the data in Tables 6-5 and 6-6. Here the total worths of reflectors 3 and 8 are compared for three different calibrations on the same core loading (assembly II-C). The data in Table 6-5 indicate that the worth of reflector 8 is more dependent on the position of reflector 10 than on the core coolant temperature, or the position of reflector 5. Similarly, the data in Table 6-6 show that the worth of reflector 3 is dependent on the position of reflector 5, which has only one intervening reflector between it and No. 3 (see Figure 6-1). These trends are in agreement with previous¹ measurements.

The fine reflector calibration data for Assemblies II-E and II-F, which are illustrated in Figures 6-2 and 6-3, are listed in Tables 6-7 through 6-10. As the data indicate, there were only nominal variations in reflector worths as a result of core loading changes.

6.2.2 Calculation of Reactivity Coefficients

The U-238 contribution to the Core II Doppler coefficient was calculated using temperature dependent cross sections at 300°K, 700°K and 1400°K that were obtained from a cross section fitting routine. Reactivity changes were calculated for a uniform fuel temperature change using 13 group cross sections and the two-dimensional synthesis' code BISYN³. The results are listed in Table 6-11.

The total calculated Core II Doppler coefficient is -0.0063 as shown in Table 6-11. This includes the U-238 value discussed above and an additional -0.0002 which is 75% (the approximate ratio of the Core II to Core I U-238 coefficients) of a previously calculated⁴ value for the Pu-240 contribution.

- 620 STANDARD FUEL RODS
- 12 IFA FUEL RODS
- 9 B₄C RODS
- 6 GUINEA PIG RODS
- 1 STAINLESS STEEL ROD
- 102 SS TIGHTENER RODS
- 6 BeO IFA TIGHTENER RODS

- INSTRUMENTED FUEL ASSEMBLIES (IFA'S)
- STAINLESS STEEL (SS) RODS
- B₄C RODS
- GUINEA PIG RODS
- CENTRAL CHANNEL (NO FUEL)

Figure 6-1 Core Loading for Assembly II-C

Table 6-1

**CALIBRATION OF REFLECTOR 3
ASSEMBLY II-C at 550°F**

(Reflector 10 down, 5 at 89 cm)

Reflector Position		Doubling Time	Reactivity Increment	Cumulative Reactivity
Initial (cm)	Final (cm)	(sec)	(ρ)	(ρ)
—	0.25	—	—	0.0
0.25	10.00	67.25	9.048	9.048
10.00	17.92	58.8	10.038	19.086
17.92	23.93	70.0	8.768	27.854
23.93	29.00	67.8	8.991	36.854
29.00	34.00	67.75	8.996	45.840
34.00	39.07	57.5	10.210	56.050
39.07	43.94	57.4	10.223	66.274
43.94	48.44	69.2	8.848	75.122
48.44	54.00	49.9	11.354	86.476
54.00	57.97	81.6	7.758	94.233
57.97	63.38	59.5	9.947	104.181
63.38	68.08	76.8	8.146	112.326
68.08	74.07	66.8	9.096	121.422
74.07	80.03	85.7	7.455	128.877
80.03	87.02	106.8	6.212	135.090
87.02	95.20	176.6	4.014	139.103

Table 6-2

CALIBRATION OF REFLECTOR 8 ASSEMBLY II-C at 550°F

(Reflector 10 down, 5 at 89 cm)

Reflector Position		Doubling Time	Reactivity Increment	Cumulative Reactivity
Initial (cm)	Final (cm)	(sec)	(ρ)	(ρ)
—	0.14	—	—	0.0
0.14	10.08	68.2	8.949	8.949
10.08	17.53	64.7	9.325	18.274
17.53	24.01	59.4	9.960	28.235
24.01	29.00	71.3	8.642	36.876
29.00	33.99	63.1	9.508	46.384
33.99	38.57	65.1	9.281	55.664
38.57	42.53	81.2	7.789	63.453
42.53	46.63	76.3	8.188	71.641
46.63	51.00	73.6	8.427	80.068
51.00	55.41	75.2	8.284	88.352
55.41	60.53	63.7	9.438	97.790
60.53	65.53	74.0	8.391	106.181
65.53	70.97	75.9	8.223	114.404
70.97	77.05	77.9	8.053	122.457
77.05	84.98	82.6	7.682	130.138
84.98	94.95	126.2	5.389	135.528

Table 6-3

**CALIBRATION OF REFLECTOR 3
ASSEMBLY II-C at 750°F**

(Reflector 10 at 65 cm)

Reflector Position		Doubling Time (sec)	Reactivity Increment (ρ)	Cumulative Reactivity (ρ)
Initial (cm)	Final (cm)			
—	0.29	—	—	0.0
0.29	10.00	64.9	9.303	9.303
10.00	17.87	55.8	10.445	19.748
17.87	24.01	60.2	9.859	29.606
24.01	29.02	70.2	8.748	38.354
29.02	33.06	82.9	7.659	46.013
33.06	37.60	68.8	8.888	54.902
37.60	41.81	77.3	8.103	63.005
41.81	46.50	62.8	9.543	72.548
46.50	50.57	74.6	8.337	80.885
50.57	54.95	69.8	8.788	89.672
54.95	59.64	67.1	9.064	98.736
59.64	63.96	84.2	7.563	106.299
63.96	68.96	76.6	8.163	114.462
68.96	74.95	70.2	8.748	123.210
74.95	83.01	66.0	9.182	132.392
83.01	95.19	83.8	7.592	139.984

Table 6-4

CALIBRATION OF REFLECTOR 8 ASSEMBLY II-C at 750°F

(Reflector 5 at 66 cm)

Reflector Position		Doubling Time (sec)	Reactivity Increment (ρ)	Cumulative Reactivity (ρ)
Initial (cm)	Final (cm)			
—	0.17	—	—	0.0
0.17	10.09	60.6	9.809	9.809
10.09	17.63	56.9	10.292	20.100
17.63	23.00	69.9	8.778	28.878
23.00	28.09	64.4	9.359	38.237
28.09	32.52	69.7	8.798	47.035
32.52	36.57	75.5	8.257	55.292
36.57	40.52	74.0	8.391	63.683
40.52	44.48	78.1	8.037	71.719
44.48	48.42	76.1	8.205	79.925
48.42	53.02	67.7	9.001	88.926
53.02	57.53	70.5	8.719	97.645
57.53	61.95	75.6	8.249	105.893
61.95	67.03	71.0	8.670	114.564
67.03	72.51	76.6	8.163	122.726
72.51	81.10	57.4	10.223	132.950
81.10	94.95	63.8	9.427	142.377

Table 6-5

WORTH OF REFLECTOR 8
IN ASSEMBLY II-C

Nominal Core Temperature (°F)	Position of Reflector 5 (cm)	Position of Reflector 10 (cm)	Worth of Reflector 8 (¢)
550	89	0 (down)	135.5
350	0 (down)	18	137.2
750	66	99 (up)	142.4

Table 6-6

WORTH OF REFLECTOR 3
IN ASSEMBLY II-C

Nominal Core Temperature (°F)	Position of Reflector 10 (cm)	Position of Reflector 5 (cm)	Worth of Reflector 3 (¢)
350	16	0 (down)	132.3
550	0 (down)	89	139.1
750	65	99 (up)	140.0

- 620 STANDARD FUEL RODS
- 12 IFA FUEL RODS
- 8 B_4C RODS
- 6 GUINEA PIG RODS
- 1 FOIL HOLDER ROD
- 1 STAINLESS STEEL ROD
- 102 SS TIGHTENER RODS
- 6 BeO IFA TIGHTENER RODS

- INSTRUMENTED FUEL ASSEMBLIES (IFA'S)
- B_4C RODS
- GUINEA PIG RODS
- FOIL HOLDER ROD
- STAINLESS STEEL (SS) ROD
- DRYWELL

Figure 6-2 Core Loading for Assembly II-E

- 618 STANDARD FUEL RODS
- 12 IFA FUEL RODS
- 3 IFR FUEL RODS
- 7 B₄C RODS
- 6 GUINEA PIG RODS
- 1 FOIL HOLDER ROD
- 1 STAINLESS STEEL ROD
- 102 SS TIGHTENER RODS
- 6 B₂O IFA TIGHTENER RODS

- INSTRUMENTED FUEL ASSEMBLIES (IFA'S)
- B₄C RODS
- GUINEA PIG RODS
- INSTRUMENTED FUEL RODS (IFR'S)
- FOIL HOLDER ROD
- STAINLESS STEEL (SS) ROD
- DRYWELL

Figure 6-3 Core Loading for Assembly II-F

Table 6-7

**CALIBRATION OF REFLECTOR 3
ASSEMBLY II-E at 750°F**

(Reflector 10 at 50 cm)

Reflector Position		Doubling Time (sec)	Incremental Reactivity (ρ)	Cumulative Reactivity (ρ)
Initial (cm)	Final (cm)			
—	0.13	—	0.0	0.0
0.13	9.92	61.0	9.742	9.742
9.92	18.16	51.1	11.137	20.878
18.16	24.00	60.5	9.804	30.682
24.00	29.02	67.7	8.985	39.667
29.02	33.07	81.5	7.751	47.419
33.07	37.60	66.3	9.133	56.552
37.60	42.10	67.0	9.058	65.610
42.10	46.50	67.1	9.048	74.658
46.50	50.04	91.7	7.040	81.698
50.04	55.16	55.6	10.455	92.153
55.16	59.96	68.0	8.954	101.107
59.96	65.47	59.0	9.994	111.101
65.47	71.05	68.8	8.872	119.973
71.05	81.20	41.5	12.954	132.927
81.20	95.19	60.3	9.829	142.755

Table 6-8

CALIBRATION OF REFLECTOR 8 ASSEMBLY II-E at 750°F

(Reflector 5 at 50 cm)

Reflector Position		Doubling Time (sec)	Incremental Reactivity (ρ)	Cumulative Reactivity (ρ)
Initial (cm)	Final (cm)			
—	0.15	—	0.0	0.0
0.15	9.99	61.7	9.657	9.657
9.99	17.52	57.0	10.260	19.916
17.52	24.47	48.7	11.539	31.456
24.47	28.73	82.8	7.653	39.109
28.73	32.97	75.0	8.286	47.395
32.97	37.01	75.4	8.251	55.646
37.01	40.99	75.4	8.251	63.898
40.99	45.05	74.9	8.295	72.193
45.05	49.04	78.7	7.973	80.166
49.04	53.40	69.8	8.772	88.938
53.40	57.90	74.8	8.304	97.242
57.90	63.05	65.6	9.209	106.451
63.05	68.03	77.1	8.106	114.557
68.03	74.10	70.8	8.674	123.231
74.10	81.93	69.7	8.782	132.013
81.93	94.85	72.8	8.485	140.498

Table 6-9

**CALIBRATION OF REFLECTOR 3
ASSEMBLY II-F at 750°F**

(Reflector 10 at 55 cm)

Reflector Position		Doubling Time (sec)	Incremental Reactivity (ρ)	Cumulative Reactivity (ρ)
Initial (cm)	Final (cm)			
—	0.30	—	0.0	0.0
0.30	10.09	63.2	9.479	9.479
10.09	17.02	63.8	9.410	18.890
17.02	23.27	58.0	10.125	29.014
23.27	28.55	61.1	9.730	38.744
28.55	33.36	62.7	9.538	48.282
33.36	38.66	51.9	11.009	59.290
38.66	42.99	66.0	9.165	68.456
42.99	47.44	62.2	9.597	78.053
47.44	51.95	63.1	9.491	87.544
51.95	56.46	66.65	9.096	96.639
56.46	60.91	74.5	8.331	104.970
60.91	66.35	62.25	9.591	114.561
66.35	72.59	60.0	9.866	124.427
72.59	81.08	54.2	10.657	135.084
81.08	87.05	126.0	5.387	140.471
87.05	95.19	168.0	4.189	144.660

Table 6-10

**CALIBRATION OF REFLECTOR 8
ASSEMBLY II-F at 750°F**

(Reflector 5 at 53 cm)

Reflector Position		Doubling Time (sec)	Incremental Reactivity (ρ)	Cumulative Reactivity (ρ)
Initial (cm)	Final (cm)			
—	0.17	—	0.0	0.0
0.17	10.12	60.0	9.866	9.866
10.12	17.55	54.9	10.555	20.421
17.55	24.10	54.9	10.555	30.976
24.10	29.08	64.8	9.297	40.273
29.08	33.56	70.2	8.733	49.006
33.56	38.08	68.1	8.944	57.950
38.08	42.48	68.1	8.944	66.893
42.48	46.88	68.5	8.903	75.796
46.88	51.44	65.3	9.242	85.038
51.44	56.57	59.9	9.879	94.917
56.57	61.69	60.7	9.779	104.696
61.69	66.39	74.4	8.340	113.035
66.39	73.02	59.5	9.930	122.965
73.02	82.04	55.25	10.505	133.469
82.04	94.95	76.0	8.199	141.669

Table 6-11

CORE II DOPPLER CALCULATIONS

U-238 Doppler $\Delta K/K$		Average U-238 DOPPLER $\frac{Tdk}{dT}$ 300° K to 1400° K	Total Doppler* $\frac{Tdk}{dT}$
300° K to 700° K	700° K to 1400° K		
-0.00541	-0.00396	-0.0061	-0.0063

*Includes a contribution of -0.0002 from Pu-240.

The non-Doppler temperature expansion reactivity coefficients were calculated for a SEFOR fully-loaded Core II containing 642 standard fuel rods and 6 B₄C poison rods uniformly distributed over the core. The two-dimensional diffusion theory synthesis code, BISYN,³ was used to obtain the results. The definitions for the calculated expansion coefficients for SEFOR Core II are as follows:

Axial Fuel Expansion: The reactivity effect due to increasing the length of the fuel segments with a corresponding reduction in fuel density and size of the gap.

Axial Fuel Cladding Expansion: The reactivity effect due to axial expansion of the fuel cladding. Most of this reactivity effect is due to the upper fuel segment moving with the fuel cladding and there is a smaller contribution due to the reduction in cladding density.

Structure Axial Expansion: The reactivity effect due to extending the length of the channels, steel side rods, tightener rod cladding, tightener sleeve, axial reflectors, and the inner vessel wall with a corresponding reduction in the respective material densities.

Structure Radial Expansion: The reactivity effect caused by radial expansion of the channels. Since the structure temperature change is accompanied by the same change in fuel and BeO cladding temperatures, core volume fractions remain unchanged during radial expansion. Displacement of sodium surrounding the core is included in this effect. Change of sodium density is not included; this appears in a separate coefficient.

Sodium Density Effect in Core and Axial Reflectors: The reactivity effect due to a change of sodium density in the core and axial reflectors.

Sodium Density Effect Between Core and Vessel: The reactivity effect due to a change of sodium density in the region between the core and the vessel wall.

B₄C Axial Expansion: The reactivity effect due to extending the length of the B₄C rods with a corresponding reduction in B₄C density.

Previously reported results⁴ for the reactivity coefficients of fuel axial expansion and fuel cladding axial expansion were used. The balance of the coefficients were calculated from several calculations in 13 neutron energy groups. The results of this analysis appear in Table 6-12.

Comparison of the Core II and previously calculated¹ Core I expansion coefficients in Table 6-12 shows that the change from the Core I coefficient to the Core II value is due primarily to a 20% increase in the negative reactivity effect of sodium density changes between the core and the vessel wall. The remaining calculated expansion coefficients are substantially the same as Core I.

6.2.3 Core II Temperature Coefficient Measurements

The SEFOR Core II uniform temperature coefficient of reactivity was measured between 350°F and 760°F at zero power. The average measured coefficients are compared with results using the predicted coefficients (see above) and also with results using a Doppler $T dk/dT$ of -0.0060 in Table 6-13. As the table indicates, use of a Doppler $T dk/dT$ of -0.0060 provides slightly better agreement than use of the predicted value of -0.0063.

The SEFOR Core II uniform temperature coefficient of reactivity was measured by heating the reactor with the primary loop trace heating system while adjusting reflector segments to keep the reactor critical at a constant power

Table 6-12

EXPANSION REACTIVITY COEFFICIENTS FOR SEFOR

Effect	Reactivity Coefficients for Fully Loaded Core	
	Core 1(a)	Core 2(b)
Fuel Axial Expansion	-0.009	-0.009
Fuel Clad Axial Expansion	-0.072	-0.072
BeO Axial Expansion	-0.003	Not present
Structure Axial Expansion	-0.014	-0.013
Structure Radial Expansion	-0.135	-0.143
Sodium Density in Core and Axial Reflector	-0.076	-0.076
Sodium Density Between Core and Vessel	-0.059	-0.071
B ₄ C Axial Expansion	+ 0.001	+ 0.001
Total Expansion Reactivity Coefficient	-0.367	-0.384

(a) Core 1 data previously reported in references 1 for 12 B₄C rods.(b) Core 2 data calculated for 6 B₄C rods.

Table 6-13

CORE II UNIFORM TEMPERATURE COEFFICIENT OF REACTIVITY
AT ZERO POWER

Temperature Range (°F)	Temperature Reactivity Coefficient		$\rho/^\circ\text{F}$
	Measured	Calculated(a) $\text{Tdk}/dT = -0.0060$	Calculated (a) $\text{Tdk}/dT = -0.0063$
350 - 550	-0.59	-0.59	-0.60
550 - 750	-0.55	-0.55	-0.56

(a) The non-Doppler effect is $-0.38 \rho / ^\circ\text{F}$.

level of about 600 watts. The magnitude of the reactivity feedback was then determined from the observed changes in the calibrated reflector positions. The reflector calibration data² for Assembly II-C at 350°F were used for readings 1 through 67, and 98 through 142, while the calibrations (above) for Assembly II-C at 550°F were used for the remaining readings. These calibrations corresponded to the coarse reflector configurations that were used for the measurements and should provide the most accurate reactivity data. One other calibration which might have been used for reading 143 onward is the calibration curve for reflector 3 in Assembly II-C at 750°F. It is very similar to the one actually used and its use would not significantly alter the results.

The temperatures and reflector positions were recorded at 15-minute intervals. The primary sodium was stabilized for approximately 2 hours at nominal temperatures of 450°F, 550°F, 650°F, and 750°F to ensure that both thermal and nuclear equilibrium were attained at these points. The time dependent behavior of the temperature is illustrated in Figures 6-4 through 6-8, and the reactivity feedback as a function of temperature is shown in Figure 6-9. The data is tabulated in Table 6-14. The data indicate that the relationship between reactivity and temperature is independent of heating rate for rates of $\sim 10^\circ\text{F/hr}$ or less. This demonstrates, in concurrence with Core I results¹, that the reactivity feedback contains no major components with very long time constants, and that reactivity transient effects are insignificant for heating rates up to 10°F/h .

Figure 6-4 Time Dependence of Temperature (10/14/71 - 10/15/71)

Figure 6-5 Time Dependence of Temperature (10/15/71)

Figure 6-6 Time Dependence of Temperature (10/26/71)

Figure 6-7 Time Dependence of Temperature (10/27/71 - 10/28/71)

Figure 6-8 Time Dependence of Temperature (10/28/71)

Figure 6-9 Temperature Dependent Reactivity Feedback

Table 6-14

CORE II ZERO POWER TEMPERATURE REACTIVITY MEASUREMENTS

Reading Number	Time 10/14/71	Reflector(a) 3		Reflector(a) 8		Coolant Temperature (°F)	Negative Reactivity Feedback (¢)
		Position (cm)	Worth (¢)	Position (cm)	Worth (¢)		
1	1530	40.00	55.34	60.34	97.70	352	1.7
2	1545	40.00	55.34	61.01	98.89	355	2.9
3	1600	40.00	55.34	62.31	101.16	360	5.2
4	1615	40.00	55.34	64.31	104.52	365	8.5
5	1630	40.00	55.34	65.97	107.19	368	11.2
6	1645	40.00	55.34	67.01	108.83	370	12.8
7	1700	40.00	55.34	68.74	111.47	374	15.4
8	1715	40.00	55.34	69.39	112.46	377	16.4
9	1730	40.98	57.14	70.00	113.38	380	19.1
10	1745	41.40	57.95	70.00	113.38	383	20.0
11	1800	42.25	59.58	70.00	113.38	386	21.6
12	1815	43.35	61.70	70.00	113.38	389	23.7
13	1830	44.44	63.80	70.00	113.38	394	25.8
14	1845	44.89	64.67	70.00	113.38	394	26.7
15	1900	45.98	66.77	70.00	113.38	396	28.7
16	1915	46.12	67.04	70.00	113.38	398	29.0
17	1930	46.53	67.84	70.00	113.38	400	29.8
18	1945	47.58	69.87	70.00	113.38	402	31.9
19	2000	48.02	70.72	70.00	113.38	403	32.7
20	2015	48.41	71.47	70.00	113.38	405	33.5
21	2030	48.85	72.33	(b)	(b)	408	34.3
22	2045	49.42	73.43			409	35.4
23	2100	50.04	74.63			411	36.6
24	2115	50.38	75.29			413	37.3
25	2130	51.30	77.06			415	39.1
26	2145	51.49	77.43			417	39.4
27	2200	52.04	78.48			418	40.5
28	2215	52.37	79.11			419	41.1
29	2230	53.19	80.66			421	42.7
30	2245	53.49	81.22			423	43.2
31	2300	54.19	82.53			424	44.5
32	2315	54.39	82.90			428	44.9
33	2330	55.48	84.91			430	46.9
34	2345	56.18	86.18			430	48.2
35	2400	56.18	86.18			431	48.2
36	0015 ^(c)	58.22	89.83			433	51.8
37	0030 ^(c)	58.22	89.83			436	51.8
38	0045 ^(c)	59.75	92.49			440	54.5
39	0100 ^(c)	60.35	93.52			443	55.5
40	0115 ^(c)	61.36	95.24			445	57.2

(a) Reflectors 5 and 10 were down for reading numbers 1-20.

(b) Reflectors 5 and 10 were down, and 8 was at 70.00 cm for reading numbers 21-67.

(c) On 10-15-71

Table 6-14 (Continued)

CORE II ZERO POWER TEMPERATURES REACTIVITY MEASUREMENTS

Reading Number	Time 10/15/71	Reflector 3 Position (cm)	Worth (¢)	Reflector 8 Position (cm)	Worth (¢)	Coolant Temperature (°F)	Negative Reactivity Feedback (¢)
41	0130	62.11	96.49	(a)	(a)	449	58.5
42	0145	63.02	97.99			450	60.0
43	0200	63.75	99.19			452	61.2
44	0215	64.24	99.98			454	62.0
45	0230	64.96	101.13			455	63.1
46	0245	65.50	101.99			457	64.0
47	0300	66.51	103.57			459	65.6
48	0315	66.65	103.78			460	65.8
49	0330	66.35	103.32			459	65.3
50	0345	66.68	103.83			460	65.8
51	0400	66.28	103.21			459	65.2
52	0415	65.02	101.23			455	63.2
53	0430	63.74	99.17			454	61.2
54	0445	63.10	98.13			453	60.1
55	0500	62.38	96.94			450	58.9
56	0515	62.38	96.94			450	58.9
57	5030	61.97	96.26			449	58.3
58	0545	62.20	96.64			448	58.6
59	0600	61.49	95.45			448	57.5
60	0615	61.60	95.64			448	57.6
61	0630	61.60	95.64			448	57.6
62	0645	61.42	95.34			448	57.3
63	0700	62.12	96.51			449	58.5
64	0715	61.76	95.91			449	58.5
65	0730	62.26	96.74			449	58.7
66	0745	63.48	98.75			451	60.8
67	0800	64.54	100.46			454	62.5
68 (b)	0815	49.97	78.24	0.0	-0.10	460	63.4
69	0830	51.21	80.79	0.0	-0.10	463	67.9
70	0845	51.76	81.92	0.0	-0.10	467	69.0
71	0900	52.82	84.08	0.0	-0.10	470	71.2
72	0915	53.64	85.75	0.0	-0.10	473	72.9
73	0930	40.00	58.01	25.04	29.95	476	75.2
74	0945	40.00	58.01	25.66	31.00	479	76.2
75	1000	40.00	58.01	26.66	32.72	482	78.0
76	1015	40.00	58.01	27.40	34.01	485	79.2
77	1030	40.00	58.01	28.52	36.01	487	81.2
78	1045	40.00	58.01	29.28	37.39	489	82.6
79	1100	40.00	58.01	29.80	38.35	491	83.6
80	1115	40.00	58.01	30.46	39.58	494	84.8

(a) Reflectors 5 and 10 were down, and 8 was at 70.00 cm for reading numbers 21-67.

(b) Data for reading numbers 68 through 80 were obtained with reflector 10 down.

Table 6-14 (Continued)

CORE II ZERO POWER TEMPERATURES REACTIVITY MEASUREMENTS

Reading Number	Time (10/15/71)	Reflector 3		Reflector 8		Coolant Temperature (°F)	Negative Reactivity Feedback (¢)
		Position (cm)	Worth (¢)	Position (cm)	Worth (¢)		
81 (a)	1130	40.00	58.01	31.30	41.17	496	86.4
82	1145	40.00	58.01	31.96	42.43	499	87.7
83	1200	40.00	58.01	32.58	43.62	500	88.9
84	1215	40.00	58.01	33.28	44.99	502	90.2
85	1230	40.00	58.01	33.83	46.07	505	91.3
86	1245	40.00	58.01	34.72	47.85	506	93.1
87	1300	40.00	58.01	35.22	48.86	508	94.1
88	1315	40.00	58.01	35.63	49.69	511	94.9
89	1330	40.00	58.01	35.98	50.40	512	95.6
90	1345	40.00	58.01	37.19	52.86	514	98.1
91	1400	40.00	58.01	37.19	52.86	516	98.1
92	1415	40.00	58.01	37.66	53.82	517	99.1
93	1430	40.00	58.01	38.12	54.75	519	100.0
94	1445	40.00	58.01	38.53	55.58	521	100.8
95	1500	40.00	58.01	38.79	56.10	522	101.3
96	1515	40.00	58.01	39.13	56.77	524	102.0
97	1530	40.00	58.01	39.49	57.48	525	102.7
98 (b)	0845	63.70	99.10	70.00	113.38	450	61.1
99	0900	63.98	99.58	70.00	113.38	453	61.6
100	0915	65.41	101.84	70.00	113.38	455	63.8
101	0930	67.16	104.57	70.00	113.38	462	66.6
102	0945	69.44	108.04	70.00	113.38	466	70.0
103	1000	70.58	109.73	70.00	113.38	471	71.7
104	1015	72.76	112.85	70.00	113.38	474	74.9
105	1030	73.80	114.27	70.00	113.38	478	76.3
106	1045	75.08	115.96	70.00	113.38	479	78.0
107	1100	75.96	117.05	70.00	113.38	482	79.1
108	1130	78.22	119.66	70.00	113.38	486	81.7
109	1200	79.88	121.44	70.00	113.38	491	83.4
110	1215	81.85	123.38	70.00	113.38	494	85.4
111	1230	81.70	123.24	70.00	113.38	494	85.2
112	1300	84.41	125.65	70.00	113.38	497	87.7
113	1330	87.43	127.97	70.00	113.38	501	90.0
114	1400	90.45	129.92	70.00	113.38	504	91.9
115	1415	92.22	130.90	70.00	113.38	506	92.9
116	1430	94.56	132.02	70.00	113.38	508	94.0

(a) Data for reading numbers 81 through 97 were obtained with reflector 10 down.

(b) Data beginning with Reading Number 98 was taken on or after 10/26/71. Reflectors 5 and 10 were down for reading numbers 98 through 142.

Table 6-14 (Continued)

CORE II ZERO POWER TEMPERATURES REACTIVITY MEASUREMENTS

Reading Number	Time 10/26/71	Reflector 3		Reflector 8		Coolant Temperature (° F)	Negative Reactivity Feedback (¢)
		Position (cm)	Worth (¢)	Position (cm)	Worth (¢)		
117 (a)	1445	95.21	132.29	70.50	114.12	510	95.0
118	1500	95.21	132.29	71.74	115.92	512	96.8
119	1515	95.21	132.29	73.34	118.17	514	99.1
120	1530	95.21	132.29	74.22	119.36	517	100.3
121	1545	95.21	132.29	75.31	120.80	521	101.7
122	1600	95.21	132.29	77.02	122.93	522	103.8
123	1615	95.25	132.31	78.41	124.57	526	105.5
124	1630	95.25	132.31	78.34	124.49	528	105.4
125	1645	95.25	132.31	79.59	125.89	529	106.8
126	1700	95.25	132.31	81.21	127.61	532	108.5
127	1715	95.25	132.31	82.61	129.00	535	109.9
128	1730	95.25	132.31	83.64	129.97	538	110.9
129	1745	95.25	132.31	86.20	132.15	539	113.1
130	1800	95.25	132.31	86.20	132.15	540	112.8
131	1815	95.25	132.31	87.89	132.42	541	113.4
132	1830	95.25	132.31	90.31	135.00	544	115.9
133	1845	95.25	132.31	90.77	135.27	545	116.2
134	1900	95.25	132.31	93.53	136.66	546	117.6
135	1915	95.25	132.31	93.83	136.79	547	117.7
136	1930	95.25	132.31	94.94	137.22	547	118.2
137	1945	95.25	132.31	94.82	137.17	548	118.1
138	2000	95.25	132.31	94.82	137.17	547	118.1
139	2015	95.25	132.31	94.82	137.17	547	118.1
140	2030	95.25	132.31	94.82	137.17	548	118.1
141	2045	95.25	132.31	94.82	137.17	547	118.1
142	2100	95.25	132.31	94.82	137.17	547	118.1
143 (b)	1100 (c)	0.27	0.01	(b)	(b)	550	120.3
144	1115	1.52	0.93			551	121.2
145	1130	1.52	0.93			552	121.2
146	1145	2.58	1.77			554	122.0
147	1200	4.52	3.44			555	123.7
148	1215	4.52	3.44			556	123.7
149	1230	6.36	5.18			556	125.4
150	1245	6.36	5.18			560	125.4
151	1300	8.23	7.10			562	127.4
152	1315	9.29	8.25			564	128.5
153	1330	10.38	9.48			566	129.7
154	1345	11.39	10.66			567	130.9

(a) Data taken with reflectors 5 and 10 down for reading numbers 98-142

(b) Data for all reading numbers from 143 onward were obtained with reflector 10 down and 8 at 89.30 cm.

(c) Data for readings numbered 143 to 154 were taken on 10-27-71.

Table 6-14 (Continued)

CORE II ZERO POWER TEMPERATURES REACTIVITY MEASUREMENTS

Reading Number	Time 10/27/71	Reflector 3		Reflector 8		Coolant Temperature (°F)	Negative Reactivity Feedback (¢)
		Position (cm)	Worth (¢)	Position (cm)	Worth (¢)		
155	1400	12.75	12.30	(a)	(a)	570	132.6
156	1415	12.75	12.30			572	132.6
157	1430	13.86	13.69			573	134.0
158	1445	14.93	15.06			575	135.3
159	1500	15.66	16.02			579	136.3
160	1515	16.89	17.67			580	137.9
161	1530	17.53	18.55			582	138.8
162	1545	18.87	20.37			586	140.6
163	1600	19.99	21.93			589	142.2
164	1615	20.75	23.02			592	143.3
165	1630	22.28	25.28			595	145.5
166	1645	23.78	27.61			598	147.9
167	1700	24.51	28.84			602	149.1
168	1715	25.00	29.68			605	149.9
169	1730	26.88	33.00			608	153.3
170	1745	27.69	34.46	(a)	(a)	611	154.7
171	1800	28.31	35.59			614	155.9
172	1815	29.33	37.42			616	157.7
173	1830	30.13	38.83			619	159.1
174	1845	30.68	39.81			621	160.1
175	1900	31.20	40.73			623	161.0
176	1915	31.91	42.00			625	162.3
177	1930	32.10	42.35			627	162.6
178	1945	32.31	42.73			629	163.0
179	2000	33.67	45.22			630	165.5
180	2015	33.67	45.22			632	165.5
181	2030	34.30	47.15			634	167.4
182	2045	35.14	48.06			637	168.3
183	2100	35.57	48.92			640	169.2
184	2115	36.20	50.91			642	171.2
185	2130	36.70	51.91			644	172.2
186	2145	37.16	52.12			644	172.4
187	2200	37.59	53.00			647	173.3
188	2215	38.28	55.10			649	175.4
189	2230	38.85	56.25			652	176.5
190	2245	39.20	56.32			653	176.6
191	2300	39.75	57.48			654	177.7
192	2315	39.93	57.86			655	178.1
193	2330	40.28	58.60			656	178.9
194	2345	40.28	58.60			657	178.9

(a) Data for readings from 143 onward were taken with reflector 10 down and reflector 8 at 89.30 cm.

Table 6-14 (Continued)

CORE II ZERO POWER TEMPERATURES REACTIVITY MEASUREMENTS

Reading Number	Time 10/28/71	Reflector 3		Reflector 8		Coolant Temperature (° F)	Negative Reactivity Feedback (¢)
		Position (cm)	Worth (¢)	Position (cm)	Worth (¢)		
195	0145	40.63	59.33	(a)	(a)	658	179.6
196	0200	40.72	59.52			658	179.8
197	0215	41.00	60.12			659	180.4
198	0230	41.32	60.79			661	181.1
199	0245	41.64	61.46			661	181.7
200	0300	42.08	62.39			662	182.7
201	0315	42.44	63.15			664	183.4
202	0330	43.05	64.43			666	184.7
203	0345	43.65	65.67			668	185.9
204	0400	44.21	66.81			670	187.1
205	0415	44.57	67.53			672	187.8
206	0430	45.09	68.56			673	188.8
207	0445	45.61	69.58			675	189.8
208	0500	45.96	70.27			677	190.5
209	0515	46.70	71.72			679	192.0
210	0530	47.56	73.40			683	193.7
211	0545	48.61	75.47			686	195.7
212	0600	49.19	76.65			688	196.9
213	0615	49.79	77.88			692	198.1
214	0630	50.25	78.82			693	199.1
215	0645	50.71	79.76			695	200.0
216	0700	51.35	81.07			697	201.3
217	0715	52.08	82.57			700	202.8
218	0730	52.51	83.45			702	203.7
219	0745	53.85	86.17			704	206.4
220	0800	54.17	86.81			706	207.1
221	0815	54.76	87.99			710	208.3
222	0830	55.44	89.33			712	209.6
223	0845	56.22	90.86			715	211.1
224	0900	57.18	92.72			718	213.0
225	0915	58.07	94.42			721	214.7
226	0930	58.87	95.94	(a)	(a)	725	216.2
227	0945	59.70	97.49			726	217.8
228	1000	60.74	99.41			729	219.7
229	1015	61.89	101.51			732	221.8
230	1030	61.96	101.64			734	221.9
231	1045	63.20	103.86			738	224.1
232	1100	64.26	105.75			741	226.0
233	1115	64.51	106.20			743	226.5

(a) Data for readings from 143 onward were taken with reflector 10 down and reflector 8 at 89.30 cm.

Table 6-14 (Continued)

CORE II ZERO POWER TEMPERATURES REACTIVITY MEASUREMENTS

Reading Number	Time 10/28/71	Reflector 3		Reflector 8		Coolant Temperature (°F)	Negative Reactivity Feedback (¢)
		Position (cm)	Worth (¢)	Position (cm)	Worth (¢)		
234	1130	65.29	107.57			744	227.8
235	1145	65.97	108.75	(a)	(a)	746	229.0
236	1200	66.88	110.31			749	230.6
237	1215	66.88	110.31			750	230.6
238	1230	67.76	111.79			751	232.1
239	1245	67.76	111.79			751	232.1
240	1300	68.42	112.88			753	233.1
241	1330	68.80	113.50			755	233.8
242	1345	68.82	113.53			754	233.8
243	1400	68.60	113.17			755	233.4
244	1415	68.53	113.06			754	233.3
245	1430	68.53	113.06			754	233.3
246	1445	68.53	113.06			755	233.3
247	1500	68.53	113.06			754	233.3
248	1515	67.72	111.73			754	232.0
249	1530	67.24	110.92			751	231.2
250	1545	66.85	110.26			751	230.5
251	1800	65.92	108.67			749	228.9
252	1615	65.98	108.77			748	229.0
253	1630	65.25	107.50	(a)	(a)	745	227.8
254	1645	63.44	104.29			743	224.6
255	1700	63.44	104.29			740	224.6
256	1715	62.64	102.86			737	223.1
257	1730	61.83	101.40			735	221.7
258	1745	61.39	100.60			734	220.9
259	1800	61.08	100.03			732	220.3
260	1815	61.08	100.03			732	220.3
261	1830	61.08	100.03			731	220.3
262	1845	61.08	100.03			731	220.3
263	1900	61.88	101.49			733	221.8
264	1915	63.12	103.72			734	224.0
265	1930	63.12	103.72			738	224.0
266	1945	63.78	104.90			740	225.2
267	2000	64.61	106.37			741	226.6
268	2015	65.21	107.43			744	227.7
269	2030	66.06	108.91			746	229.2
270	2045	66.72	110.04			746	230.3
271	2100	67.12	110.72			748	231.0
272	2115	67.74	111.76			751	232.0
273	2130	68.10	112.36			752	232.6
274	2145	67.83	111.91			751	232.2
275	2200	67.83	111.91			752	232.2
276	2215	67.83	111.91			752	232.2

(a) Data for readings from 143 onward were taken with reflector 10 down and reflector 8 at 89.30 cm.

A good least squares fit of the temperature reactivity data between 350°F and 550°F is a straight line with a slope of $-0.59\text{¢}/^\circ\text{F}$. A straight line also provides a good fit to the data between 550°F and 750°F. The slope for the latter curve is $-0.55\text{¢}/^\circ\text{F}$.

For a delayed neutron fraction of 0.0031 the Doppler value of $-0.0060 \Delta K/K$ is equivalent to -193.5 cents. For a non-Doppler value of $-0.38\text{¢}/^\circ\text{F}$, the uniform temperature coefficient of reactivity may thus be expressed as follows:

$$\frac{dk}{dT} = -0.38 - \frac{193.5}{(T+460)}$$

where the reactivity coefficient (dk/dT) is in units of $\text{¢}/^\circ\text{F}$ and the temperature T is in $^\circ\text{F}$.

The measured reactivity as a function of temperature is compared with the calculated curve:

$$K = -0.38(T-350) - 193.5 \ln [(T+460)/810]$$

in Figure 6-9. As the results in Table 6-13 and Figure 6-9 indicate, the measured reactivity effects are in excellent agreement with values calculated using a Doppler coefficient of $T dk/dT = -0.0060$, and the calculated non-Doppler coefficient of $-0.38\text{¢}/^\circ\text{F}$.

6.2.4 Core II Flow and Pressure Coefficients of Reactivity

To enable the ultimate determination of the Doppler reactivity coefficient, a number of experiments are performed to determine the existence of any relationship between reactivity and plant variables such as flow, pressure, core inlet temperature, etc. The experiments discussed here were performed to determine the relationship between reactivity and coolant flow, and between reactivity and reactor vessel cover gas pressure.

In these experiments, the flow and vessel cover gas pressure were separately and independently changed in increments over their operating ranges while the reflector position was adjusted to maintain a constant flux level at zero power. The reactivity effect of the flow or pressure change was then determined from the change in position of the previously calibrated reflector. The reactivity effects of any small variations in reactor temperature were accounted for using a previously determined temperature coefficient of reactivity.

The data are tabulated in Tables 6-15 and 6-16 and illustrated in Figures 6-10 and 6-11. The data indicate no correlation between reactivity and flow, or between reactivity and pressure, and the deviations from the mean reactivity are of the same order of magnitude ($\pm 0.5\text{¢}$) as the previously estimated¹ standard deviation in zero power reactivity measurements. The flow and pressure coefficients of reactivity may thus be considered equal to zero in agreement with predictions⁵ and Core I measurements¹.

Table 6-15

FLOW REACTIVITY MEASUREMENTS

Coolant Flow (gpm)	Reflector 3		Temperature (°F)	Relative Reactivity ^(a) at 750°F (¢)	Deviation from Mean Reactivity (¢)
	Position (cm)	Worth (¢)			
4700	65.50	108.89	754	106.73	+0.03
4200	65.50	108.89	754	106.73	+0.03
3675	65.36	108.65	754	106.49	+0.27
3675	65.70	109.22	754	107.06	-0.30
3125	64.35	106.96	751	106.42	+0.34
2650	64.59	107.37	750	107.37	-0.61
2100	64.86	107.82	752	106.74	+0.02
1050	64.75	107.63	752	106.55	+0.21
				106.76	

(a) Reactivity corrections for temperature changes were made using a coefficient of $-0.54\text{¢}/^\circ\text{F}$.

Table 6-16

PRESSURE REACTIVITY MEASUREMENTS

Cover Gas Pressure (psig)	Reflector 8		Deviation From Mean Reactivity (ρ)
	Position (cm)	Worth (ρ)	
20.0	62.25	106.43	+0.36
15.3	62.25	106.43	+0.36
10.0	62.45	106.79	0.00
4.9	62.62	107.09	-0.30
0.4	62.70	107.23	-0.44
20.0	62.45	106.79	0.00
		<hr/> 106.79	

No reactivity temperature correction was required as there were no observable temperature changes during these measurements.

Figure 6-10 Flow Reactivity Measurements

Figure 6-11 Pressure Reactivity Measurements

6.2.5 Oscillator Rod Worth Measurements in Core II

The reactivity worth of the oscillator rod in Core II was measured as a function of rod position above the core midplane to determine a region where the reactivity worth varied linearly with position. A sufficiently linear relation was observed with the tip of the rod at 4 inches above the midplane, and this position was used during the later oscillator tests. The total worth of the rod, as well as the shape of the worth versus position curve for Core II were nearly the same as previously⁶ observed in Core I.

The worth versus oscillator rod position measurements were made as the rod was lowered by increments into the core and they were repeated as the rod was withdrawn from the core. The reactivity effect of moving the oscillator rod was compensated by moving a previously calibrated fine reflector segment. The worth of the rod was then determined from the observed changes in reflector position. The data are tabulated in Table 6-17.

The data are plotted in Figure 6-12 where they are compared with similar measurements in Core I.⁶ The differential worth of the rod at a location 4 inches is 2.63 ρ /in. This value is compared below with a corresponding value from the zero power oscillator tests.

6.2.6 Core II Zero Power Oscillator Tests

DESCRIPTION OF EXPERIMENT

The zero power oscillator test was performed by oscillating a boron-carbide rod in the central dry well to produce sinusoidal oscillations in the reactivity and the neutron flux. The time dependent rod position and the signals from two of the operational neutron monitors located below the vessel (and approximately 5 ft below the core) were recorded on magnetic tape with the data acquisition system. The sampling rate was controlled by the oscillator rod position so that 32 nearly equally spaced samples were recorded in each cycle of oscillation.

During the experiment, the amplitudes of the power oscillations were always less than 20% of the mean value and the mean was maintained at a low level (~ 1 KW) so that power dependent feedback effects were negligible.

The oscillator rod was positioned so that the lower end of the 26-inch long poison section was at an indicated mean height of 4.0 inches above the core midplane. This location was selected because oscillator rod worth

Table 6-17

CORE II
OSCILLATOR POISON ROD CALIBRATION

Rod Position Above Core Midplane (in.)	Reflector 8		Core Temperature (°F)	Relative ^(a) Reactivity at 746°F
	Position (cm)	Worth (β)		
20.06	0.16	-0.01	746.5	+0.54
18.06	0.16	-0.01	746.5	+0.54
16.00	1.80	1.31	746.2	-0.94
14.00	3.58	2.88	746.2	-2.51
12.00	6.08	5.33	745.5	-5.34
10.00	8.94	8.45	745.8	-8.30
8.00	12.58	12.94	746.2	-12.57
6.00	15.90	17.53	746.2	-17.16
4.00	19.16	22.48	745.5	-22.49
2.00	22.46	27.94	746.2	-27.57
0.17	25.58	33.51	745.5	-33.52
-1.83	28.77	39.56	746.2	-39.19
-3.83	32.42	46.83	746.0	-46.57
-1.83	28.77	39.56	745.0	-39.84
0.17	25.58	33.51	746.5	-32.98
2.00	22.46	27.94	745.0	-28.22
4.00	19.06	22.32	745.0	-22.60
6.00	15.78	17.35	745.0	-17.63
8.00	12.37	12.67	745.0	-12.95
10.00	8.94	8.45	745.0	-8.73
12.00	5.91	5.15	745.0	-5.43
16.00	1.42	1.00	744.5	-1.55
20.05	0.16	-0.01	744.5	-0.54

^(a) Reactivity corrections for temperature changes were made using a coefficient of $-0.54\beta/^\circ\text{F}$.

Figure 6-12 Oscillator Rod Reactivity Worth

measurements (above) had indicated a nearly linear dependence of reactivity on rod position in this region of the core. In order to limit the amplitude of the power oscillations, the rod was oscillated with an amplitude that ranged between 3 inches or less at high frequencies to 0.4 inch at low frequencies. Eleven different frequencies of oscillation ranging between ~ 0.25 Hz and 0.0018 Hz were used and experiments were repeated at selected frequencies to reaffirm that, as previously⁶ observed during Core I experiments, the data was very reproducible.

The nominal frequencies of oscillation are listed in Table 6-18. For reference purposes, the data tape and file numbers, as well as comments describing the data, are given in Table 6-19. Figures 6-13 through 6-16 illustrate the various degrees of flux drift that were observed during the measurements, and Figures 6-17 and 6-18 illustrate the sinusoidal time dependence of the rod oscillator for two widely separated frequencies. The large flux drifts that occurred during the low frequency experiments were expected⁵ during the planning stages and were also observed, particularly for the ~ 10 minute period oscillations, during the earlier⁶ Core I experiments.

Table 6-18

FREQUENCIES OF OSCILLATION

Designation	Radians/Second	Hertz
F2	1.56	0.25
F3	0.98	0.16
F4	0.61	0.097
F5	0.35	0.056
F6	0.22	0.035
S1	0.13	0.021
S2	0.078	0.012
S3	0.049	0.0078
S4	0.031	0.0049
S5	0.018	0.0029
S6	0.011	0.0018

Table 6-19

CORE II ZERO POWER OSCILLATOR DATA

File on Tape ^(a) 25	Rod Amplitude (ϕ)	Frequency (rad/sec)	Number of Cycles of Data	Comments
5	5.55	1.557	15	
11	5.56	0.6191	15	
12	5.56	0.9840	15	
13	5.56	1.568	15	
14	5.54	0.2268	15	small flux drift during measurement
15	5.55	0.3589	15	small flux drift during measurement
16	5.54	0.07817	10	used only first 9 cycles of data
17	5.54	0.1293	15	flux drift during measurement
18	5.54	0.04902	8	flux drift-used only first 6 cycles of data
19	4.14	0.04905	8	flux drift-used only first 6 cycles of data
20	4.13	0.03099	6	
21	3.19	0.03081	6	flux drift-used only first 3 cycles of data
22	2.57	0.01785	9	large flux drift-used only last 6 cycles (last 5 for the mean)
23	1.11	0.01134	4	large flux drift-used only first 3 cycles
24	5.59	0.6093	15	slight drift
25	5.60	0.2166	15	slight drift
26	5.61	0.07726	10	slight drift-used only first 9 cycles of data
27	1.14	0.01118	3	large drift

^(a) This is recorded as Tape #135 at the SEFOR site.

Figure 6-13 Flux Oscillations at Frequency of 0.984 Rad/sec

Figure 6-14 Flux Oscillations at Frequency of 0.227 Rad/sec

Figure 6-15 Flux Oscillations at Frequency of 0.0490 Rad/sec

Figure 6-16 Flux Oscillations at Frequency of 0.0113 Rad/sec

Figure 6-17 Oscillator Rod Oscillations at Frequency of 0.227 Rad/sec

Figure 6-18 Oscillator Rod Oscillations at Frequency of 0.0113 Rad/sec

RESULTS

The calculated SEFOR complex zero power transfer function, G_0 , at frequency ω (radians/sec) may be expressed as follows:

$$G_0^{-1} = i\omega \left(\ell/\beta + \sum_{j=1}^6 \sum_{k=1}^4 \frac{\beta_{jk}/\beta}{i\omega + \lambda_{jk}} \right)$$

where $i = \sqrt{-1}$, and where the Core II delayed neutron parameters, β_{jk} , etc., are defined, and values listed as in reference 2. The amplitude and phase of this expression are tabulated in Table 6-20 as a function of frequency.

Table 6-20

CALCULATED CORE II TRANSFER FUNCTION

Frequency (rad/sec)	Amplitude (% Power)/(¢ Reactivity)	Phase (degrees)
0.005	17.840	-80.65
0.0063	14.348	78.16
0.008	11.527	-75.77
0.01	9.466	-72.87
0.0125	7.843	-69.62
0.016	6.450	-65.64
0.02	5.478	-61.78
0.025	4.721	-57.78
0.0315	4.113	-53.71
0.04	3.627	-49.82
0.05	3.263	-46.67
0.063	2.945	-43.97
0.08	2.657	-41.66
0.1	2.414	-39.72
0.125	2.194	-37.81
0.16	1.979	-35.57
0.2	1.810	-33.36
0.25	1.664	-30.97
0.315	1.538	-28.32
0.4	1.432	-25.47
0.5	1.353	-22.86
0.63	1.288	-20.30
0.8	1.233	-17.93
1	1.191	-15.95
1.25	1.154	-14.16
1.6	1.120	-12.34
2	1.093	-10.80
2.5	1.072	- 9.38
3.15	1.053	- 8.02

The experimental data was analyzed to obtain the fundamental components of the neutron flux and oscillator rod position signals. Perssons⁷ method of binomial weights per half-cycle was used to minimize the drift contamination of the Fourier components. Based on the Core I experience⁶, the method was used with six, and integer multiples of six, successive half-cycles (i.e., 3 cycles) of data. In view of the excellent agreement between calculated and measured low frequency transfer functions, it appears that this approach satisfactorily eliminated the contaminating effects of the drift.

To compute the values of the zero power transfer function at each frequency, the relation between the measured oscillator rod amplitude in inches, and reactivity in cents must be known. Previous experience⁶ on Core I indicated that the conversion factor could best be obtained from normalization of the amplitude of the measured transfer function between percent power and inches displacement to the amplitude of the calculated transfer function in units of percent power per cents reactivity. Such an approach is valid of course, only if the frequency dependent shape of the measured and calculated curves are the same, so that the conversion factor is indeed constant and independent of frequency. As in Core I⁶, this is the case, and a conversion factor of 2.778 ± 0.010 d/in. was determined from such a normalization. This "dynamic" value is $\sim 5\%$ larger than the previously determined (see above) "static" value of 2.63 d/in. that was obtained from rod position versus reactivity measurements. This apparent difference is in the same direction but is not as large in magnitude as the 9% difference observed in Core I.

The measured zero power transfer function data are tabulated and compared with calculated values in Table 6-21. The measured values include a correction for a time delay of 7 msec, since delays of this order were observed⁸ during Core I transient tests. The measured and calculated values are also compared in Figures 6-19 through 6-22. As illustrated, there is excellent agreement for both detectors between calculation and measurement throughout the entire range of frequencies.

6.2.7 Similar Core I and Core II Arrangements

Zero power critical conditions were attained in Core II, Assembly II-E, that were nearly identical to those in Core I, Assembly I-N. The coolant temperature was exactly the same in both cores (751°F) and the reflector positions differed only by a 4 cm displacement of one of the fine reflectors. The close correspondence in temperature and reflector geometry eliminates differences other than those of core composition, and provides a point of calculation and comparison.

The critical reflector configurations for the two cores are tabulated in Table 6-22. The core loading for Assembly II-E is illustrated in Figure 6-2 and that of Assembly I-N in Figure 6-23. The differences in core composition are tabulated in Table 6-23.

Also shown in Table 6-23 are the reactivity changes that have been estimated, using previously reported² measurements for a direct transition from Assembly I-N to II-E. Since both assemblies are critical, the net change is zero. That the actual and estimated change (Table 6-23) are close, reaffirms the previously estimated² Core II minimum critical mass and the reactivity worth measurements.

6.2.8 SEFOR Fuel Temperature Calculations

Fuel temperature calculations that have been performed for SEFOR fuel rods at linear powers up to 27 kW/ft are described below. The calculational model accounted for central void formation and fuel densification, but neglected plutonium migration, and any axial movement of molten fuel. The calculations used thermal conductivity, and fuel to cladding heat transfer coefficients which have given agreement⁶ with measured SEFOR fuel temperatures. The thermal conductivity of molten fuel was taken equal to that of the solid at the melting point. In addition, the calculational model was extended to investigate fuel temperature behavior at low power levels subsequent to operation at high temperatures.

The calculations indicate that for the nominal condition:

1. the peak temperature in a standard rod at the core center (at a linear power of 18.5 kW/ft) is 4600°F
2. the peak temperature in a guinea pig rod located under one of the innermost ports (where the linear power is 21 kW/ft) is 5050°F
3. the peak temperature in a guinea pig rod located at the core center (where the linear power is 24 kW/ft) would be 5550°F .

The calculations also indicate that at low power levels marked reductions in fuel temperatures may occur as a result of intervening operation at high power. Such trends are in the direction to account for observed reductions in power reactivity feedback.

An effective thermal conductivity for use in calculating SEFOR fuel temperatures, and Doppler effects, with a simpler model was also calculated.

Table 6-21

CORE II ZERO POWER TRANSFER FUNCTION

Frequency (rad/sec)	Amplitude of Transfer Function (% Power)/(d reactivity)			Phase of Transfer Function (degrees)		
	Measured		Calculated	Measured ^(a)		Calculated
	Channel 27	Channel 28		Channel 27	Channel 28	
1.557	1.09	1.13	1.123	-12.3	-12.3	-12.5
1.568	1.12	1.13	1.122	-12.7	-12.5	-12.5
0.9840	1.19	1.18	1.194	-16.7	-16.3	-16.1
0.6191	1.30	1.30	1.292	-21.3	-20.7	-20.5
0.6093	1.30	1.29	1.296	-21.2	-20.8	-20.7
0.3589	1.49	1.49	1.477	-27.6	-27.3	-26.8
0.2268	1.72	1.73	1.725	-32.5	-32.5	-32.0
0.2166	1.77	1.75	1.755	-32.9	-32.8	-32.5
0.1293	2.16	2.14	2.163	-38.0	-37.6	-37.5
0.07817	2.66	2.67	2.683	-42.0	-41.5	-41.9
0.07726	2.71	2.67	2.697	-42.2	-42.1	-42.0
0.04902	3.28	3.24	3.292	-47.3	-46.8	-46.9
0.04905	3.30	3.27	3.292	-47.4	-46.8	-46.9
0.03099	4.18	4.12	4.151	-54.1	-54.1	-54.0
0.03081	4.16	4.15	4.165	-53.9	-53.9	-54.1
0.01785	5.94	5.85	5.943	-63.6	-63.5	-63.8
0.01134	8.74	8.62	8.504	-70.7	-71.1	-71.1
0.01118	8.91	8.65	8.606	-70.9	-70.5	-71.3

(a) Includes corrections ranging between 0.6 and 0.1 degrees at nominal frequencies between 1.6 and 0.13 rad/sec respectively to account for a detector-system delay time of ~7 msec that was observed during Core I transient tests. The estimated standard deviation in the measurements is $\pm 1\%$ in amplitude, and ± 0.3 degrees in phase.

Figure 6-19 Amplitude of Zero Power Transfer Function for Channel 27

Figure 6-20 Phase of Zero Power Transfer Function for Channel 27

Figure 6-21 Amplitude of Zero Power Transfer Function for Channel 28

Figure 6-22 Phase of Zero Power Transfer Function for Channel 28

Table 6-22

CRITICAL CONFIGURATIONS FOR ASSEMBLIES I-N AND II-E

Assembly	Date (1971)	Coolant Temperature (°F)	Reflector (a) 3 Position (cm)	Reflector (a) 8 Position (cm)
I-N	9/8	751	45.41	0.15
II-E	12/6	751	49.25	0.15

(a) Other reflectors completely raised.

Table 6-23

COMPARISON OF CORE LOADINGS FOR ASSEMBLIES I-N AND II-E

Core Location	Radius (cm)	Material		Estimated Reactivity ^(a) Worth of Material Exchange
		Assembly I-N	Assembly II-E	
(102 tightener rods)		BeO	stainless steel	-2.52 ⁽²⁾ ± 0.10
E1.5N1.0B	12.8	B ₄ C	fuel	+1.01 ± 0.04
E0.0S2.0D	12.8	B ₄ C	fuel	+1.01 ± 0.04
W1.5N1.0E	15.5	B ₄ C	fuel	+0.95 ± 0.04
E2.0N2.0C	18.6	foil holder	guinea pig	+0.50 ± 0.02
E2.0N2.0B	19.6	fuel	fuel holder	-0.32 ± 0.02
W3.0S2.0F	25.1	guinea pig	stainless steel	-0.41 ± 0.02
E0.0N4.0A	26.6	stainless steel	B ₄ C	-0.34 ± 0.02
		Sum		-0.12 ± 0.13
		Worth of Reflector Difference		+0.07
		Estimated* Net Change (the change is actually zero)		-0.05 ± 0.13

(a) Using data of reference 2

- 618 STANDARD FUEL RODS
- 12 IFA FUEL RODS
- 102 STANDARD BeO TIGHTENER RODS
- 6 BeO IFA TIGHTENER RODS
- 10 B₄C RODS
- 6 GUINEA PIG RODS
- 1 STAINLESS STEEL ROD
- 1 FOIL HOLDER ROD

- ○ ○ INSTRUMENTED FUEL ASSEMBLY (IFA)
- B₄C ROD
- GUINEA PIG ROD
- ⊕ STAINLESS STEEL ROD
- ⊖ FOIL HOLDER ROD

Figure 6-23 Core Loading for Assembly I-N

TEMPERATURES DURING INITIAL OPERATION

The steady state heat conduction equation in cylindrical geometry can be written for region i, as follows:

$$\frac{1}{r} \frac{\partial}{\partial r} (rk \frac{\partial T}{\partial r}) = -Q_i$$

where Q_i is the heat generation rate per unit volume in region i, k is the thermal conductivity, T is the temperature, and r is the radial dimension.

For a constant heat generation rate, integration of the above equation gives the following relation in region i.

$$rk \frac{\partial T}{\partial r} = \frac{Q_i}{2} (R_i^2 - r^2) + rk \frac{\partial T}{\partial r} \Big|_{r=R_i} \quad \text{Equation (1)}$$

A second integration gives,

$$\int_{T_i}^T k d\theta = \frac{Q_i}{4} (R_i^2 - r^2) - \left[\frac{Q_i R_i^2}{2} + rk \frac{\partial T}{\partial r} \Big|_{r=R_i} \right] \ln (R_i/r)$$

where T_i is the temperature at R_i .

The above equations are readily solved once the temperature dependence of the thermal conductivity is prescribed. In the sketch (Figure 6-24) a fuel pellet has been divided into four regions to conform with the model for fuel thermal conductivity. In this model, thermal conductivity changes are correlated with fuel density changes. The heat generation rate per unit mass is assumed constant. The heat generation rate per unit volume thus varies proportionally with the density in each region. Since the total fuel mass per unit length of rod is $\pi \rho_a R_o^2$, and the densities increase in the central regions of the pellet as it is heated, conversion of mass requires (assuming no axial fuel motion) that

$$\rho_a R_o^2 = \rho_a (R_o^2 - R_1^2) + \rho_b (R_1^2 - R_2^2) + \rho_c (R_2^2 - R_3^2)$$

where the radii, and densities are as defined in Figure 6-24.

Note that this relation is equivalent to the following:

$$QR_o^2 = Q_a (R_o^2 - R_1^2) + Q_b (R_1^2 - R_2^2) + Q_c (R_2^2 - R_3^2) \quad \text{Equation (2)}$$

where Q_a , Q_b , and Q_c are defined in Figure 6-24.

Using the boundary condition that

$$rk \frac{\partial T}{\partial r} \Big|_{r=R_3} = 0$$

requiring continuity of heat flux ($-rk \partial T / \partial r$) at boundaries between regions, and utilizing Equation (1) and (2) gives:

$$rk \frac{\partial T}{\partial r} \Big|_{r=R_o} = -QR_o^2/2$$

$$R_o = 1.1334 \text{ cm}$$

$$Q_a = Q \quad \rho_a = 92\% \text{ theoretical}$$

$$Q_b = Q \rho_b / \rho_a \quad \rho_b = 97\% \text{ theoretical}$$

$$Q_c = Q \rho_c / \rho_a \quad \rho_c = 99\% \text{ theoretical}$$

Figure 6-24 Fuel Pellet Model

$$rk \frac{\partial T}{\partial r} \bigg|_{r=R_1} = -QR_1^2/2$$

$$rk \frac{\partial T}{\partial r} \bigg|_{r=R_2} = \frac{Q\rho_b}{2\rho_a} (R_1^2 - R_2^2) - \frac{QR_1^2}{2}$$

and

$$rk \frac{\partial T}{\partial r} \bigg|_{r=R_3} = \frac{Q\rho_c}{2\rho_a} (R_2^2 - R_3^2) + \frac{Q\rho_b}{2\rho_a} (R_1^2 - R_2^2) - \frac{QR_1^2}{2} = 0$$

Note, that (as it must be) the last equation is identically zero by virtue of Equation (2).
The above relations give:

In Region A

$$\int_{T_s}^T k d\theta = \frac{Q}{4} (R_o^2 - r^2)$$

Equation (3)

In Region B

$$\int_{T_1}^T k d\theta = \frac{Q}{4\rho_a} \left[\rho_b (R_1^2 - r^2) - R_1^2 (\rho_b - \rho_a) \ln \left(\frac{R_1}{r} \right)^2 \right]$$

Equation (4)

and, in Region C

$$\int_{T_2}^T k d\theta = \frac{Q}{4} \frac{\rho_c}{\rho_a} \left[R_2^2 - r^2 - R_3^2 \ln \left(\frac{R_2}{r} \right)^2 \right] \quad \text{Equation (5)}$$

The fuel temperature distribution throughout the rod, including the maximum fuel temperature, T_m , can be calculated from the previous relations provided the power density Q , the surface temperature T_s , the conductivity, and the radii R_1 , and R_2 are specified.

To determine the temperatures, let it be assumed that the fuel rod has never operated at a higher power density than the one, whatever its magnitude, to be used for the calculation. Then, the fuel thermal conductivity, density, and temperature ranges are correlated by the model⁹ as follows: (For SEFOR the initial fuel density is 92% of theoretical)

92% dense	k^*	$= 0.05304 - 3.255 \times 10^{-5} T$	$400^\circ\text{C} \leq T \leq 600^\circ\text{C}$
92% dense	k	$= 0.011 + 13.510/T$	$600^\circ\text{C} \leq T \leq 1650^\circ\text{C}$
97% dense	k	$= 0.011 + 19.344/T$	$1650^\circ\text{C} \leq T \leq 2150^\circ\text{C}$
99% dense	k	$= 0.0219$	$2150^\circ\text{C} \leq T$

where the thermal conductivity k is in units of $\text{w/cm}^\circ\text{C}$, and the temperature T is in $^\circ\text{C}$. This model thus dictates that the radii R_1 and R_2 of Figure 6-24 correspond to the temperatures at which the thermal conductivity and density change, i.e., $T_1 = 1650^\circ\text{C}$ and $T_2 = 2150^\circ\text{C}$, if $T_m \geq 1650^\circ\text{C}$ (2150°C).

With these assumptions, $R_1 = R_2 = R_3 = 0$ if $T_m \leq 1650^\circ\text{C}$. If the maximum temperature is $\geq 1650^\circ\text{C}$, R_1 is determined from the following relation:

$$\left(\frac{R_1}{R_0} \right)^2 = 1 - \int_{T_s}^{1650^\circ\text{C}} k d\theta / (QR_0^2/4) \quad \text{if } T_m \geq 1650^\circ\text{C} \quad \text{Equation (6)}$$

R_2 is then determined from:

$$R_2^2 = R_1^2 (\rho_b - \rho_a) / \rho_b \quad \text{if } 1650^\circ\text{C} \leq T_m \leq 2150^\circ\text{C} \quad \text{Equation (7)}$$

and from the following if $T_m \geq 2150^\circ\text{C}$

$$\int_{1650^\circ\text{C}}^{2150^\circ\text{C}} k d\theta = 10.62 \text{ w/cm} = \frac{QR_1^2}{4} \frac{\rho_b}{\rho_a} \left[1 - \left(\frac{R_2}{R_1} \right) + \frac{\rho_b - \rho_a}{\rho_b} \ln \left(\frac{R_2}{R_1} \right)^2 \right]$$

If $1650^\circ\text{C} \leq T_m \leq 2150^\circ\text{C}$, the radius $R_3 = R_2$, while if $T_m \geq 2150^\circ\text{C}$, the radius R_3 is determined from

$$R_3^2 = R_1^2 (\rho_b - \rho_a) / \rho_c + R_2^2 (\rho_c - \rho_b) / \rho_c \quad \text{Equation (8)}$$

The fuel surface temperature is calculated from the following expression, which neglects the small contribution due to direct heating in the cladding.

$$T_s = T_c + \frac{QR_0^2}{2} \left[\frac{1}{R_0 h_f} + \frac{x_t}{k_t R_t} + \frac{1}{R_c h_c} \right]$$

*This is a linear fit to a portion of normalized (to 92% theoretical density) Schmidt¹⁰ data

where T_c is the coolant temperature, h_f is the fuel to cladding heat transfer coefficient, x_t is the cladding thickness, k_t is the cladding conductivity, R_t is the mean cladding radius, R_c is the cladding outer radius, h_c is the cladding to coolant heat transfer coefficient, and the other terms have been previously defined.

For:

$$\begin{aligned} h_c &= 1.58 \text{ w/cm}^2 \text{ } ^\circ\text{F} = 5000 \text{ Btu/ft}^2 \text{ } ^\circ\text{F} \\ x_t &= 0.104 \text{ cm} \\ k_t &= 0.145 \text{ w/cm} \\ R_t &= 1.186 \text{ cm} \\ R_c &= 1.238 \text{ cm} \\ R &= 1.1334 \text{ cm} \\ T_c &= 760^\circ\text{F} \end{aligned}$$

$$T_S = 760 + Q [0.5667/h_f + 0.71685]$$

The model for h_f that provided correlation⁶ with the SEFOR fuel temperature measurements (and which was obtained by neglecting heat generation in the cladding, and using the above values for h_c , x_t , etc.) is as follows:

$$h_f = 0.04109 + 5.521 \times 10^{-4} Q + 8.738 \times 10^{-6} Q^2$$

where h_f is in units of $\text{w/cm}^2 \text{ } ^\circ\text{F}$ and Q is in w/cm^3 .

The above relations specify the problem so that the maximum fuel temperature can be calculated for any given power density Q . The results of such calculations for power densities between 0 and 220 w/cm^3 (equivalent for SEFOR to linear powers between 0 and 27.06 kW/ft) are listed in Table 6-24, and the maximum temperature is illustrated as a function of power density in Figure 6-25.

Figure 6-25 Peak Fuel Rod Temperatures in SEFOR

Table 6-24

FUEL ROD TEMPERATURES FOR SEFOR

Power density Q (w/cm ³)	$\left(\frac{R_1}{R_0}\right)^2$	$\left(\frac{R_2}{R_0}\right)^2$	$\left(\frac{R_3}{R_0}\right)^2$	Gap Coefficient h (w/cm ² · °F)	Surface Temperature T_S (°F)	Linear Power $Q\pi R_0^2$ (kw/ft)	$4\pi \int_{T_S}^{T_m} kd\theta$ T_S (kw/ft)	Peak Temperature T_m (°F)
0	0.0	0.0	0.0	0.04109	760	0.0	0.0	760
5	0.0	0.0	0.0	0.04407	827.9	0.615	0.615	904.0
10	0.0	0.0	0.0	0.04748	886.5	1.230	1.230	1046.4
15	0.0	0.0	0.0	0.05134	936.3	1.845	1.845	1188.5
20	0.0	0.0	0.0	0.05563	978.1	2.460	2.460	1331.4
25	0.0	0.0	0.0	0.06035	1012.7	3.075	3.075	1474.8
30	0.0	0.0	0.0	0.06552	1041	3.69	3.69	1618
35	0.0	0.0	0.0	0.07112	1064	4.31	4.31	1762
40	0.0	0.0	0.0	0.07715	1082	4.92	4.92	1906
45	0.0	0.0	0.0	0.08363	1097	5.54	5.54	2050
50	0.0	0.0	0.0	0.09054	1109	6.15	6.15	2195
55	0.0	0.0	0.0	0.09789	1118	6.77	6.77	2341
60	0.0	0.0	0.0	0.1057	1125	7.38	7.38	2488
65	0.0	0.0	0.0	0.1139	1130	8.00	8.00	2636
70	0.0	0.0	0.0	0.1226	1134	8.61	8.61	2787
75	0.0	0.0	0.0	0.1317	1137	9.23	9.23	2939
80	0.038	0.002	0.002	0.1412	1138	9.84	9.78	3066
85	0.095	0.005	0.005	0.1512	1140	10.46	10.30	3177
90	0.146	0.008	0.008	0.1616	1140	11.07	10.81	3288
95	0.191	0.010	0.010	0.1724	1140	11.69	11.33	3401
100	0.231	0.012	0.012	0.1837	1140	12.30	11.84	3516

Table 6-24 (Continued)

FUEL ROD TEMPERATURES FOR SEFOR

Power density Q (w/cm ³)	$\left(\frac{R_1}{R_0}\right)^2$	$\left(\frac{R_2}{R_0}\right)^2$	$\left(\frac{R_3}{R_0}\right)^2$	Gap Coefficient h (w/cm ² ·°F)	Surface Temperature T_s (°F)	Linear Power $Q\pi R_0^2$ (kw/ft)	$4\pi \int_{T_s}^{T_m} kd\theta$ (kw/ft)	Peak Temperature T_m (°F)
105	0.267	0.014	0.014	0.1954	1140	12.92	12.36	3631
110	0.300	0.015	0.015	0.2076	1139	13.53	12.88	3749
115	0.330	0.017	0.017	0.2201	1138	14.15	13.39	3867
120	0.358	0.065	0.019	0.2332	1138	14.76	13.90	3978
125	0.383	0.107	0.022	0.2466	1137	15.38	14.40	4083
130	0.407	0.144	0.023	0.2605	1136	15.99	14.89	4189
135	0.428	0.176	0.025	0.2749	1135	16.61	15.39	4293
140	0.448	0.206	0.027	0.2896	1134	17.22	15.88	4398
145	0.467	0.234	0.028	0.3049	1133	17.84	16.38	4503
150	0.484	0.260	0.030	0.3205	1133	18.45	16.87	4608
155	0.501	0.284	0.031	0.3366	1132	19.07	17.36	4713
160	0.516	0.306	0.032	0.3531	1131	19.68	17.86	4818
165	0.531	0.327	0.033	0.3701	1131	20.30	18.35	4923
170	0.544	0.347	0.035	0.3875	1130	20.91	18.84	5028
175	0.557	0.366	0.036	0.4053	1130	21.53	19.33	5133
180	0.569	0.384	0.037	0.4236	1130	22.14	19.82	5238
185	0.581	0.400	0.037	0.4423	1130	22.76	20.32	5343
190	0.592	0.416	0.038	0.4614	1130	23.37	20.81	5448
195	0.603	0.431	0.039	0.4810	1130	23.99	21.30	5554
200	0.612	0.446	0.040	0.5010	1130	24.60	21.79	5659
205	0.622	0.459	0.041	0.5215	1130	25.22	22.28	5765
210	0.631	0.472	0.041	0.5424	1130	25.83	22.77	5871

Table 6-24 (Continued)

FUEL ROD TEMPERATURES FOR SEFOR

Power density Q (w/cm ³)	$\left(\frac{R_1}{R_0}\right)^2$	$\left(\frac{R_2}{R_0}\right)^2$	$\left(\frac{R_3}{R_0}\right)^2$	Gap Coefficient h (w/cm ² -°F)	Surface Temperature T _s (°F)	Linear Power QπR ₀ ² (kw/ft)	$4\pi \int_{T_s}^{T_m} kd\theta$ T _s (kw/ft)	Peak Temperature T _m (°F)
215	0.640	0.485	0.042	0.5637	1130	26.45	23.26	5976
220	0.648	0.497	0.043	0.5855	1131	27.06	23.75	6082

For SEFOR, the maximum power density in a standard fuel rod at the core center is calculated⁶ to be 150 w/cm³, while the core average power density is 85.2 w/cm³. The maximum power density in a guinea pig rod under an inner port is 171 w/cm³, and the maximum density if a guinea pig rod were to be located at the core center is estimated to be 195 w/cm³. The corresponding maximum fuel temperatures are readily determined from Table 6-24 or Figure 6-25.

The actual linear power ($Q\pi R_o^2$) is compared with the quantity

$$4\pi \int_{T_s}^{T_m} k d\theta \text{ in Figure 6-26.}$$

For computer programs, such as WEDOP¹¹, which assume a constant power per unit volume throughout the rod and do not allow for a central void, a modified, effective, thermal conductivity must be used to calculate the correct dependence of rod central temperature on power density. Simple programs of this type equate the actual linear power to 4π times the integral of the conductivity. Thus, for SEFOR, this effective conductivity is $1/(4\pi)$ times the slope of the linear power curve, $Q\pi R_o^2$, in Figure 6-26. This slope is equal to the actual conductivity, given by the model described above for $T_m \leq 1650^\circ\text{C}$. For $1650^\circ\text{C} \leq 2150^\circ\text{C}$, this effective conductivity can be approximated by a constant 0.02525 w/cm²·°C, and for $T_m \geq 2150^\circ\text{C}$; this effective conductivity is well approximated by a constant value of 0.0275 w/cm²·°C.

Low Power Temperatures Following Restructuring

According to the above model, fuel densification and central void formation never occurs in fuel rods which are always operated below a central temperature of 1650°C. For these rods, there is a unique unchanging relation (for SEFOR, the curve in Figure 6-25) between power density and central fuel temperature. Once the rod has operated at a high enough power density however, a central void will be formed as fuel in the central regions density. If the central void remains when the fuel rod is subsequently operated at a lower power density, the fuel temperature versus power relationship might be different than it was during the initial low power operation.

Figure 6-26 Linear Power and Integral Conductivity vs SEFOR Peak Fuel Rod Temperature

— The fuel temperature versus power density relationship for low power operation subsequent to extended operation at a higher density Q_0 may be calculated if it is assumed that the fuel does not restructure[†] as a result of low power operation, and if it is assumed that the radii and density boundaries remain unchanged from the values dictated by the above model during the high power operation at Q_0 . The temperatures are then obtained as a function of power density $Q \leq Q_0$ from Equations 3 to 5, but with the radii R_1 , R_2 and R_3 calculated using the value $Q=Q_0$ in Equations 6 to 8. Since the thermal conductivity is density dependent, as well as temperature dependent, the conductivity model for use in Equations 3 to 5 is as follows:

Region A 92% dense	$k^* = 0.05304 - 3.255 \times 10^{-5} T$ $k = 0.011 + 13.510/T$	$400^\circ\text{C} \leq T \leq 600^\circ\text{C}$ $T \geq 600^\circ\text{C}$
Region B 97% dense	$k^* = 0.06843 - 4.199 \times 10^{-5} T$ $k = 0.011 + 19.344/T$	$400^\circ\text{C} \leq T \leq 600^\circ\text{C}$ $T \geq 600^\circ\text{C}$
Region C 99% dense	$k^* = 0.07908 - 4.853 \times 10^{-5} T$ $k = 0.011 + 23.384/T$ $k = 0.0219$	$400^\circ\text{C} \leq T \leq 600^\circ\text{C}$ $600^\circ\text{C} \leq T \leq 2150^\circ\text{C}$ $T \geq 2150^\circ\text{C}$

Along with the above it will be assumed that the fuel to cladding heat transfer coefficient retains its original dependence on power density as specified above. If instead, it were assumed that this coefficient retained the value corresponding to the power density, Q_0 , which might, as a result of restructured and expanded fuel, be a more appropriate assumption, the difference between initial and subsequent operating characteristics would be larger than shown here.

The results of calculations using the above model for the hottest standard fuel rod in SEFOR, (150 w/cm^3) are illustrated in Figure 6-27 and tabulated in Table 6-25. Comparison with the temperatures that would be expected during the initial rise in power (Table 6-24 or Figure 6-27) shows substantial difference between pre and post operation at higher powers. Changes such as these, as well as reductions in fuel temperature at lower power levels occurring as a result of fuel to cladding gap coefficient changes, are in the direction to explain previously observed⁶ reductions in the power dependent reactivity feedback. These reductions, which over a period of time, amount to a total change of the order of 10% at both 5 and 10 MW, would correspond to change in the effective core average Doppler temperature of $\sim 70^\circ\text{F}$. If some restructuring actually occurs as a result of "annealing" at low power densities, the changes depicted here may exaggerate the real effect due to thermal conductivity changes; however, as indicated above, it probably underestimates the effects of changes due to modified fuel to cladding gap coefficients.

Figure 6-27 Comparison of Peak Fuel Rod Temperatures Before and After Operation at 150 w/cm^3

*Normalized Schmidt data

†Actually some restructuring probably does occur

Table 6-25

**CALCULATED FUEL ROD TEMPERATURES
SUBSEQUENT TO INITIAL OPERATION
at 150 w/cm³**

Power Density	Linear Power	$4\pi \int_{T_S}^{T_m} kd\theta$	Surface Temperature	Peak Temperature
(w/cm ³)	(kw/ft)	(kw/ft)	T _S (°F)	T _m (°F)
0	0	0	760	760
10	1.230	1.125	886.5	1014.4
20	2.460	2.249	978.1	1258.1
30	3.690	3.374	1041	1498
40	4.92	4.50	1082	1733
50	6.15	5.62	1109	1967
60	7.38	6.75	1125	2203
70	8.61	7.87	1134	2443
80	9.84	9.00	1138	2689
90	11.07	10.12	1140	2942
100	12.30	11.25	1140	3203
110	13.53	12.37	1139	3472
120	14.76	13.50	1138	3751
130	15.99	14.62	1136	4037
140	17.22	15.74	1134	4323
150	18.45	16.87	1133	4608

6.2.9 Static Test Doppler Measurements

The power levels, coolant temperatures, and flow rates that were measured during Core II steady state operation at power are tabulated in Tables 6-26 through 6-28. The corresponding reflector configurations and reactivity feedback are tabulated in Tables 6-29 through 6-32. The steady state data at the transient test points (see the tables for specific cases) were obtained prior to lowering the B₄C rod into the core for the indicated transient tests. A comparison of pre and post transient data indicates, as with the Core I data in Subsection 5.3.2, that no change in feedback occurred as a result of transient testing. These data were generally obtained two or more hours prior to actual transient initiation. The reactivity feedback in the tables were obtained by subtracting the average reactivities at zero power for each assembly that is shown in Tables 6-33 through 6-35. The reactivity feedback values were corrected for temperature variations using the relation indicated in the tables. This relation approximates the theoretical dependence of the average temperature coefficient at a 760°F coolant temperature. The first term in the relation is the expected non-Doppler contribution, while the latter term approximates the Doppler effect. Since the corrections are small, slight variations in the indicated coefficient will have an insignificant effect on the results.

Since the average coolant temperature was maintained constant, the reactivity feedback in Tables 6-29, 6-31, and 6-32 contains only two components: 1) the loss in reactivity due to axial expansion of the fuel and cladding as it is heated, and 2) the loss in reactivity resulting from Doppler broadening of the nuclear cross sections. SEFOR was explicitly designed,⁴ using segmented fuel rods and dished fuel pellets, so that the former effect would be small and the dominant component of the power dependent feedback would be the Doppler effect.

Table 6-26

HEAT BALANCE DATA

(Assembly II-C)

Date (1971)	Main Primary System			Auxiliary Primary System			Thermal Power (MW)	Average Coolant Temperature (°F)
	Inlet Temperature (°F)	Outlet Temperature (°F)	Flow (gpm)	Inlet ^(a) Temperature (°F)	Outlet Temperature (°F)	Flow (gpm)		
11/1	748.3	777.5	1503	742.3	775.4	247	1.99	762.3
11/2	730.7	789.2	1502	732.2	785.6	248	3.86	759.8
11/2	721.9	796.7	1503	729.4	790.9	249	4.88	759.4
11/2	729.2	784.1	2082	725.8	780.1	244	4.87	756.3
11/3	729.1	788.3	2418	731.2	783.5	248	5.96	758.6
11/3	729.9	785.2	3490	729.3	780.1	241	7.84	757.4
11/3	729.1	778.3	4875	724.8	772.8	230	9.58	753.5
11/4	700.2	815.6	1914	703.4	804.1	247	9.46	757.4
11/5	630.8	686.0	4674	640.3	680.1	232	10.56	658.5
11/5	597.7	717.3	1999	612.8	705.7	252	10.37	657.7
11/5	497.7	618.4	1997	510.4	605.9	247	10.70	558.1
11/6	530.1	582.5	4676	532.6	577.7	229	10.33	556.2

(a) Auxiliary inlet temperatures on and after 11/5/71 have been increased 12°F to account for a zero power offset that appeared during the low temperature operation.

Table 6-27
HEAT BALANCE DATA
(ASSEMBLY II-E)

Sub-Prompt Transient Test	Date (1971)	Main Primary System			Auxiliary Primary System			Thermal Power (MW)	Average Coolant Temperature (°F)
		Inlet Temperature (°F)	Outlet Temperature (°F)	Flow (gpm)	Inlet ^(a) Temperature (°F)	Outlet Temperature (°F)	Flow (gpm)		
1	12/3	754.1	764.5	4956	744.6	762.6	229	2.14	759.0
2	12/3	751.8	761.2	4750	742.1	760.2	226	1.88	756.3
3	12/4	746.7	772.1	4936	749.8	769.2	230	5.00	759.4
4	12/4	746.0	772.3	4804	749.0	770.2	228	5.05	759.2
4A	12/5	748.3	774.9	4910	754.0	771.4	231	5.18	761.6
5	12/5	737.9	788.9	4968	744.1	783.6	237	10.12	763.4
6	12/6	735.0	786.4	4874	748.5	781.3	231	9.94	760.9
7	12/7	734.4	786.1	4884	748.0	781.2	234	10.02	760.4

(a) Includes a 12°F increase in auxiliary inlet temperature to account for an observed offset at zero power.

Table 6-28

HEAT BALANCE DATA
(Assembly II-F)

Super-Prompt Transient Test	Date (1971)	Main Primary System			Auxiliary Primary System			Thermal Power (MW)	Average Coolant Temperature (°F)
		Inlet Temperature (°F)	Outlet Temperature (°F)	Flow (gpm)	Inlet ^(a) Temperature (°F)	Outlet Temperature (°F)	Flow (gpm)		
1	12/11	749.8	760.3	4932	759.5	760.5	237	2.00	755.3
2	12/11	750.4	761.4	4869	760.1	760.9	234	2.07	756.1
3	12/14	748.4	775.9	4821	755.9	773.4	225	5.26	762.3
-	12/14	749.7	774.3	4951	754.1	771.9	239	4.85	762.0
4	12/15	748.6	776.1	4800	753.5	773.7	239	5.27	762.4
5	12/16	721.1	761.0	5006	734.1	756.8	233	7.89	741.2
8†	12/17	753.1	764.1	4944	762.3	764.2	230	2.11	758.8
-	12/17	731.4	758.2	4963	740.9	756.0	235	5.26	745.0
6	12/17	721.1	762.9	4988	734.4	758.5	237	8.25	742.2
-	12/19	722.0	779.4	2070	734.6	774.4	235	4.93	751.1
-	12/20	699.4	817.7	2066	723.0	806.2	235	10.21	759.2
-	12/20	699.9	814.6	2501	717.3	803.1	245	11.90	757.5
-	12/20	700.8	816.8	2935	712.6	803.9	241	14.00	758.8
-	12/20	699.7	814.4	3166	710.9	801.2	238	14.88	757.0
-	12/20	698.7	813.7	3452	710.6	800.7	236	16.13	756.0
-	12/20	701.1	808.2	4080	712.8	796.1	235	17.66	754.6
-	12/20	700.6	803.3	4669	712.0	790.9	229	19.25	751.9

^(a) Includes a 12°F increase in auxiliary inlet temperature to account for an observed offset at zero power

[†] Sub-prompt critical transient.

Table 6-29

POWER REACTIVITY DATA
(Assembly II-C)

Date (1971)	Reflector 3		Reflector 8		Average Core Coolant Temperature (°F)	Thermal Power (MW)	Neutron Instrumentation (MW)	Negative ^(b) Reactivity Feedback at 760°F Coolant Temperature (¢)
	Position (cm)	Worth (¢)	Position (cm)	Worth (¢)				
10/29-11/1	-	-	-	-	760.0	0.0	0.0	0.0 ^(a)
11/1	40.00	59.50	47.19	77.38	762.3	1.99	1.94	23.3
11/2	40.00	59.50	56.13	94.97	759.8	3.86	4.08	42.3
11/2	40.00	59.50	61.08	104.31	759.4	4.88	5.07	51.8
11/2	40.00	59.50	60.30	102.87	756.3	4.87	5.01	51.9
11/3	40.00	59.50	66.66	113.97	758.6	5.96	6.12	61.9
11/3	40.00	59.50	77.34	128.87	757.4	7.84	8.14	77.3
11/3	40.00	59.50	92.49	141.37	753.5	9.58	10.08	91.6
11/4	40.00	59.50	92.41	141.33	757.4	9.46	10.06	89.8

(a) Using the average value from Table 6-33

(b) Reactivity corrections for temperature changes were made using a coefficient of $-[0.38 + \frac{0.16(1220)}{1220+75P}]$ ¢/°F at power level P in MW.

Table 6-30

**COOLANT TEMPERATURE REACTIVITY DATA AT 10 MW
(Assembly II-C)**

Date (1971)	Reflector 3		Reflector 8		Thermal Power (MW)	Neutron Instrumentation (MW)	Flow (gpm)	Average Coolant Temperature (°F)	Reactivity Change at ^(b) A Constant Thermal Power of 10.0 MW (ρ)
	Position (cm)	Worth (ρ)	Position (cm)	Worth (ρ)					
11/4	40.00	59.50	92.49	141.37	9.58	9.34 ^(a)	4875	753.5	-0.4
11/4	40.00	59.50	92.41	141.33	9.46	9.32 ^(a)	1914	757.4	+0.4
11/5	40.00	59.50	59.24	100.89	10.56	9.88	4674	658.5	-47.5
11/5	40.00	59.50	58.27	99.06	10.37	9.90	1999	657.7	-48.1
11/5	40.00	59.50	35.10	52.26	10.70	9.82	1997	558.1	-97.1
11/6	40.00	59.50	33.43	48.87	10.33	9.23	4676	556.2	-98.0

^(a) Actual WRM readings were 10.08, and 10.06 respectively, but readings have been adjusted to conform to an instrument calibration change on 11/4/71.

^(b) Reactivity corrections for power changes were made using a coefficient of $-6.8\text{ } \rho/\text{MW}$.

Table 6-31

POWER REACTIVITY DATA
(Assembly II-E)

Date (1971)	Reflector 3		Reflector 8		Average Core Coolant Temperature (°F)	Thermal Power (MW)	Neutron Instrumentation (MW)	Relative Reactivity ^(a) Change @ 760°F Coolant Temperature
	Position (cm)	Worth (ρ)	Position (cm)	Worth (ρ)				(ρ)
12/2-12/6	-	-	-	-	760.0	0.0	0.0	0.0 ^(b)
12/3	40.00	61.37	33.03	47.52	759.0	2.14	1.95	23.2
12/3	40.00	61.37	31.76	44.98	756.3	1.88	1.85	22.1
12/4	40.00	61.37	47.73	77.55	759.4	5.00	4.87	53.0
12/4	40.00	61.37	48.00	78.09	759.2	5.05	4.92	53.7
12/5	40.00	61.37	48.94	79.97	761.6	5.18	4.90	54.4
12/5	40.89	63.16	70.00	117.53	763.4	10.12	9.91	92.9
12/6	40.00	61.37	70.00	117.53	760.9	9.94	9.92	92.3
12/7	40.00	61.37	70.00	117.53	760.4	10.02	9.81	92.5

(a) Reactivity corrections for temperature changes were made using a coefficient of $- [0.38 + \frac{0.16(1220)}{1220+75P}] \rho/^\circ\text{F}$ at power level P in MW.

(b) Using the average value from Table 6-34

Table 6-32

POWER REACTIVITY DATA
(Assembly II-F)

Date (1971)	Reflector 3		Reflector 8		Average Core Coolant Temperature (°F)	Thermal Power (MW)	Neutron Instrumentation (MW)	Negative Reactivity ^(b) Feedback at 760°F Coolant Temperature (¢)
	Position (cm)	Worth (¢)	Position (cm)	Worth (¢)				
12/10-12/19	-	-	-	-	760.0	0.0	0.0	0.0
12/11	40.00	62.11	35.41	52.41	755.3	2.00	1.91	22.3
12/11	40.00	62.11	36.13	54.07	756.1	2.07	1.96	23.6
12/14	40.00	62.11	52.79	87.67	762.3	5.26	5.08	54.0
12/14	40.00	62.11	51.00	84.16	762.0	4.85	4.71	50.7
12/15	40.00	62.11	52.35	86.82	762.4	5.27	5.03	53.1
12/16	40.00	62.11	59.63	100.81	741.2	7.89	7.74	77.5
12/17	40.00	62.11	36.95	55.70	758.8	2.11	1.95	23.8
12/17	40.00	62.11	48.71	79.53	745.0	5.26	-	54.5
12/17	40.00	62.11	61.53	104.40	742.2	8.25	8.07	80.6
12/19	40.00	62.11	48.69	79.49	751.1	4.93	4.88	51.4
12/20	44.00	70.63	70.00	118.69	759.2	10.21	10.10	95.1
12/20	48.89	81.14	70.00	118.69	757.5	11.90	11.62	106.4
12/20	56.37	96.46	70.00	118.69	758.8	14.00	13.84	121.1
12/20	58.52	100.56	70.00	118.69	757.0	14.88	14.64	126.0
12/20	62.29	107.47	70.00	118.69	756.0	16.13	15.98	133.4
12/20	67.04	115.72	70.00	118.69	754.6	17.66	17.60	142.3
12/20	71.88	123.38	70.00	118.69	751.9	19.25	19.31 ^(a)	151.1

(a) Actual reading of 19.76 has been adjusted to account for a calibration change between 17.6 and 19 MW.

(b) Reactivity corrections for average coolant temperature changes were made using a coefficient of

$$- \left[0.38 + \frac{0.16(1220)}{1220+75P} \right] \text{ ¢/°F at power level P in MW.}$$

Table 6-33

**ZERO POWER CRITICAL REFLECTOR
CONFIGURATIONS FOR ASSEMBLY II-C**

Date (1971)	Reflector 3		Reflector 8		Reactor Coolant ^(a)	Relative Reactivity† at 760° F
	Position (cm)	Worth (¢)	Position (cm)	Worth (¢)	Temperature (° F)	
10/29	0.29	0.0	64.00	109.51	753	113.29
10/29	65.28	108.52	0.19	0.0	753	112.30
10/29	62.25	103.38	0.19	0.0	745	111.48
10/29	62.45	103.72	0.19	0.0	745	111.82
10/29	62.93	104.55	0.16	0.0	746	112.11
11/1	40.00	59.50	35.37	52.82	759	112.86
						<hr/> 112.31

(a) Observed temperatures were increased by 3°F to account for a calibration change prior to power operation.

† Reactivity corrections to temperature of 760°F were made using a reactivity coefficient of $-0.54\beta/^\circ\text{F}$.

Table 6-34

**ZERO POWER CRITICAL REFLECTOR
CONFIGURATIONS FOR ASSEMBLY II-E**

Date (1971)	Average Core Coolant Temperature (°F)	Reflector 3		Reflector 8		Relative Reactivity ^(a) @760°F and Zero Power (β)
		Position (cm)	Worth (β)	Position (cm)	Worth (β)	
Dec. 2	749	00.13	0	49.00	80.07	86.01
Dec. 3	745	11.00	11.04	42.82	67.66	86.80
Dec. 4 ^(b)	748	40.00	61.37	17.15	19.36	86.49
Dec. 4	751	40.00	61.37	17.35	19.66	85.89
Dec. 5 ^(b)	753	40.00	61.37	19.00	22.24	86.67
Dec. 5	755	40.00	61.37	19.38	22.85	86.92
Dec. 6	752	40.00	61.37	17.63	20.09	85.78
Dec. 6	751	49.25	80.13	00.15	0	84.99
Average =						86.19

(a) Reactivity temperature corrections were made with a coefficient of $-0.54\beta/^\circ\text{F}$.

(b) Critical at $30 \times 10^{-2}\%$ full power, a correction of -0.72β was applied to obtain the zero power reactivity.

Table 6-35

**ZERO POWER CRITICAL REFLECTOR CONFIGURATIONS
FOR ASSEMBLY II-F**

Date Dec. 1971	Reflector 3		Reflector 8		Temperature (°F)	Relative Reactivity ^(a) at 760°F (¢)
	Position (cm)	Worth (¢)	Position (cm)	Worth (¢)		
10	40.00	62.11	22.92	28.95	756	93.22
11	40.00	62.11	23.76	30.39	755	95.20
14	40.00	62.11	24.92	32.45	758	95.64
14	40.00	62.11	23.61	30.13	756	94.40
14	40.00	62.11	23.80	30.46	755	95.27
16	40.00	62.11	22.55	28.33	751	95.30
17	40.00	62.11	22.36	28.01	752	94.44
17	40.00	62.11	20.16	24.44	744	95.19
19	40.00	62.11	22.40	28.08	755	92.89
Average =						94.62

(a) Reactivity corrections for temperature changes were made using a coefficient of $-0.54\text{¢}/^{\circ}\text{F}$.

The experimentally determined values of the Doppler component of the Core II feedback are listed in Table 6-36. These were obtained from the values in Table 6-29, 6-31, and 6-32 by correcting for the calculated fuel and cladding axial expansion coefficient^{4,6} of -0.5¢/MW .

The Core I steady state measurements of Doppler feedback as a function of power level during 1971 are listed in Table 6-37. These were taken directly from reference 6 and, using the above coefficient of -0.5¢/MW , from the data in Subsection 5.3.2. Earlier Core I data is not included, as there appeared⁶ to be an early reduction in feedback with time, probably as a result of a changing relationship (see Subsection 6.2.8) between fuel temperature and power caused by fuel cracking and swelling during initial power operation. This reduction apparently did occur subsequent to operation above ~ 17.5 MW (peak fuel temperatures above 2150°C — see Subsection 6.2.8).

The Core I and Core II Doppler-power data were fit with polynomials that minimized the weighted sum of the residuals between the measured and calculated values. (The weights were unity, except at zero power where they were equal to the number of zero power measurements.) Various order polynomials were tried. The best fits were obtained for a third order polynomial in Core I and for a fourth order in Core II. The fourth order fit for Core II was only very slightly better (0.2% in the sum of the residuals) than the third order fit however, and the latter is used for comparative purposes. These fits for the Doppler feedback reactivity, K , in cents, as a function of power, P , in MW, were as follows:

$$\begin{aligned}\text{Core I; } K &= 0.07 - 14.770P + 0.41045P^2 - 0.0068016P^3 \\ \text{Core II; } K &= -0.03 - 11.309P + 0.29173P^2 - 0.0044598P^3\end{aligned}$$

These equations are shown as solid curves in Figure 6-28 where they are compared with the measured data. The estimated standard deviation for the Core I data, as obtained from the sum of the residuals, is $\pm 1.3\text{¢}$, and the maximum difference between the fitted curve and any data point is 3.0¢ . The corresponding estimated standard deviation for Core II is $\pm 0.5\text{¢}$, and the maximum deviation between the curve and measured data is 1.9¢ .

Calculations indicate that the only significant difference between the Doppler feedback in Core I and Core II is a reduction in magnitude of the Doppler reactivity for Core II. This being the case, it should be possible to represent the Core II feedback data with an equation obtained by multiplying the fitted curve for Core I with a constant. Such a constant, α , was determined by minimizing the quantity S defined by

$$S = 1/20 \int_0^{20} [K_2 - \alpha K_1]^2 dP$$

where K_1 and K_2 are the Doppler feedback equations (above) for Core I and Core II respectively, and where the range of integration covers the range of measurements between zero and 20 megawatts.

The resultant value for α was 0.782 and the value for S was 0.087. The maximum variation between the Core II curve and the normalized Core I curve, i.e., $K_2 - \alpha K_1$, was 0.47¢ . Because of the good correspondence in shape between the Core I and Core II data, the value of α is approximately the ratio $(\bar{K}_2/\bar{K}_1)$ of the average Doppler feedback ($\bar{K}_2 = 83.14$) in Core II to the average feedback ($\bar{K}_1 = 106.5\text{¢}$) in Core I. The approximate fractional deviation in α can thus be estimated from the square root of the sum of the squares of the fractional deviations in $\bar{K}_2$ and $\bar{K}_1$. Using the values of 1.3¢ and 0.5¢ (above) for these deviations, gives a fractional uncertainty in α of 0.014. The estimated ratio including uncertainties is thus 0.782 ± 0.011 .

The above results verify that the steady state Doppler behavior for Core II is the same as for Core I except for a reduction in magnitude. Furthermore, the magnitude of this reduction, which is known to a high degree of accuracy, is independent of uncertainties in fuel thermal conductivity, fuel to cladding heat transfer coefficients, local power densities, etc. As such, this ratio provides an excellent benchmark for Doppler calculational methods.

The magnitude of the Core II Doppler coefficient is readily obtained from the Core I value by multiplying by the constant $\alpha = 0.782$. Since this constant was determined from measurements using reactivity units of cents (or equivalently, dollars) it is also necessary when using the Core I value⁶ in absolute units (-0.0081) to multiply by the ratio of the Core II to Core I effective delayed neutron fractions. In absolute units, the measured coefficient $T dk/dT$ for Core II is thus estimated to be

$$-0.0081(.782) \left(\frac{0.00310}{0.00327} \right) = -0.0060$$

Table 6-36

CORE II STATIC DOPPLER REACTIVITY FEEDBACK

Date (1971)	Thermal Power (MW)	Negative Doppler Feedback (ρ)	Date (1971)	Thermal Power (MW)	Negative Doppler Feedback (ρ)
10/29-11/1	0.0 ^(a)	0.0 ^(a)	12/10-12/19	0.0 ^(a)	0.0 ^(a)
12/2-12/6	0.0 ^(a)	0.0 ^(a)	12/11	2.0	21.3
12/3	1.9	21.2	12/11	2.1	22.6
11/1	2.0	22.3	12/17	2.1	22.7
12/3	2.1	22.1	12/14	4.9	48.3
11/2	3.9	40.3	12/19	4.9	48.9
11/2	4.9	49.4	12/14	5.3	51.4
11/2	4.9	49.5	12/17	5.3	51.9
12/4	5.0	50.5	12/15	5.3	50.5
12/4	5.1	51.2	12/16	7.9	73.6
12/5	5.2	51.8	12/17	8.3	76.5
11/3	6.0	58.9	12/20	10.2	90.0
11/3	7.8	73.4	12/20	11.9	100.5
11/4	9.5	85.1	12/20	14.0	114.1
11/3	9.6	86.8	12/20	14.9	118.6
12/6	9.9	87.3	12/20	16.1	125.3
12/7	10.0	87.5	12/20	17.7	133.5
12/5	10.1	87.8	12/20	19.3	141.5

(a) The zero power reactivities on 10/29-11/1, 12/2-12/6, and 12/10-12/19 are averages of 6, 8, and 9 measurements on Assemblies II-C, II-E, and II-F respectively.

Table 6-37

CORE I STATIC DOPPLER REACTIVITY FEEDBACK

Date (1971)	Thermal Power (MW)	Negative Doppler Feedback (β)	Date (1971)	Thermal Power (MW)	Negative Doppler Feedback (β)
1/25-2/2	0.0 ^(a)	0.0 ^(a)	8/12-8/13	0.0 ^(a)	0.0 ^(a)
1/25	5.1	63.7	8/16-8/30	0.0 ^(a)	0.0 ^(a)
1/28	5.2	65.4	8/14	1.3	17.8
1/28	10.0	113.7	8/12	2.0	27.0
1/26	10.1	112.6	8/14	2.1	29.9
2/2	10.1	117.3	8/17	2.1	30.0
1/26	14.7	148.7	8/19	2.1	28.3
1/28	14.8	150.7	8/13	3.9	52.2
2/2	15.1	155.6	8/13	5.0	65.4
1/26	15.6	155.0	8/21	5.2	66.7
1/26	15.7	156.4	8/23	5.2	67.3
1/26	17.7	169.6	8/13	7.0	87.3
1/28	18.0	172.2	8/30	8.0	93.5
1/26	18.7	175.3	8/28	8.0	94.1
1/29	19.6	184.2	8/26	8.1	95.0
1/30	19.6	184.6	8/13	9.0	107.1
1/30	19.6	184.0			
1/30	19.6	184.0			
1/29	19.8	181.8			

(a) The zero power reactivities on 1/25-2/2, 8/12-8/13, and 8/16-8/30 are averages of 3, 2, and 7 values on Assemblies I-J, I-L, and I-M, respectively.

Figure 6-28 Core I and Core II Doppler Feedback Versus Power.

The estimated deviation in the Core II value is $\pm 10\%$ or ± 0.0006 . This deviation was calculated assuming a 10% deviation in the Core I Doppler measurements, a 3% uncertainty is the ratio of the Core II to Core I delayed neutron fractions, and a 1% (above) uncertainty in the value of α .

6.2.10 Sub-Prompt Critical Transient Analysis

Core II sub-prompt critical transients which provide significant reactivity feedback are initiated from a nominal power ≥ 2 MW by ejecting (by means of the Fast Reactivity Excursion Device (FRED)) a B_4C rod worth of approximately 94¢ or more in a time interval of ~ 0.14 sec. The net reactivity, and the energy release during the transient are computed from measured flux data using standard methods which are described in detail in reference 8. After the FRED rod has been completely ejected from core regions of reactivity influence, and prior to any insertions of negative reactivity from reactor scram or re-entry of the FRED rod into the core, changes in the net reactivity and the energy release are dependent⁸ only upon reactivity feedback effects. The feedback energy coefficient of reactivity can thus be obtained, as in Core I⁸, from the slope of net reactivity versus energy curve during the time when external reactivity changes are zero.

Data from a sub-prompt critical transient initiated from a nominal 5 MW with a 94¢ FRED rod (Core II sub-prompt transient No. 4) that was obtained during the time interval when external reactivity effects were zero are illustrated in Figure 6-29. The slope of the curve, $-0.35¢/\text{MW-sec}$, is the total reactivity feedback, including Doppler, per MW-sec of energy produced. Calculations using the FORE¹² computer program indicate that for this transient $\sim 85\%$ of* the total feedback is Doppler. Since only⁸ 88% of the energy produced during a transient is actually absorbed in the SEFOR fuel during the time interval in question, the transient Doppler energy coefficient at 5 MW is $-0.35(0.85)/0.88 = -0.34$ cents per MW-sec of energy absorbed in the fuel.

The intercept (93.8¢) at zero energy of the curve in Figure 6-29 is the dynamic total** worth of the FRED rod for this transient. The slopes and intercepts for the various sub-prompt transients are listed in Table 6-38. The transient power for typical transients are shown in Figure 6-30 through 6-36.

* The corresponding percentage in Core I was⁸ $\sim 88\%$ since the Core I Doppler coefficient was larger, relative to non-Doppler effects, than the Core II coefficient.

** Total worth, as used here, signifies the net change of reactivity, in the absence of feedback, when the FRED rod is moved from its initial position to one several inches outside the core.

Figure 6-29 Reactivity versus Energy Measurements for Core II, Sub-Prompt Transient 4

Figure 6-30 Time Dependent Power for Sub-Prompt Transient 1

Table 6-38

CORE II SUB PROMPT CRITICAL TEST RESULTS

Test	Nominal Initial Power (MW)	Indicated Maximum FRED Worth (ϕ)		Energy Range (MW-sec)	Energy Coefficient (ϕ /MW-sec)		Calculated ^(a)
		Channel A	Channel B		Channel A	Channel B	
1	2	49.5	49.6	<1	-	-	-
2	2	76.7	76.5	<2	-	-	-
3	5	89.3	89.3	<15	-0.35	-0.35	-0.35
4	5	93.7	93.8	<25	-0.35	-0.35	-0.35
4A	5	93.6	93.7	<20	-0.35	-0.34	-0.35
5	10	93.8	94.0	<20	-0.29	-0.30	-0.29
6	10	94.0	94.1	<30	-0.30	-0.30	-0.29
7	10	87.9	88.0	<20	-0.29	-0.30	-0.29
8	2	98.7	98.6	<30	-0.39	-0.39	-0.42

(a) Calculated using a Doppler $T \frac{dK}{dT}$ of -0.0060, assuring 15% of the total feedback is non-Doppler and assuming only 88% of the energy produced is absorbed in the fuel during a transient.

Figure 6-31 Time Dependent Power for Sub-Prompt Transient 2

Figure 6-32 Time Dependent Power for Sub-Prompt Transient 4A

Figure 6-33 Time Dependent Power for Sub-Prompt Transient 4

Figure 6-34 Time Dependent Power for Sub-Prompt Transient 6

Figure 6-35 Time Dependent Power for Sub-Prompt Transient 7

Figure 6-36 Time Dependent Power for Sub-Prompt Transient 8

The measured and calculated energy coefficients for the sub-prompt critical transients are summarized in Table 6-38. The Doppler calculations were performed using the WEDOP¹¹ program with a Doppler $T dk/dT$ of -0.0060 , effective fuel thermal conductivity values as determined in Subsection 6.2.8; and a fuel heat capacity (C in units of joules/gram $^{\circ}F$) of $C = 0.179 + 1.5 \times 10^{-6} (T-700)$ where T is in $^{\circ}F$. This is a linear approximation to the expression given by Hein and Fagella¹³. The new effective conductivity and heat capacity will subsequently be applied to Core I data. As the values in the table indicate, there is good agreement between the calculated and measured coefficients, thus substantiating the Doppler $T dk/dT = -0.0060$ inferred from the static test data.

Two different FRED rods were used to initiate the transients. The "sub-prompt slug" was used for transients 1 through 7, and the "super-prompt slug" was used for transient 8. The initial axial positions for the slugs are shown in Table 6-39.

Table 6-39

INITIAL SLUG POSITIONS BEFORE FRED-FIRING IN SUB-PROMPT TRANSIENT

SLUG	Nominal Slug Reactivity (ρ)	Lower Position of Slug (in.)	Test
Sub-prompt	50	8	1
	77	3.75	2
	88	1.80	7
	89	1.50	3
	94	0.76	4,4A,5,6
Super-prompt	98	3.80	8

The total reactivity worths of the FRED rod that were obtained from analysis of the sub-prompt transient data (the "dynamic" worth) are shown in Table 6-38. These values compare favorably with the static values of Section 6.2.12. Thus, the "dynamic" worth is the same as that obtained from reflector swap, and asymptotic period measurements (the "static" worth). This is in contrast to Core I where the dynamic worths were larger by amounts between ~ 3 and $\sim 7\%$, depending on the particular static measurement, than the static worths. The reason for the agreement in Core II and the disparities in Core I is apparently twofold: In Core II the reflectors were calibrated for the core and reflector configuration in which the FRED was used. This apparently reduced or eliminated the disparity of 4% or so that may result from using reflector calibration data obtained in one core loading for static reactivity determination in another core configuration. Secondly, the Core II static measurements were based on the calculated inhour equation (the relation between reactivity and period), whereas the Core I static measurements were based on an inhour equation that was adjusted to fit the Core I zero power oscillator test data. Had the calculated relation appropriate to Core I been used the apparent difference between Core I static and dynamic measurements would have been reduced by⁶ 2.3%. The sum of these two effects is sufficient to account for the apparent disparity between Core I static and dynamic worth measurements.

In addition to evaluation of the energy coefficients, analysis of the data during the time interval when the FRED reactivity was constant enabled the time dependent FRED-reactivity to be determined by subtracting the extrapolated feedback from the net reactivity calculated using the spatially independent kinetic equation. Figure 6-37 shows the FRED and net reactivities determined in this manner. It is seen that there is an "overshooting" of $\sim 0.35\%$ in the FRED reactivity before its final value is attained. Such overshooting was previously observed during the Core I transients, and an overshoot also can be observed in the static test measurements (Table 6-44) at an axial FRED position of ~ 26 inches. This "overshoot" is believed to be the result of neutron-reflective properties of the stainless steel lower end cap on the FRED slug. As the FRED rod containing B_4C is expelled from the core, the stainless steel cap is the last portion of the rod to leave region of reactivity influence.

The overshootings determined for each of the sub-prompt transients are illustrated in Figure 6-38. Very conspicuous is the difference between the overshooting for test 8 ($\sim 0.35\%$) and the overshooting for the other tests ($\sim 0.6\%$). This difference is consistent with the above postulate that the "overshooting" is a result of the reflective

Figure 6-37 FRED and Net Reactivity for Sub-Prompt Test 8, Channel A

Figure 6-38 Overshooting of FRED-Reactivity

properties of the FRED rod as its tip is near the top of the core because the super-prompt slug (see Table 6-39) used in Test 8 had a thinner (by ~ 0.9 inch) lower end cap. Also evident is the fact that the time dependence of the FRED worth is influenced by its starting position (Table 6-39). This is to be expected since the FRED displacement versus time behavior² is relatively constant while the behavior of the displacement versus reactivity change dependence is the initial starting location of the FRED rod.

6.2.11 Core II Super-Prompt Critical Transients

There are six super-prompt critical transients in the Core II experimental program. The transients are initiated by rapid insertion of a positive reactivity (produced by ejecting a B_4C slug from a central channel in a time interval of ~ 0.1 sec) in excess of $\$1.0$. The tests are terminated by introduction of large negative reactivities (reactor scram) within ~ 0.3 sec of transient initiation. These transients result in peak power levels that are more than 3 orders of magnitude larger than initial values, and the prompt behavior of the inherent Doppler feedback reactivity is demonstrated by the prompt turn-around of the transient power.

The data from one of the detector channels is illustrated for the super-prompt critical transients in Figures 6-39 through 6-43. The small secondary peak in the power for the 1.2% transients was expected, and occurs because the positive reactivity used to initiate the transients is still being inserted for a short time following the power turn-around.

During the super-prompt transients a logarithmic amplifier is used to convert the detector current from two U-238 fission chambers into a voltage signal that is proportional to the logarithm of the current. This data is recorded and reconverted, by exponentiation, using a measured current-voltage characteristic into a signal proportional to power. The procedures for smoothing this flux data, calculating reactivity, energy, etc. are described in detail in reference 8. As expressed there, the net reactivity, $K_n(t)$, is determined from the recorded power trace, $P(t)$, using the following expression

$$K_n(t) = 1 + \left(\frac{\beta}{\rho}\right) \frac{1}{P} \frac{dP(t)}{dt} + \frac{P(t) - P(0)}{P(t)} - \frac{1}{P(t)} \int_0^t [P(u) - P(0)] D(t-u) du$$

Figure 6-39 Time-Dependent Power for Super-Prompt Transient 1

Figure 6-40 Time Dependent Power for Super-Prompt Transient 3

Figure 6-41 Time Dependent Power for Super-Prompt Transient 4

Figure 6-42 Time Dependent Power for Super-Prompt Transient 5

Figure 6-43 Time Dependent Power for Super-Prompt Transient 6

where ℓ/β is the ratio of the prompt neutron lifetime to the effective delayed neutron fraction, and where $D(t)$ is the delayed neutron kernel (defined in reference 8). Since ℓ/β is of the order of 1.4×10^{-4} sec, and $P(t)$ is much larger than $P(0)$ during all but the initial portions of the super-prompt critical transients, the term containing ℓ/β contributes to the reactivity only when the rate of change of the power, dP/dt , is very large; specifically for a few millisec just prior to, and just after, the peak power point.

The feedback reactivity, K_{fb} , is the difference between the net reactivity, K_n , and the input reactivity, K_F , generated by the Fast Reactivity Excursion Device (FRED), i.e.,

$$K_{fb}(t) = K_n(t) - K_F(t)$$

In the time interval around the power peak the input reactivity is time dependent, and the apparent net reactivity determined from the power trace is dependent on the value of ℓ/β . Thus, small percentage uncertainties in K_F or uncertainties in ℓ/β and thus in K_n , may cause relatively large uncertainties in the feedback reactivity $K_{fb}(t)$. The sensitivity of results to variations in ℓ/β and in amplifier voltage-current characteristics are currently being investigated. Preliminary results of an iterative procedure to determine ℓ/β indicate a value between 1.4×10^{-4} and 1.6×10^{-4} sec in agreement with the measured value of 1.4×10^{-4} sec.

To avoid the above uncertainties, the feedback and energy data were (as for the sub-prompt transients) analyzed during the time interval following the complete ejection of the FRED from reactor regions of reactivity influence, but prior to reactor scram or re-entry of the poison slug into the core. During this time interval (between ~ 140 msec and ~ 270 msec after transient initiation), the input reactivity K_F is a constant and any changes in the net reactivity are a result of changes in the feedback. In this interval, since $K_F = K_0$, a constant, the net reactivity can be expressed as

$$K_n(t) = K_0 + \sum_{j=1}^J A_j E^j(t)$$

A least square fit of the above expression to the data during the stated time interval indicated that for the limited energy range under consideration an essentially linear relationship exists between energy release and reactivity. The slopes of these linear relations, or the energy coefficients, as well as the approximate energy intervals over which the analyses were performed, are shown in Table 6-40. Note that the coefficients tend to decrease slightly in magnitude with increasing energy release from the same initial power level, and they also decrease in magnitude with increasing initial power level.

Table 6-40

CORE II SUPER PROMPT TRANSIENT ENERGY COEFFICIENT

Test	Nominal Initial Power (MW)	Nominal FRED Worth (\$)	Energy Range (MW-sec)	Measured Average Energy Coefficient (β /MW-sec)	
				channel A	channel B
1	2	1.12	60-90	-0.38	-0.38
2	2	1.18	80-115	-0.38	-0.37
3	5	1.12	75-105	-0.33	-0.33
4	5	1.21	105-145	-0.33	-0.30
5	8	1.12	85-125	-0.30	-0.28
6	8	1.21	115-160	-0.30	-0.27

The coefficients in Table 6-40 were corrected for a calculated (see the previous section) $\sim 15\%$ non-Doppler (i.e., the fuel and cladding axial expansion, sodium and structure effects, etc.) reactivity effect, and they were adjusted by a factor⁵ of 0.88 to account for the difference between the energy produced during a transient; and the energy absorbed in the fuel during a transient. The resultant averaged Doppler energy coefficients, in units of cents per MW-sec of energy absorbed in the fuel, are compared in Table 6-41 with the results obtained from the earlier sub-prompt transients, and with calculated values appropriate to the initial power levels and energy ranges of analysis.

The calculations were performed with the WEDOP¹¹ program using a value of -0.0060 for the Doppler $T \frac{dk}{dT}$, and fuel thermal conductivity and fuel to cladding heat transfer coefficients and heat capacities discussed in the previous section. The computer program calculates an initial steady state temperature distribution for fuel rods throughout the core, and performs a power squared weighting of the logarithm of the local temperatures to obtain the Doppler feedback. For transients, new temperature distributions, and reactivity changes, are calculated under the assumption that the transient is sufficiently rapid to prevent any appreciable heat diffusion from the rod during the time interval (~ 0.3 sec) under consideration. For the SEFOR one-inch fuel rods (having a time constant of ~ 30 sec), this assumption is valid.

It is seen in Table 6-41, that both the measured and calculated Doppler coefficient decrease with increasing energy release at a given power level and with increasing initial power level. Although the calculated and measured reduction in coefficients with increasing power level is comparable, the calculated coefficients decrease more rapidly with increasing energy than do the measured values. More detailed analysis is now being performed and this trend will be investigated.

6.2.12 Static FRED Slug Worth Measurements in Core II

The FRED rod used for the sub-prompt critical transients (reactivities $< 1\%$) was calibrated in Assembly II-D as a function of axial position using asymptotic period measurements, and the total rod worth was also measured by each of the calibrated fine reflectors. The total rod worth from these static measurements ranged between 97.3¢ (period technique) to 94.8¢ (reflector 3). The measurements were repeated in Assembly II-E, after the fine reflectors had been recalibrated in the same assembly. The worth at 0.76 inch was 93.5¢ in agreement with a value of 93.8¢ interpolated from the asymptotic period measurements.

The same rod was used for the Core I sub-prompt transients where its total static worth was 97.0¢ as measured by reflector 8, and its dynamic worth (had it not been shimmed to provide a static worth of 93¢, and a dynamic worth of 97¢) would have been $\sim 101\%$. The constant static worth between Core I and Core II agrees with earlier² B_4C worth measurements.

The reactivity worth of the FRED rod for the sub-prompt critical transients in Core II was calibrated as a function of axial position in Assembly II-D (Figure 6-44). The calibration was performed at low power on the critical core by moving the FRED rod a specified increment, measuring the resultant positive reactor period, and moving a reflector to again bring the reactor to critical at low power. This process was repeated until measurements were performed along the entire stroke of the FRED positioner and the measured periods (doubling times) were converted to reactivities using the Core II inhour equation.² These data are tabulated in Table 6-42 and are compared with the previous Core I measurements in Figure 6-45.

Table 6-41
INITIAL CORE II TRANSIENT TEST RESULTS

Initial Power (MW)	Nominal FRED Worth (\$)	Energy Range of Analysis (MW-sec)	Doppler Energy Coefficient	
			Measured ¢/MW-sec	Calculated ^(a) (¢/MW-sec)
2	0.99	< 30	-0.38	-0.40
2	1.12	60-90	-0.37	-0.35
2	1.18	80-115	-0.36	-0.34
5	0.94	< 25	-0.34	-0.34
5	1.12	75-105	-0.32	-0.30
5	1.21	105-145	-0.30	-0.28
8	1.12	85-125	-0.28	-0.26
8	1.21	115-160	-0.27	-0.25
10	0.94	< 30	-0.29	-0.28

(a) Calculations were performed assuming a Doppler $T \frac{dk}{dT} = -0.0060$.

Figure 6-44 Core Loading for Assembly II-D

Table 6-42

FRED WORTH USING PERIOD MEASUREMENTS
(Assembly II-D)

FRED Rod Position		Measured Doubling Time (sec)	Incremental Worth (¢)	Cumulative Worth (¢)
Initial (in.)	Final (in.)			
—	0.16		—	0.0
0.16	0.99	147.2	4.71	4.7
0.99	2.74	57.1	10.25	15.0
2.74	4.50	53.5	10.76	25.7
4.50	6.50	47.4	11.77	37.5
6.50	8.76	39.2	13.49	51.0
8.76	10.74	52.7	10.88	61.9
10.74	13.68	39.0	13.53	75.4
13.68	18.00	35.8	14.36	89.8
18.00	29.61	83.8	7.58	97.3

Figure 6-45 Comparison of Sub-Prompt FRED Calibration in Core I and Core II

The total worth of the FRED rod was also measured using each of the fine reflectors 3 and 8. For these measurements, the worth was obtained by adjusting a reflector to maintain criticality as the FRED rod was inserted (withdrawn) from the core. The earlier reflector calibrations (at $\sim 750^\circ\text{F}$ in Assembly II-C) were then used to convert the observed changes of reflector position into reactivity. The data are tabulated in Table 6-43. The slight (1 ρ) difference between the worths determined using the two different reflector calibrations is nearly within the estimated calibration accuracy ($\sim \pm 1\%$) of each reflector, and such variations might be expected even if there had been no core loading change (removal of a B_4C rod at location EO.ON4.OA from Assembly II-C) between the time the reflectors were calibrated and the FRED worth was measured. The somewhat larger differences (up to 2.5 ρ) between the worths from the reflector measurements, and the worth from the period measurement is apparently the result of using reflector calibration curves obtained in one core (Assembly II-C) for measurements in another core (Assembly II-D). This effect is illustrated by the remeasurement of the FRED worth in Assembly II-E in which reflector calibrations appropriate to this core were used. These data are tabulated in Table 6-44. The total worth at 0.76 inch, (the point to which the FRED rod was shimmed for the sub-prompt transients) of 93.5 ρ in Table 6-44 is in good agreement with a value of 93.8 ρ interpolated from the asymptotic period measurements in Table 6-42.

The reactivity worth of the FRED rod used in the Core II super-prompt transients was measured (prior to the transients) as a function of axial position using reflector swap and asymptotic period techniques. The maximum rod worths (119.4 ρ and 119.6 ρ) obtained by the two methods, as well as the measurements of the dependence of reactivity on position are in excellent agreement. The data are tabulated in Tables 6-45 and 6-46 and are compared in Figure 6-46.

6.2.13 Subcriticality and λ/β Measurements

The ratio (β/λ) of the effective delayed neutron fraction to the prompt neutron lifetime and the subcritical reactivity at various shutdown conditions were measured in SEFOR by Oak Ridge National Laboratory (ORNL) personnel using noise analysis, neutron source multiplication, and inverse kinetic methods. Measurements were performed on both Core I and Core II at zero power and a nominal coolant temperature of 350°F . The Core I measurements were performed on Assembly I-P (this is the same as Assembly I-N of Figure 6-23 except that the foil holder rod was removed at E2.ON2.O leaving an empty location), and Core II measurements were performed on Assembly II-A (Figure 6-3 of reference 2) and on Assembly II-C (Figure 6-13 of reference 8). Assembly I-P was critical at 350°F with 3 1/2 reflectors lowered while Assembly II-A was critical with 1 1/2 reflectors lowered and Assembly II-C was critical with ~ 3 1/2 reflectors lowered. Thus, Assemblies I-P and II-C had similar reflector configurations, but different core compositions, while Assemblies II-A and II-C had similar core compositions, but different reflector configurations.

Table 6-43

**FRED WORTHS USING REFLECTORS
ASSEMBLY II-D**

FRED Rod Position (in.)	Reflector 3		Reflector 8		Relative FRED Worth	
	Position (cm)	Worth (¢)	Position (cm)	Worth (¢)	Using No. 3 (¢)	Using No. 8 (¢)
0.16	56.44	92.62	47.03	77.05	0.0	-
0.16	47.03	73.64	56.61	95.89	-	0.0
29.61	0.30	0.01	46.00	74.89	94.8 ^(a)	-
29.61	47.03	73.64	0.18	0.01	-	95.9

(a) Including a contribution of 2.2¢ for the movement of reflector 8 between 47.03 cm and 46.00 cm.

Table 6-44

**CORE II SUB-PROMPT FRED ROD CALIBRATION
Assembly II-E
(Reflector 8)**

FRED Position (in.)	Reflector 8		Relative FRED Worth (¢)
	Position (cm)	Worth (¢)	
29.61	17.07	19.24	93.46
28.01	17.07	19.24	93.46
26.00	16.60	18.53	94.17
24.00	16.85	18.91	93.79
22.00	17.63	20.09	92.61
20.00	19.05	22.32	90.38
18.00	21.33	26.06	86.64
16.00	24.32	31.19	81.51
14.00	28.25	38.22	74.48
12.00	32.83	47.11	65.59
10.00	37.91	57.51	55.19
8.00	43.40	68.84	43.86
6.00	49.57	81.24	31.46
4.00	55.66	93.17	19.53
2.00	62.42	105.36	7.34
0.76	66.84	112.70	0.00

Table 6-45

**SUPER-PROMPT CRITICAL FRED CALIBRATION
BY REFLECTOR SWAP**

(Assembly II-F)

FRED Position (in.)	Reflector 8 Position (cm)	Worth (β)	Temperature ($^{\circ}$ F)	Relative ^(a) FRED Worth (β)
29.59	10.00	9.71	756	119.4
28.00	10.00	9.71	756	119.4
26.01	10.00	9.71	756	119.4
24.00	10.66	10.56	756	118.5
21.99	12.24	12.66	756	116.4
20.00	14.74	16.20	756	112.9
18.00	18.57	21.97	756	107.1
16.00	23.06	29.19	756	99.9
13.99	28.59	39.33	756	89.8
12.00	34.32	50.50	756	78.6
10.00	40.87	63.61	756	65.5
8.00	47.61	77.29	756	51.8
6.00	54.67	91.29	756	37.8
4.00	62.48	106.15	756	23.0
2.00	71.40	120.72	756	8.4
0.76	77.90	129.10	756	0.0
2.79	67.86	115.41	756	13.7
4.51	60.65	102.75	756	26.4
6.00	55.40	92.69	756	36.4
7.51	49.89	81.92	757	47.7
9.00	44.88	71.75	757	57.9
10.49	39.73	61.29	757	68.4
11.99	34.93	51.70	757	78.0
14.01	29.08	40.27	757	89.4
16.00	23.61	30.13	757	99.5
18.99	17.09	19.71	757	109.9
29.61	10.43	10.26	757	119.4

(a) Temperature corrections were made using a reactivity temperature coefficient of $-0.55\beta/^{\circ}\text{F}$.

Table 6-46

**SUPER-PROMPT CRITICAL FRED
CALIBRATION BY ASYMPTOTIC PERIOD
(Assembly II-F)**

FRED Position		Doubling Time (sec)	Incremental Reactivity (β)	Cumulative Reactivity (β)
Initial (in.)	Final (in.)			
—	0.76	—	0.0	0.0
0.76	2.79	37.9	13.81	13.8
2.79	4.51	46.2	11.99	25.8
4.51	6.00	56.2	10.37	36.2
6.00	7.51	50.7	11.20	47.4
7.51	9.00	54.0	10.69	58.1
9.00	10.49	55.3	10.50	68.6
10.49	11.99	62.6	9.55	78.1
11.99	14.01	48.1	11.64	89.8
14.01	16.00	58.3	10.09	99.8
16.00	18.99	53.7	10.73	110.6
18.99	29.61	67.4	9.02	119.6

Figure 6-46 Core II Super-Prompt FRED Reactivity Worth

A counting loss experiment was performed at ORNL following the experiment to provide data for correcting the Core I neutron source multiplication results. High counting rates were observed in Core I because of the higher (by a factor of 18) neutron source from photo-neutron reactions in BeO.

Since several measurements in each core configuration were made very near critical (1 to 8 cents), "best" pooled ℓ/β estimates were obtained by coupling source multiplication and noise analysis using several independent sets of experiments near critical.

The ORNL Noise Analyzer has small (~ 10 millivolt) systematic inaccuracies (feedthru) associated with the multipliers. Accordingly, a post-SEFOR experiment was performed which determined these feedthru characteristics, and the resulting information was programmed into the data reduction package. These corrections to the raw data produced less than 1% change in reactivity values, but enhanced the appearance of the noise spectra and precision of the final data.

The SEFOR WRM and ORNL fission counter readings during the experiments, as well as the reflector configurations are listed in Tables 6-47 through 6-49 for reference purposes. (These data were provided by ORNL.)

The experimental results provided by ORNL are presented in Tables 6-50 through 6-52. The respective prompt die-away time constant (ℓ/β) in microseconds and the prompt break-frequency in Hertz are listed at the top of each table. The remainder of the tables shows the subcriticalities as determined by the different methods. More than one normalization point is used for the neutron source multiplication to show the influence of results on the normalization point.

The intercomparison between inverse kinetics and noise analysis methods is shown in Table 6-53 for all three core configurations. The number of reflector drops and the initial pre-drop reactivity are given for the inverse kinetics results to illustrate reproducibility of the measurements and to show the influence of initial reactivity level (which affects the drop's dynamic range) on the derived subcriticality.

It is seen from the tables that:

1. The inverse kinetics derived reactivities in Table 6-50 are ~ 5 -9% greater than the corresponding noise analysis values. However, an inverse kinetics value of \$1.10 was used for the calibration and, as shown in Table 6-53, four drops from \$0.16 gave a value of only \$1.04. Had this later value been used, the source multiplication comparisons in Table 6-50 would agree to within $\sim 3\%$.
2. The internal agreement of reactivities listed in Table 6-51 for Core II is excellent. The only notable exception is the \$7.15 predicted by noise (Experiment 29). However, the standard deviation of this measurement is $\sim \pm \$1$ and reliable inverse kinetics or noise measurements of subcriticality were not anticipated below 3 or 4 dollars subcritical.
3. The agreement of reactivities given in Table 6-52 is in general good.
4. The values of ℓ/β for Core I and Core II assemblies having the same reflector configuration are identical, whereas the Core II value for a different reflector configuration is $\sim 5\%$ greater than the others.
5. The intercomparison between inverse kinetics and noise analysis in Table 6-53 shows satisfactory agreement for all three core configurations.

6.2.14 Conventional Oscillator Tests

Conventional oscillator tests were performed at nominal power levels of 2, 5, and 10 MW in Core I to demonstrate stability and to obtain information concerning reactivity feedback and fuel frequency response parameters. As was previously demonstrated in Core I, the reactor was quite stable. Preliminary analysis of the reactivity feedback indicates reasonable agreement with the theoretical model, but as in Core I the power reactivity coefficients were the same as those determined from the static tests only if the coolant temperature oscillations were assumed nearly zero.

The experiments were performed in the same manner as the zero power oscillator tests described in a previous section, while the method of analysis is described in detail in reference 6. The power reactivity transfer functions from two of the flux monitors are tabulated in Tables 6-54 through 6-56.

The at power reactivity transfer functions are compared with the zero power transfer function, and with each other in Figures 6-47 and 6-48. The results of the analysis of the 2 MW feedback data indicate that the power reactivity coefficient that was determined when the maximum measured coolant oscillators are used is smaller in magnitude than when the coolant temperature reactivity effect is assumed to be zero. The value of the power coefficient, as determined from the equation in Subsection 6.2.9 agrees more closely with the value obtained from the oscillator analysis when the coolant oscillators are set equal to zero.

Table 6-47

FLUX READINGS AND REFLECTOR POSITIONS IN ASSEMBLY I-P

Experiment	Reactivity (- β)	WRM Readings ^(a)			ORNL Counts/sec	Reflector Positions
		<u>1</u>	<u>2</u>	<u>3</u>		
6	0.163	9.8-5	12.8-5	11.8-5	3.972×10^6	3 = 47.06 cm 5,10,8 = DOWN
7	1.01	13.8-6	19.0-6	18.5-6	6.107×10^5	3 = 47.06 cm 5,10,8,7 = DOWN
8	2.16-2.33	61.0-7	9.0-6	7.9-6	2.795×10^5	3 = 47.06 cm 5,10,8,7,2 = DOWN
9	0.478	24.-6	33.-6	32.5-6	1.097×10^6	3 = 47.06 cm 5,10,8 = DOWN 7 = 51.1 cm
11	4.27-4.65	27.-7	41.-7	39.-7	1.316×10^5	3 = 47.06 cm 1 = UP
12	0.101	16.6-5	15.5-5	14.85-5	5.097×10^6	3 = 50.28 cm 5,8,10 = DOWN

^(a) Numbers in these three columns denote % of full power; e.g., 9.8-5 denotes 9.8×10^{-5} % of full power.

Table 6-48

FLUX READINGS AND REFLECTOR POSITIONS IN ASSEMBLY II-A

Experiment	Reactivity (- β)	WRM Readings ^(a)			ORNL Counts/sec	Reflector Positions
		<u>1</u>	<u>2</u>	<u>3</u>		
23	0.01	12.2-5	15.9-5	15.0-5	3.910 X 10 ⁶	-----
24	Critical	12.3-5	16.0-5	15.2-5		3 = 49.5 cm 8 = DOWN
25	0.052	19.-6	26.-6	25.-6	6.560 X 10 ⁵	3 = 47.35 cm 8 = DOWN
26	1.13	12.-7	19.-7	18.-7	3.161 X 10 ⁴	3 = 47.94 cm 7,8 = DOWN
27	2.44-2.59	7.-7	12.5-7	11.-7	1.451 X 10 ⁴	3 = 47.94 cm 2,7,8 = DOWN
28	0.45	24.-7	34.-7	33.-7	7.528 X 10 ⁴	3 = 47.94 cm 7 = 52.0 cm 8 = DOWN
29	5.66-5.98		OFF RANGE		5.797 X 10 ³	3 = 47.94 cm 2,7,8,4,6,9 = DOWN
33	0.59	19.5-7	23.5-7	22.-7	5.851 X 10 ⁴	3 = 47.94 cm 7 = 44.2 cm 8 = DOWN

(a) Numbers in these three columns denote % of full power; e.g., 12.2-5 denotes 12.1 X 10⁻⁵% of full power

Table 6-49

FLUX READINGS AND REFLECTOR POSITIONS IN ASSEMBLY II-C

Experiment	Reactivity (- β)	WRM Readings ^(a)			ORNL Counts/sec	Reflector Positions
		<u>1</u>	<u>2</u>	<u>3</u>		
43	---	5.8-6	7.8-6	7.5-6	2.036×10^5	3 = 17.80 cm 8 = 76.87 5,10 = DOWN
44	1.56	9.5-7	15.5-7	14-7	2.488×10^4	3 = 17.80 cm 5,8,10 = DOWN
45	0.45	24.-7	34.-7	32.-7	8.040×10^4	3 = 17.80 cm 8 = 60.72 cm 5,10 = DOWN
46	7.20-7.64	---	---	---	5.057×10^3	---

(a) Numbers in these three columns denote % of full power; e.g., 5.8-6 denotes 5.8×10^{-6} % of full power.

Table 6-50

SUMMARY OF ORNL EXPERIMENTAL RESULTS IN SEFOR CORE I ASSEMBLY I-P

$$\lambda/\beta = 130.5 \pm 2.5 \mu\text{sec}$$

$$\text{Break Frequency} = 1220 \pm 27 \text{ Hz}$$

Experiment	Subcriticality from Inverse Kinetics (-)	Subcriticality from Noise Analysis (-)	Subcriticality from Neutron Source Multiplication		
			Normalized to Inverse Kinetics at \$1.10 (-)	Normalized to Noise Analysis at \$0.163 (-)	Normalized to Noise Analysis at \$1.01 (-)
12	---	0.101	0.118	0.111	0.109
6	---	0.163	0.174	0.163	0.160
9	---	0.478	0.582	0.546	0.534
4	---	0.824	0.879	0.835	0.806
7	1.10	1.01	1.10	1.03	1.01
8	2.27	2.16	2.33	2.19	2.14
11	---	4.88	4.65	4.36	4.27
1	---	---	5.87	5.50	5.39

Table 6-51

SUMMARY OF ORNL EXPERIMENTAL RESULTS IN SEFOR CORE II ASSEMBLY II-A

$$\ell/\beta = 142.6 \pm 2.8 \text{ usec}$$

$$\text{Break frequency} = 1116 \pm 22 \text{ Hz}$$

Experiment	Subcriticality from Inverse Kinetics (-%)	Subcriticality from Noise Analysis (-%)	Subcriticality from Neutron Source Multiplication		
			Normalized to Inverse Kinetics at \$1.11 (-%)	Normalized to Noise Analysis at \$1.13 (-%)	Normalized to Noise Analysis at \$0.01 (-%)
23	---	0.01	0.01	0.01	0.01
25	---	0.052	0.054	0.055	0.052
28	---	0.45	0.46	0.47	0.44
33	---	0.59	0.57	0.58	0.55
26	1.11	1.13	1.11	1.13	1.07
27	2.59	2.82	2.40	2.44	2.31
29	---	7.15	5.87	5.98	5.66
21	---	---	9.12	9.28	8.79

Table 6-52

SUMMARY OF ORNL EXPERIMENTAL RESULTS IN SEFOR CORE II ASSEMBLY II-B

$\ell/\beta = 131 \pm 4.3 \mu\text{sec}$
 Break frequency = $1215 \pm 37 \text{ Hz}$

Experiment	Subcriticality from Inverse Kinetics (-%)	Subcriticality from Noise Analysis (-%)	Subcriticality from Neutron Source Multiplication		
			Normalized to Inverse Kinetics at \$1.47 (-%)	Normalized to Noise Analysis at \$1.56 (-%)	Normalized to Noise Analysis at \$0.45 (-%)
42	---	0.08	0.03	0.03	0.03
45	---	0.45	0.45	0.48	0.45
44	1.47	1.56	1.47	1.56	1.46
46	---	---	7.20	7.64	7.16

Table 6-53

**COMPARISON OF NOISE ANALYSIS AND INVERSE KINETICS RESULTS
FROM ORNL SUBCRITICALITY EXPERIMENT ON SEFOR**

	Noise Analysis (- β)	(- β)	Inverse Kinetics Number of Drops	(- β) Before Drops
Core I	1.01 $\pm$ 03	1.04 $\pm$.01	4	0.16
Assembly I-P		1.10 $\pm$.01	2	0.52
	2.35 $\pm$.10	2.28 $\pm$.03	4	1.04
Core II	1.13 $\pm$.06	1.11 $\pm$.00	2	0.52
Assembly II-A		1.11 $\pm$.02	2	0.45
	2.82 $\pm$.17	2.59 $\pm$.04	3	1.09
Core II	1.56 $\pm$.05	1.47	1	0.027
Assembly II-C		1.44	1	0.38

Table 6-54

CORE II POWER REACTIVITY TRANSFER FUNCTION AT 2 MW

Frequency (rad/sec)	Power Reactivity Transfer Function			
	Amplitude (% Power/ β reactivity)		Phase (degrees)	
	Channel 27	Channel 28	Channel 27	Channel 28
1.5071	1.12	1.12	-13.7	-13.2
0.9400	1.20	1.19	-16.7	-16.5
0.5936	1.32	1.31	-20.8	-20.7
0.3363	1.54	1.55	-26.2	-26.0
0.3388	1.52	1.52	-26.2	-26.0
0.2092	1.83	1.83	-30.3	-30.2
0.1278	2.27	2.25	-31.6	-31.6
0.07688	2.86	2.87	-29.6	-29.3
0.04811	3.48	3.47	-23.3	-23.3
0.03022	3.85	3.87	-17.3	-17.1
0.01731	4.15	4.14	-11.9	-11.7
0.01089	4.64	4.66	-6.2	-6.1

Table 6-55

CORE II POWER REACTIVITY TRANSFER FUNCTION AT 5 MW

Frequency (rad/sec)	Amplitude (% Power/ δ reactivity)		Phase (degrees)	
	Channel 27	Channel 28	Channel 27	Channel 28
1.5671	1.13	1.14	-13.5	-12.2
0.9787	1.20	1.20	-15.5	-15.8
0.6123	1.31	1.31	-19.5	-19.6
0.6182	1.31	1.30	-19.3	-19.2
0.3526	1.53	1.53	-23.8	-23.9
0.2224	1.84	1.83	-26.1	-26.2
0.2248	1.81	1.82	-25.9	-25.7
0.1294	2.36	2.35	-23.7	-23.7
0.07860	2.87	2.87	-13.9	-14.1
0.07830	2.85	2.86	-14.3	-14.2
0.04910	2.97	2.96	-1.1	-1.2
0.03100	2.69	2.70	7.5	7.7
0.03100	2.67	2.68	8.0	8.0
0.01800	2.45	2.45	9.7	9.8
0.01140	2.40	2.41	13.7	13.5
0.01150	2.43	2.41	13.6	13.6

Table 6-56

CORE II POWER REACTIVITY TRANSFER FUNCTION AT 10 MW

Frequency (rad/sec)	Amplitude (% Power/ δ reactivity)		Phase (degrees)	
	Channel 27	Channel 28	Channel 27	Channel 28
1.5773	1.13	1.13	-12.4	-12.0
0.9909	1.20	1.20	-14.8	-14.8
0.6225	1.31	1.31	-18.0	-18.1
0.6249	1.29	1.29	-18.0	-17.9
0.3609	1.54	1.54	-21.6	-21.5
0.2303	1.84	1.84	-22.0	-22.0
0.2322	1.81	1.81	-22.1	-22.2
0.1300	2.34	2.34	-14.7	-14.7
0.07889	2.60	2.61	2.2	2.1
0.07879	2.61	2.61	1.8	1.6
0.04952	2.28	2.28	16.9	16.9
0.03141	1.80	1.80	22.4	22.4
0.03122	1.81	1.81	22.3	22.3
0.01843	1.56	1.57	19.1	19.1
0.01187	1.49	1.49	21.8	22.0
0.01187	1.49	1.49	21.2	21.4

Figure 6-47 Phase of Core II Power Reactivity Transfer Functions

Figure 6-48 Amplitude of Core II Power Reactivity Transfer Functions

6.2.15 Core II IFA and IFR Measurements

The fuel temperature rise above coolant temperature and channel coolant temperature and flow were measured during Core II power ascension to 10 MW, transient testing, and subsequent power ascension to 20 MW full power. These data are listed on Tables 6-57 and 6-58 for the six installed IFAs and three IFRs installed prior to the super-prompt transient testing. The three fuel thermocouples of the IFR operated successfully and without failure during the transient testing and power ascension as shown in Figure 6-49. The IFR fuel temperature measurements are within $\pm 10\%$ of the expected results demonstrating their reliable operation. The status of the IFA fuel thermocouples was six remaining that provide reproducible and reliable measurements with sixteen having decalibrated or failed temperature response. The IFA coolant thermocouple status was three of six inlet and five of six outlet obtaining reliable measurements. The IFA flowmeters show three of six still operating without failure or decalibration.

Fuel thermocouple responses to the super-prompt transients for IFA and IFR are given in Tables 6-59 and 6-60. Table 6-59 is the measured initial and maximum temperatures recorded by the thermocouples during each transient. Table 6-60 is the observed rise time for each thermocouple during the transients. The characteristic time constant of the thermocouples is expected to reduce the measured maximum temperature. Preliminary analysis has shown an estimate can be made of the discrepancy between actual and measured maximum based on the measured rise time during the transient. This effect of thermocouple response introduces a 2 to 15% systematic error in measurement. It is anticipated that the data in Table 6-60 will become the basis for further analysis providing a correction to the measured temperature data in Table 6-59.

The IFR transient data shows good agreement between measured and expected fuel temperature rise in Figure 6-50. The maximum fuel temperature transient increase can be calculated by assuming an adiabatic process. The temperature rise then is directly proportional to the energy released during the transient. This assumption requires the fuel to have minimum transient heat transfer occurring when the maximum energy release is reached. This is a good approximation since the energy release reaches a maximum in less than 0.5 second. By comparison the fuel heat transfer time constant is 30 seconds. Qualitatively the fuel is expected to reach a maximum temperature adiabatically before significant heat transfer occurs. The relationship between the local fuel maximum transient temperature rise and the maximum total transient energy release is given below:

$$\Delta T/r = B \cdot \Delta Q$$

where ΔT = maximum local fuel transient temperature rise ($^{\circ}\text{F}$)

r = local power density P/A ratio

B = proportionality constant ($2.31^{\circ}\text{F/MW-sec}$)

ΔQ = maximum total transient energy release

and

$B = A/V\rho C_p$

A = fraction of released energy absorbed in fuel

V = fuel volume

ρ = fuel density

C_p = fuel heat capacity

A correction to the measured transient fuel temperature rise for the effect of the thermocouple response characteristics has not been applied to these results. The IFR thermocouples are high response devices that should require only a small adjustment to their measured transient data. This is supported by the close agreement in Figure 6-50 of the IFR uncorrected data with expected results.

6.2.16 Core II Calculations

The SEFOR Core II configuration was analyzed in two dimensions with both direct and synthesis diffusion theory calculations. In Table 6-61 and Table 6-62 the power distributions shown in Figure 6-51 and Figure 6-52 are summarized. In the figures, the axial and radial power distributions calculated are compared with foil measurements and the Core I data. The radial power distribution used in Core I is calculated data adjusted to observations and comparisons with the foil measurements then available. The calculated Core I power distribution is close to that calculated for Core II; however, the Core II measurements appear to confirm the calculation.

Table 6-57

FUEL TEMPERATURE RISE ABOVE COOLANT TEMPERATURE (~760°F)

Date (1971)	Thermal Power (MW)	IFA-1				IFA-2			
		Inner Rod		Outer Rod		Inner Rod		Outer Rod	
		Upper 1 (°F)	Lower 2 (°F)	Upper 3 (°F)	Lower 4 (°F)	Upper 5 (°F)	Lower 6 (°F)	Upper 7 (°F)	Lower 8 (°F)
Dec. 3	2.14	127	379	24	16	181	299	221	*
Dec. 3	1.88	15	361	36	21	192	285	180	*
Dec. 4	5.00	245	873	96	*	488	792	517	*
Dec. 4	5.05	193	878	33	*	497	799	520	*
Dec. 5	5.18	187	886	9	*	486	807	589	*
Dec. 5	10.12	453	1548	225	*	1019	1669	1200	335
Dec. 6	9.94	412	1550	239	*	1016	1671	1198	305
Dec. 7	10.02	320	1538	389	*	1021	1650	1170	239

Date (1971)	Thermal Power (MW)	IFA-3				IFA-4			
		Inner Rod		Outer Rod		Inner Rod		Outer Rod	
		Upper 9 (°F)	Lower 10 (°F)	Upper 11 (°F)	Lower 12 (°F)	Upper 13 (°F)	Lower 14 (°F)	Upper 15 (°F)	Lower 16 (°F)
Dec. 3	2.14	178	*	169	264	30	150	136	211
Dec. 3	1.88	161	*	157	253	21	141	130	203
Dec. 4	5.00	497	*	425	680	48	379	331	520
Dec. 4	5.05	436	*	430	689	61	384	333	525
Dec. 5	5.18	442	*	438	696	69	380	339	523
Dec. 5	10.12	890	*	883	1439	104	771	705	1044
Dec. 6	9.94	893	*	882	1441	111	748	665	990
Dec. 7	10.02	885	*	871	1434	101	727	649	956

* No emf response above coolant temperature

Table 6-57 (continued)

FUEL TEMPERATURE RISE ABOVE COOLANT (~760°F)

Date (1971)	Thermal Power (MW)	IFA-5				IFA-6			
		Inner Rod		Outer Rod		Inner Rod		Outer Rod	
		Upper 17 (°F)	Lower 18 (°F)	Upper 19 (°F)	Lower 20 (°F)	Upper 21 (°F)	Lower 22 (°F)	Upper 23 (°F)	Lower 24 (°F)
Dec. 3	2.14	*	*	*	*	122	107	178	*
Dec. 3	1.88	*	*	*	*	117	103	172	*
Dec. 4	5.00	*	32	*	114	296	272	449	*
Dec. 4	5.05	*	96	*	128	299	275	455	*
Dec. 5	5.18	*	11	*	126	302	273	464	*
Dec. 5	10.12	*	56	*	690	591	641	928	*
Dec. 6	9.94	*	48	*	677	591	639	931	*
Dec. 7	10.02	*	94	*	701	589	635	927	*

* No emf response above coolant temperature

Table 6-57 (continued)

FUEL TEMPERATURE RISE ABOVE COOLANT TEMPERATURE (~760°F)

Date (1971)	Thermal Power (MW)	IFA-1				IFA-2			
		Inner Rod		Outer Rod		Inner Rod		Outer Rod	
		Upper 1 (°F)	Lower 2 (°F)	Upper 3 (°F)	Lower 4 (°F)	Upper 5 (°F)	Lower 6 (°F)	Upper 7 (°F)	Lower 8 (°F)
Super-Prompt									
Dec. 11	2.00	*	386	Disconnected and replaced with IFR on December 8, 1971.	Disconnected and replaced with IFR on December 8, 1971.	195	300	191	*
Dec. 11	2.07	*	386			174	306	215	*
Dec. 12	5.26	*	900			515	828	566	*
Dec. 14	4.85	*	876			477	769	528	*
Dec. 16	7.89	*	1346			807	1350	898	*
Dec. 17	8.25	*	1356			801	1368	917	*
Post Super-Prompt Power Ascension Series									
Dec. 19	4.93	*	906	Disconnected and replaced with IFR on December 8, 1971.	Disconnected and replaced with IFR on December 8, 1971.	481	806	617	*
Dec. 20	10.21	*	1621			1090	1737	1399	503
Dec. 20	11.90	191	1801			1262	1982	1479	1263
Dec. 20	14.00	171	2032			1503	2336	1899	1814
Dec. 20	14.88	195	2112			1593	2463	2018	2121
Dec. 20	16.13	273	2244			1746	2655	2106	2377
Dec. 20	17.66	684	2390			1884	2841	2226	2960
Dec. 20	19.25	2516	2569			1997	3073	2442	3881

* No emf response above coolant temperature

Table 6-57 (continued)

Date (1971)	Thermal Power (MW)	IFA-3				IFA-4			
		Inner Rod		Outer Rod		Inner Rod		Outer Rod	
		Upper 9 (°F)	Lower 10 (°F)	Upper 11 (°F)	Lower 12 (°F)	Upper 13 (°F)	Lower 14 (°F)	Upper 15 (°F)	Lower 16 (°F)
Super-Prompt									
Dec. 11	2.00	171	*	168	275	9	136	129	189
Dec. 11	2.07	211	*	206	313	16	153	130	192
Dec. 12	5.26	457	*	455	738	65	367	331	511
Dec. 14	4.85	426	*	422	685	37	335	301	462
Dec. 16	7.89	729	*	723	1191	47	575	506	757
Dec. 17	8.25	735	*	729	1205	50	576	499	758
Post Super-Prompt Power Ascension Series									
Dec. 19	4.93	453	*	444	722	91	363	311	484
Dec. 20	10.21	959	*	942	1540	238	749	649	980
Dec. 20	11.90	1097	*	1080	1764	210	781	731	1100
Dec. 20	14.00	1300	*	1272	1918	247	616	866	1366
Dec. 20	14.88	1373	*	1344	1878	264	604	915	1333
Dec. 20	16.13	1496	*	1469	2241	285	627	991	1425
Dec. 20	17.66	1645	*	1619	2385	311	691	1122	1251
Dec. 20	19.25	1789	*	1723	2677	321	886	1252	1526

*No emf response above coolant temperature

Table 6-57 (continued)

		IFA-5				IFA-6			
		Inner Rod		Outer Rod		Inner Rod		Outer Rod	
Date (1971)	Thermal Power (MW)	Upper 17 (°F)	Lower 18 (°F)	Upper 19 (°F)	Lower 20 (°F)	Upper 21 (°F)	Lower 22 (°F)	Upper 23 (°F)	Lower 24 (°F)
Super-Prompt									
Dec. 11	2.00	*	Disconnected and replaced with IFR on December 8, 1971.	*	*	128	111	187	*
Dec. 11	2.07	*		*	*	134	116	195	*
Dec. 12	5.26	*		*	83	345	308	515	*
Dec. 14	4.85	*		*	43	320	287	480	*
Dec. 16	7.89	*		*	472	546	539	838	*
Dec. 17	8.25	*		*	499	554	553	852	*
Post Super-Prompt									
Power Ascension Series									
Dec. 19	4.93	*		*	12	361	342	528	*
Dec. 20	10.21	*		*	546	712	803	1082	*
Dec. 20	11.90	*		*	700	818	975	1260	*
Dec. 20	14.00	*		*	810	973	1299	1518	*
Dec. 20	14.88	*		*	816	1029	1400	1610	*
Dec. 20	16.13	*		*	712	1120	1646	1750	*
Dec. 20	17.66	*		*	685	1227	2093	1917	*
Dec. 20	19.25	*		*	257	1343	2701	2090	*

*No emf response above coolant temperature

Table 6-57 (continued)

FUEL TEMPERATURE RISE ABOVE COOLANT TEMPERATURE (~760°F)

CORE II IFF's

Date (1971)	Thermal Power (MW)	CR-1 (°F)	CR-3 (°F)	CR-5 (°F)
Super-Prompt Series				
Dec. 11	2.00	325	316	387
Dec. 11	2.07	336	332	376
Dec. 12	5.26	563	531	622
Dec. 14	4.85	493	498	566
Dec. 16	7.89	845	832	968
Dec. 17	8.25	851	840	978
Post Super-Prompt Power Ascension Series				
Dec. 19	4.93	508	510	602
Dec. 20	10.21	1037	1064	1251
Dec. 20	11.90	1195	1221	1425
Dec. 20	14.00	1432	1457	1667
Dec. 20	14.88	1503	1539	1752
Dec. 20	16.13	1641	1681	1903
Dec. 20	17.66	1786	1848	1962
Dec. 20	19.25	1938	2034	2116

Table 6-58

IFA COOLANT TEMPERATURES AND FLOW

Date (1971)	Thermal Power (MW)	IFA-1			IFA-2			IFA-3			IFA-4		
		Outlet 31 (°F)	Inlet 32 (°F)	Flow (gpm)	Outlet 33 (°F)	Inlet 34 (°F)	Flow (gpm)	Outlet 35 (°F)	Inlet 36 (°F)	Flow (gpm)	Outlet 37 (°F)	Inlet 38 (°F)	Flow (gpm)
Dec. 3	2.14	765.2	766.0	*	766.0	756.0	42.08	766.6	755.8	49.78	816.5	*	49.41
Dec. 3	1.88	761.0	762.7	*	762.7	753.1	40.27	763.6	753.4	49.75	800.5	*	49.44
Dec. 4	5.00	758.0	774.0	*	773.3	748.9	42.56	774.8	748.5	49.71	826.8	*	49.65
Dec. 4	5.05	774.4	757.7	*	774.8	749.1	40.59	776.3	749.2	49.71	810.6	*	49.45
Dec. 5	5.18	489.5	759.9	*	777.8	752.4	42.09	779.1	752.2	49.72	819.2	*	49.06
Dec. 5	10.12	332.9	756.8	*	791.4	743.5	42.69	796.1	744.0	49.63	846.1	*	49.11
Dec. 6	9.94	302.2	753.5	*	789.7	740.3	42.35	793.6	740.9	49.61	839.5	*	49.61
Dec. 7	10.02	306.2	755.2	*	783.3	740.1	42.17	792.4	740.0	49.61	842.3	*	49.27

Date (1971)	Thermal Power (MW)	IFA-5			IFA-6		
		Outlet 39 (°F)	Inlet 40 (°F)	Flow (gpm)	Outlet 41 (°F)	Inlet 42 (°F)	Flow (gpm)
Dec. 3	2.14	765.4	765.8	*	765.5	756.2	30.30
Dec. 3	1.88	762.8	763.8	*	762.9	753.6	30.27
Dec. 4	5.00	773.0	773.8	*	771.5	748.5	30.26
Dec. 4	5.05	770.2	775.1	*	772.1	748.5	30.22
Dec. 5	5.18	776.3	766.9	*	773.7	751.1	30.27
Dec. 5	10.12	790.2	791.2	*	788.1	743.6	30.22
Dec. 6	9.94	787.7	789.9	*	785.8	740.7	30.20
Dec. 7	10.02	787.2	789.4	*	784.9	739.3	30.20

*No emf response

Table 6-58 (Continued)

IFA COOLANT TEMPERATURES AND FLOW

Date (1971)	Thermal Power (MW)	IFA-1			IFA-2			IFA-3		
		Outlet 31 (°F)	Inlet 32 (°F)	Flow ^a (gpm)	Outlet 33 (°F)	Inlet 34 (°F)	Flow (gpm)	Outlet 35 (°F)	Inlet 36 (°F)	Flow (gpm)
Super-Prompt										
Dec. 11	2.00	777.8	757.2	*	761.7	752.2	42.50	761.5	751.4	49.74
Dec. 11	2.07	772.1	756.9	*	762.0	751.8	42.41	761.5	751.4	49.74
Dec. 12	5.26	609.8	779.4	*	774.3	748.6	42.61	778.9	750.0	49.74
Dec. 14	4.85	835.2	763.3	*	776.4	753.1	45.49	778.3	752.7	49.74
Dec. 16	7.89	97.8	750.2	*	770.1	730.7	42.80	773.4	730.7	49.54
Dec. 17	8.25	85.3	744.1	*	763.6	723.9	48.04	766.9	723.6	49.50
Post Super-Prompt Power Ascension Series										
Dec. 19	4.93	784.9	759.1	*	785.9	727.0	84.80	784.5	728.6	22.35
Dec. 20	10.21	832.2	782.8	*	833.4	714.5	88.80	840.2	717.4	22.95
Dec. 20	11.90	823.8	776.5	*	823.9	711.0	4.09	830.5	713.3	27.59
Dec. 20	14.00	826.3	776.5	*	823.8	711.2	20.36	833.0	713.3	32.22
Dec. 20	14.88	821.4	722.3	*	819.8	708.5	30.88	827.9	710.8	34.62
Dec. 20	16.13	819.9	770.4	*	818.1	706.6	46.23	826.4	708.9	37.79
Dec. 20	17.66	812.8	766.3	*	810.1	706.6	8.59	815.3	707.8	44.65
Dec. 20	19.25	805.4	761.2	*	802.9	705.0	32.97	807.7	706.0	49.31

*No emf response

Table 6-58 (Continued)

IFA COOLANT TEMPERATURES AND FLOW

<u>Date</u> (1971)	Thermal <u>Power</u> (MW)	IFA-4			IFA-5			IFA-6		
		<u>Outlet</u> <u>37</u> (°F)	<u>Inlet</u> <u>38</u> (°F)	<u>Flow</u> (gpm)	<u>Outlet</u> <u>39</u> (°F)	<u>Inlet</u> <u>40</u> (°F)	<u>Flow</u> (gpm)	<u>Outlet</u> <u>41</u> (°F)	<u>Inlet</u> <u>42</u> (°F)	<u>Flow</u> (gpm)
<u>Super-Prompt</u>										
Dec. 11	2.00	738.1	*	49.34	757.7	761.6	*	760.0	750.9	30.29
Dec. 11	2.07	777.1	*	49.65	761.6	762.1	*	761.5	752.0	30.29
Dec. 12	5.26	800.1	*	49.53	775.8	776.9	*	774.5	726.8	30.28
Dec. 14	4.85	774.0	*	49.61	774.9	776.3	*	773.7	751.9	30.28
Dec. 16	7.89	765.5	*	49.50	768.2	770.3	*	760.3	730.2	30.15
Dec. 17	8.25	774.7	*	49.50	762.9	764.7	*	759.6	723.1	30.13
<u>Post Super-Prompt</u>										
<u>Power Ascension Series</u>										
Dec. 19	4.93	743.7	*	21.00	781.8	783.3	*	780.2	729.1	13.71
Dec. 20	10.21	849.1	*	22.26	827.7	829.4	*	773.7	689.6	14.20
Dec. 20	11.90	830.7	*	25.73	819.8	823.1	*	813.4	710.6	16.89
Dec. 20	14.00	839.5	*	30.53	824.4	826.0	*	815.9	710.3	19.91
Dec. 20	14.88	839.3	*	32.91	820.5	822.1	*	812.3	708.7	20.76
Dec. 20	16.13	854.5	*	35.63	818.2	821.3	*	811.2	706.6	23.08
Dec. 20	17.66	854.2	*	42.10	811.3	813.8	*	803.6	706.2	26.72
Dec. 20	19.25	854.2	*	47.99	806.8	807.6	*	798.8	704.9	29.93

*No emf response

Figure 6-49 Instrumented Fuel Rod Fuel Thermocouples Temperature Measurements to 20 MW (December 1971)

Table 6-59

CORE II SUPER-PROMPT TRANSIENT TESTS
MEASURED FUEL TRANSIENT TEMPERATURE IN IFA

		Maximum Transient Temperature													
		1		2		3		4		5		6			
T/C DAS		Initial (°F)	Maximum (°F)	Initial (°F)	Maximum (°F)	Initial (°F)	Maximum (°F)	Initial (°F)	Maximum (°F)	Initial (°F)	Maximum (°F)	Initial (°F)	Maximum (°F)		
IFA-1	1	*	*	Data Unavailable		*	*	*	*	*	*	*	*		
	2	1152	1383			1582	1865	1599	1976	1990	2283	1971	2345		
	3	Replaced by IFR													
	4	Replaced by IFR													
IFA-2	5	1000	1215			1264	1513	1306	1630	1533	1808	1536	1878		
	6	1070	1443			1509	1925	1533	2097	1991	2441	1965	2535		
	7	921	1247			1255	1620	1277	1750	1554	1949	1533	2048		
IFA-3	8	*	*			*	*	*	*	*	*	*	*		
	9	971	1163			1238	1446	1247	1522	1496	1735	1482	1788		
	10	*	*			*	*	*	*	*	*	*	*		
IFA-4	11	971	1159			1234	1460	1243	1539	1495	1763	1482	1815		
	12	1070	1335			1479	1781	1503	1900	1907	2243	1890	2307		
	13	*	*			*	*	*	*	*	*	*	*		
IFA-5	14	912	1097			1114	1316	1126	1393	1309	1533	1294	1580		
	15	917	1070			1107	1280	1104	1345	1269	1470	1255	1509		
	16	963	1213			1243	1519	1248	1611	1479	1802	1460	1873		
IFA-6	17	*	*			*	*	*	*	*	*	*	*		
	18	Replaced by IFR													
	19	Dummy Thermocouple													
IFA-6	20	306	1401			799	976	827	1068	*	*	1179	1416		
	21	926	1047			1107	1269	1170	1356	1187	1505	1358	1553		
	22	912	1027			1107	1224	1135	1356	*	*	*	*		
	23	999	1186			1316	1534	1345	1643	1659	1917	1657	1979		
	24	Dummy Thermocouple													

*No transient temperature response

Table 6-59 (continued)

CORE II SUPER-PROMPT TRANSIENT TESTS
MEASURED FUEL TRANSIENT MAXIMUM TEMPERATURE IN IFR

IFR	Transient Temperature											
	1		2		3		4		5		6	
	Initial (°F)	Maximum (°F)	Initial (°F)	Maximum (°F)	Initial (°F)	Maximum (°F)	Initial (°F)	Maximum (°F)	Initial (°F)	Maximum (°F)	Initial (°F)	Maximum (°F)
CR-1	963	1199	Data Unavailable		1264	1539	1281	1643	1568	1879	1556	1948
CR-3	959	1195			1251	1516	1272	1631	1549	1853	1539	1925
CR-5	992	1260			1325	1638	1341	1753	1658	2011	1647	2094

Table 6-60
THERMOCOUPLE RESPONSE
TIME TO 90% MAXIMUM TEMPERATURE
CORE II SUPER PROMPT TRANSIENT TESTS

		Transient Tests					
	T/C DAS #	1 (sec)	2 (sec)	3 (sec)	4 (sec)	5 (sec)	6 (sec)
IFA-1	2	2.50		2.14	2.23	1.84	1.72
	3 ^(a)	1.17		0.99	1.02	0.99	0.96
	4 ^(a)	1.25		1.06	1.11	0.98	1.06
IFA-2	5	3.54		2.65	3.59	2.96	2.84
	6	4.12		3.34	3.65	2.92	3.06
	7	0.72		0.77	0.89	0.73	0.71
IFA-3	9	3.96		2.93	3.28	3.08	2.99
	11	1.14		0.96	0.92	0.80	0.77
	12	4.31		3.28	3.34	3.15	-
IFA-4	14	2.31		2.34	2.32	2.19	2.29
	15	2.48		2.06	2.13	1.65	1.75
	16	2.51		2.17	2.10	1.75	1.85
IFA-5	18 ^(a)	1.28		1.08	1.06	0.99	0.96
	20	5.53		3.36	3.96	-	3.04
IFA-6	21	2.98		3.03	3.10	2.77	2.87
	22	2.38		1.44	2.62	-	-
	23	1.57		0.93	0.96	0.79	0.86

Note: The uncertainty is $\sim \pm 0.1$ sec.

^(a) Disconnected and replaced with IFR on December 8, 1971.
— Erratic or intermittent emf response to temperature transient.

Figure 6-50 Core II – Super-Prompt Transient Tests, Transient Fuel Temperature Rise, Instrumented Fuel Rods (IFR), Measured Temperature Rise versus Transient Energy Release

Figure 6-51 Radial Power Distribution

Figure 6-52 Axial Power Distribution

Table 6-61

CORE II CALCULATED FRACTION OF FISSION BY ISOTOPE

U-235	1%
U-238	10%
Pu-240	2%
Pu-239	87%

Table 6-62

CORE II CALCULATED POWER DISTRIBUTION

Full Power Average Power Density	38.2	kW/liter
Radial P/A	1.45	
Axial P/A	1.25	
Core P/A	1.81	

Calculated material worth for standard and guinea pig fuel rods, UO_2 rods, and B_4C poison rods are shown in Figures 6-53, 6-54 and 6-55. The two-dimensional synthesis and direct calculations in first order perturbation theory are compared with the measured data. The results appear to be consistent with measurement and with the calculated predictions being qualitatively accurate.

The prompt neutron lifetime for the Core II fully-reflected configuration with full-sized core containing six B_4C poison rods was calculated by perturbation methods. The two-dimensional synthesis perturbation calculation gave a value of $\ell = 0.4442 \mu\text{sec}$. The same perturbation calculation using the calculated flux and adjoint from a direct two-dimensional diffusion theory gave a value of $\ell = 0.5654 \mu\text{sec}$. With the value of $\beta = 0.0031$ used for Core II, the calculated ℓ/β from synthesis and direct calculations are 143 microseconds and 182 microseconds respectively.

6.2.17 Fuel Examination

Three guinea pig rods, A16, A02, and A18 have been sectioned and fuel examination is presently being conducted. Preliminary visual results are available and these photographs are shown in Figures 6-56, 6-57 and 6-58. Each rod received a final irradiation at 20 MW full power for several days with a peak linear power of 21 kW/ft. The observed fuel structure in each rod is similar and characteristic of fuel operation above melt temperatures. More precise analysis is planned to confirm this preliminary observation.

Each guinea pig rod was sectioned at the calculated peak power axial position. A sample of fuel was prepared for metallographic analysis and another for burn-up analysis. The photographs for each rod are the cross-section of the fuel polished smooth and the β - γ emission autoradiograph of distributed fission products.

The metallographic samples will be photographed in 50x enlargements to show grain structure characteristics and α autoradiographs will be made of α -emitters (primarily Pu-fuel) distributed in the fuel. Enlargements of photographs of fuel-cladding interfaces will be made to visually observe any change from pre-irradiation conditions. The ratio of Pu/Pu+U will be determined by electron microprobe analysis to determine any Pu migration that occurred at power operation. Complete results of this fuel examination are being prepared in a separate topical report.

Figure 6-53 Fuel Material Worth - Core II

Figure 6-54 UO_2 Material Worth - Core II

Figure 6-55 B_4C Material Worth — Core II

(a) Polished Surface

(b) β - γ Autoradiograph

Figure 6-56 Guinea Pig Fuel Rod Metallography
Rod A16
Maximum linear power - 21 kW/ft

(a) Polished Surface

(b) β - γ Autoradiograph

Figure 6-57 Guinea Pig Fuel Rod Metallography
Rod A02
Maximum linear power - 21 kW/ft

(a) POLISHED SURFACE

(b) β - γ AUTORADIOGRAPH

Figure 6-58 Guinea Pig Fuel Rod Metallography
Rod A18
Maximum linear power - 21 kW/ft

7. SEFOR SAFETY AUDIT AND LICENSING

7.1 OBJECTIVES

The objectives of Safety and Licensing in relation to SEFOR are: (1) to provide an independent safety audit of SEFOR operations; (2) to provide support in assessing the safety significance of events related to reactor operations and of modifications made to the reactor plant; (3) to make reports to the DRL as required by the operating license.

7.2 CURRENT RESULTS

Safety evaluations were completed for the following items:

- (1) Calibration of the FRED poison slugs in Core II
- (2) Additional contact protection for the Reactor Safety System
- (3) Positioner shim to limit the maximum worth of FRED poison slugs for Core II
- (4) Instrumented Fuel Rods for Core II.

A report describing the independent stress analysis of the reactor vessel main flange was sent to the DRL. This report completed the evaluation and documentation of changes made in operating procedures to reduce head bolt stresses to an acceptable value.

Four other reports required by the license were sent to the DRL; two involved malfunctions of mercury-wetted relays; one involved the malfunction of a CR-120 industrial relay and one involved a change in the equation used to predict the reflector positions required for reactor operating conditions in Core II.

A letter was sent to the Division of Nuclear Materials Safeguards, AEC, in response to their questions regarding compliance with the provisions of 10 CFR, Parts 70 and 73.

Changes 7, 8, and 9, to the Technical Specifications were approved by the DRL, completing action on all Proposed Changes submitted thus far. These changes included the following items:

Change No. 7:

Increased the allowable pump-around-pump flow rate to a nominal value of 2 GPM. This completed action on items in Proposed Change No. 2.

Change No. 8:

Incorporated BRD and SEFOR organization changes into the Administrative Controls section of the Technical Specifications. This completed action on Proposed Change No. 7.

Change No. 9:

Permitted initiation of the Core II transient test program after completing static and oscillator tests at power levels up to 10 MWt in Core II; permitted a linear interpolation between the two previous limits for the maximum permissible FRED poison slug worth as a function of Doppler coefficient and reduced the frequency for required fuel surveillance and sodium sampling during the Core II transient test program. This completed action on Proposed Change No. 8.

Our request for an 18 month extension of the reactor operating license was granted by the DRL.

The Eighth Meeting of the SEFOR Safety Review Committee was held in Sunnyvale on November 15 and 16, 1971.

A safety audit trip was made to the site to obtain information on problems with mercury-wetted relays in the safety system. The number of malfunctions which have occurred is small, and most of them can be traced to faulted conditions resulting from safety system tests while the reactor was shut down. An engineering review of the safety system has been made and system modifications have been designed to provide additional contact protection for mercury-wetted relays. It is expected that these modifications will minimize or eliminate future malfunctions of relays in the safety system.

8. SEFOR SUPPORT

The Plant Engineering effort is a supporting function to the SEFOR facility. During November and December, the Core II test program was accomplished including the rise to power, oscillator, sub-prompt and super-prompt transients. In addition a foil irradiation was accomplished at 10 MW. Final reactor operation on January 5, 1972 concluded the totally successful in-reactor experimental testing program.

The following engineering support work was completed in support of plant operations:

- Design modification of drawings and specifications for the reactor protection system were completed. This modification will provide contact protection for the mercury-wetted relays, and additional circuit fusing.
- Updating of the P&ID electrical and mechanical drawings was initiated.
- Establishment of requirements for installation of baffles in the Argon reservoir tank to minimize carryover.
- The elastomer head seal was replaced with one of an improved silicone material (circular cross-section and slightly larger in the cross-section than the original). The better high temperature creep properties of this material are expected to provide extended seal life.
- Design modification drawings were completed for a modification to the half-ton hoist grapple which will positively lock the grapple-to-load cable fitting against relating motion. This modification will replace the jam nut arrangement now in use.

9. SEFOR FACILITY

9.1 EXPERIMENTAL PROGRAM

9.1.1 Reflector Calibrations

I-D3 — Reflector Calibration at 550°F and 750°F

Period measurement calibrations were performed on fine reflectors 3 and 8 at core average temperatures of 550°F and 750°F. The integral worths of these reflectors were somewhat higher than the calibrations under the same condition on Core I.

Calibrations were repeated on reflectors 3 and 8 at each core rearrangement. The measured worths varied only slightly ($\pm 3\%$) among the measurements. While the change in worths were not large, the measurements were useful in making the static measurements of the FRED slug worth.

9.1.2 I-C3 — Isothermal Temperature Coefficient

Isothermal temperature coefficient measurements were performed between 350°F and 760°F by raising the sodium temperatures with the traceheating. On-site analysis gave the following values:

Temperature Range	Coefficient $\Delta/\text{°F}$
350° - 450°	0.598
450° - 550°	0.595
550° - 650°	0.548
650° - 750°	0.559

9.1.3 I-C4 — Flow Coefficient

The flow coefficient for Core II was determined at zero power by decreasing the main primary sodium flow from full flow to zero flow in incremental steps. The changes in reflector positions and temperature were recorded at each step to obtain the relative reactivity. The plot of reactivity versus coolant flow readily shows that the flow coefficient is negligible as was expected.

9.1.4 I-D1 — Pressure Coefficient

As part of the pressure-reactivity coefficient measurements in Core II, the reactor cover gas pressure was varied from 20 psig to 0 psig in steps of 5 psig. The resulting reactivity changes, if any, were compensated by changing the fine reflector positions. The data indicates that any reactivity effects which may accompany changes in pressure are negligible in Core II.

9.1.5 I-C1 — Oscillator Poison Rod Calibration

The oscillator poison rod used for Core II is the same as was used in Core I. The poison rod was differentially calibrated, by "rod-swap" technique. This involved lowering the poison rod from full out (20.06 inches) to 0 inch in 2-inch incremental steps, while compensating the resulting reactivity by moving the calibrated fine reflectors. The positioner motor control was used to lower the slug from 20.06 inches to 0 inch. The poison rod was lowered further to a distance of 4 inches (below the core center line) using the amplitude control. The total integral reactivity worth of the poison rod from 20.06 inches to -4.0 inches is 45.70¢.

9.1.6 I-C2 — Zero Power Transfer Function

"Zero" power transfer function measurements were performed with the reactor critical. The oscillator poison rod was oscillated at several frequencies, up to a maximum of 2 inches amplitude. The converted data was sent to Sunnyvale for detailed analysis.

9.1.7 II-4 — Power Ascension and Static Tests

The power ascension through 20 MW was completed. Static tests were performed under the following conditions:

Tav (°F)	Power Level (MW)
760	0
	2
	4
	5
	6
	8
	10
	12
	14
	15
	16
	17.5
	18
	19
	20
660	10
560	10

The power ascension was halted at 10 MW in an effort to preserve the remaining IFA fuel thermocouples for the transient tests. After the transient tests were completed the power ascension was resumed. Through 20 MW, the Core II power reactivity coefficients were roughly three-fourths that of Core I. This is consistent with the reduction in the Doppler coefficient from Core I to Core II.

9.1.8 II-9 – Flow Rate Oscillation Tests

The main primary flow was oscillated at several frequencies and at power levels of 5, 10 and 15 MW. Flow amplitudes of up to a maximum of 180 gpm were used.

9.1.9 II-2 – Conventional Oscillator Tests

Conventional oscillator tests were performed at 2, 5 and 10 MW power levels, with poison rod lowered to a positioner position of 4 inches. The data was analyzed on-site using offline Fourier analysis, and Fourier coefficients were obtained from this data. Nyquist plots were constructed, and the phase margin of the point where the Nyquist plot crosses the unit circle at 2, 5 and 10 MW are 85.7 degrees, 77.5 degrees, and 73 degrees, respectively. These are well in excess of 30 degrees limit set by technical specifications.

9.1.10 I-B-7 – Activation Measurements

The calculation of the Core II radial and axial flux profiles were completed. The relative fission ratios were also completed. The following results were obtained:

$$\frac{\text{Plutonium}}{\text{Enriched U}} = 0.933$$

$$\frac{\text{Depleted U}}{\text{Enriched U}} = 0.033$$

9.1.11 Sub-prompt Slug (E.P. No. 6332) Calibration

The sub-prompt poison slug used in Core II is the same as used for Core I. On November 15, 1971 the poison slug was calibrated by period-measurements method. When the slug was completely inserted into the core (corresponding to a positioner indication of 0.00 inch) the total reactivity worth was evaluated to be 98.2¢. Since the technical specification limits the worth to be less than or equal to 98¢, a "collar" was installed in the positioner such that the lowest position the slug could be lowered was limited to 0.76 inch. After rearranging core to configuration Core II-E,

the slug was recalibrated up to the position of 0.76 inch by rod-swap method. The total reactivity worth was evaluated to be 94¢. Thus, with the collar in place, the slug was used for all sub-prompt transient tests.

9.1.12 Transient Detector Calibration

In preparation of sub-prompt transient tests in Core II the transient detector system was calibrated at 0, 2 and 5 MW power levels.

The transient detector system consists of two U-238 fission chambers and two miniature gamma chambers. The gamma chambers were designed to be used for higher power levels whereas fission chambers are designed for lower power levels during the transient tests. However Core I test results showed that fission chambers will respond satisfactorily throughout the entire power range expected during all transient tests in Core II. Therefore, gamma chambers are not being used.

The transient detector system calibration consists of two methods: 1) one is essentially the amplifier calibration performed through a calibration box. This type of calibration will be done before and after each transient test, 2) the other method is to measure the detector output in millivolts at several different reactor steady-state power levels. This type of calibration was performed extensively in Core I. In Core II, the second type of calibration was performed once just to verify the operability of the system.

The results of the present detector calibration agreed very well with Core I values. All four of the transient amplifiers were operated in "log" mode.

9.1.13 Sub-prompt Transient Tests, Core II

For Core II, a total of 9 sub-prompt transient tests were performed. The conditions for these tests are given below:

Test No.	Nominal Slug Worth ¢	Initial Power Level
1	50	2.0
2	80	2.0
3	90	5.0
4	98	5.0
4A	98	5.0
5	98	10.0
6	98	10.0
7	98	10.0
8	98	2.0

During all these subprompt transients, only fission chambers with amplifiers in the "log" mode were used. Gamma chambers with the associated "switch-over" logic were not used.

On-site analysis of data indicated the peak power values and energy liberated agreed well with predictions. These values are considerably below the limitations set by the technical specifications.

9.1.14 Super-prompt Transients

Six super-prompt transients with core configuration II-F have been performed. These are:

Test No.	Nominal Initial Power	Nominal Slug Worth
1	2 MW	\$1.12
2	2 MW	\$1.21
3	5 MW	\$1.12
4	5 MW	\$1.21
5	8 MW	\$1.12
6	8 MW	\$1.21

On-site analysis of the tests shows the maximum power, energy liberated and average fuel temperature rise to agree very well with predictions.

9.1.15 Fuel Surveillance

Fuel surveillance was performed after these events:

- Power Ascension 10MW
- Sub-prompt Tests — After completion of all tests
- Super-prompt Tests — After each series of tests at 2, 5 and 8 MW, initial power
- Fuel Shipping — Rod A18 prior to shipment to Vallecitos Nuclear Center for destructive testing.

No cladding defects or dimensional changes in excess of technical specifications was observed in any inspection.

9.1.16 Installation of Instrumented Fuel Rods

Three instrumented fuel rods (IFR's) were installed into the reactor prior to the start of Core II super-prompt tests. On-site activities leading up to installation included:

- a. Inspection upon arrival.
- b. Characterization of the IFR thermocouples by resistance and time domain reflectometer (TDR) measurements.
- c. Assembly and placement in the refueling cell.
- d. Fuel transfers were made to empty the channels into which the IFR's were installed.

After installation the response of the IFR's was measured and additional TDR and resistance measurements were made. The IFR performance through the initial checkout was good. Numerous computer programs were modified to accept the new thermocouple conversion routines.

All transient testing was completed without failure of any IFR T/C. The inner most IFR failed (open) during the power ascension to 20 MW. The other two IFR's failed during the high power irradiation of the foil holder rod for the measurement of the Pu capture to fission ratio.

9.1.17 Reactivity Adjustments

Two adjustments of reactivity were made: the first was to assure that sufficient excess reactivity was available to perform the transient tests. The adjustment was made by replacing a B₄C rod with the foil holder rod used to measure the capture/fission ratios; the second was made to install the instrumented fuel rods.

The reactivity adjustments involved can be best understood in terms of the excess reactivity at 20 MW.

Port Position	Core II-C(D)	Core II-E	Core II-F
E0.5S3D	805	805	IFR
E2.N2B	807	Foil Rod	A03
W3S2F	X40	SD	SD
E0N4B	A03	A03	Foil Rod
W3S2E	SD	807	IFR
E0N4A	X46(hole)	X40	IFR
Excess Reactivity at 20 MW	8¢	36¢	29¢

Numerous additional moves in the transition from Core II-C to Core II-E were made in advance for the installation of the Core II IFR's.

In preparation for the follow-on program, the fuel moves listed below were made. The notation was changed to F-1 and F-2 (F for Follow-on). A18 was removed for shipment to Vallecitos Nuclear Center.

Thru-head Port	Core Position	In from Core Cen	Core F-1	Worth	Core F-2	Worth
1	E0.0N4.0		SS Tightener	0.0¢	Empty	0.0¢
	A	10.4	IFR1	+1.4¢	IFR1	+1.4¢
	B	9.7	Empty	0.0¢	Empty	0.0¢
3	W3.0S2.0		SS Tightener	0.0¢	Empty	0.0¢
	E	10.4	IFR3	+1.4¢	IFR3	+1.4¢
	F	9.4	SD	0.0¢	Empty	0.0¢
4	E2.0N2.0		SS Tightener	0.0¢	Empty	0.0¢
	B	7.5	A03	+51.2¢	Empty	0.0¢
	C	7.2	A10	+51.2¢	Empty	0.0¢
5	E0.5S3.0		SS Tightener	0.0¢	SS Tightener	0.0¢
	D	7.7	IFR5	+1.4¢	IFR5	+1.4¢
	E	7.3	A15	+51.0¢	A15	+51.0¢
6	W2.5N1.0		SS Tightener	0.0¢	Empty	0.0¢
	A	7.3	Empty	0.0¢	Empty	0.0¢
	F	7.7	806	+30.4¢	Empty	0.0¢
				+188.3¢		+55.2¢

Since Core F-1 excess was determined at about 20 MW to be -12.1¢, the excess for Core F-2 will be -145.2¢ at 20 MW with a 700°F Core inlet temperature.

9.1.18 Reflector Position Program

The REPOS computer program was modified to include changes in the Doppler reactivity feedback equation and reflector calibrations appropriate for Core II. Other changes in the reactivity feedback equation that were made reflect the results of analysis of additional Core I static tests. The Core I equation is as follows:

$$F = -0.692 (T_{av}-350) + 0.0001785 (T_{av}-350)^2 - 0.03\Delta T$$

$$-238 \ln \left(1 + \frac{77P}{840+0.5 T_{av}} \right) - 0.5P - K_o$$

where F = feedback, in cents

T_{av} = average coolant temperature

ΔT = $T_{inlet} - T_{outlet}$

P = Power, in Megawatts

K_o = Reference value, cents

The coefficients of this equation were not valid for Core II so the equation was rewritten as follows:

$$F (\text{Core II}) = -0.597 (T_{av}-350) + 0.000048 (T_{av}-350)^2 - 0.015\Delta T$$

$$-178 \ln \left(1 + \frac{77P}{460+T_{av}} \right) - 0.5P - K_o$$

The first two terms are the zero power feedback and is a mixture of Doppler, expansion, and reduction of sodium density which is not experimentally separable. The effect of changes in ΔT is very small compared with other reactivity effects so it was difficult to measure precisely. The reduction by a factor of two was indicated as desirable in one study

of the Core I static test results. The reduction in the coefficient of the logarithmic Doppler feedback term is roughly proportionate to the change in the Doppler feedback from $T dk/dT = -0.0081$ to -0.0060

A statistical study was made of the error in predicting the reflector configurations for 29 different power levels and temperatures. The standard deviation of the error was 1.9%, a considerable improvement over the standard deviation of errors for Core I of 4.3% at the same state of development.

9.2 FOLLOW-ON PROGRAM PREPARATIONS

9.2.1 Inverse Kinetics Rod Drop Reactivity Measurements

Three rod drop experiments were performed from critical and two subcriticality levels to establish the feasibility of performing these experiments using existing neutron instrumentation to make precise inverse kinetics measurements. Analysis is still in progress on this data. The problem that is likely to be encountered in these measurements is improper gamma compensation of the neutron detectors which would cause the current level in the detector to be an imperfect representation of the neutron population.

9.2.2 Source Multiplication and Neutron Noise Analysis

Three GE representatives were sent to Oak Ridge National Laboratory for one week to learn the use of the experimental equipment and data analysis procedures required to perform on site to verify that no shipping damage had occurred.

9.2.3 Tightener Rod Removal and Storage

Tightener rod storage racks were built and installed. Fuel Transfer Authorizations were prepared to perform the necessary moves to reinstall the BeO tightener rods in the reactor.

9.3 DECOMMISSIONING WORK

A scoping document was prepared and the decommissioning task was broken down into sub tasks. Responsibilities for each sub task were assigned to members of Maintenance, Operations and to Program and Analysis in accordance with the experience of the group and the nature of the job. Cataloging and storage of all Core I and Core II data was completed.

Distillation Station Heating Characteristics

A tube containing many thermocouples was assembled and inserted into the distillation station to determine the heating rates and temperatures of the open distillation station. A Temporary Operating Procedure was written to perform this test. The test was completed before the cessation of Follow-on work and is of greatest interest to the decommissioning task.

9.4 OPERATION AND MAINTENANCE

Reactor Operation Statistics

	Current Month 12/15/72 - 1/15/72	Current Quarter 10/15/71 - 1/15/72	Total to Date 1/15/72
Hours Critical (h)	127	480	3,895
Power Generated (MWH)	1,811	2,864	25,764
Startups	10	28	573
Scrams	6	20	179 ²
Operating Efficiency ¹ (%)	56.0	54.7	43.6

(1) This represents the percent of time that the reactor complex was available for performance of the test program or work necessary for the operation of the reactor such as normally scheduled License Test Procedures. Accountability ceased on January 10, 1972, with the completion of the SEFOR Experimental Program. The accountability is to the nearest full day.

(2) Fifty scrams have been intentional, for FRED or other tests.

The reactor was shutdown briefly at the beginning of the reporting period for inspections inside the nitrogen zones. A refueling cell outage to replace the reactor outer head backup seal which was leaking followed the nitrogen zone inspections. Operation was resumed on October 26, 1971 with plant heat-up for isothermal temperature measurements. Core II zero power testing was completed on October 29 after the zero power oscillator tests were complete. Core II power ascension began on November 1, 1971 and reached 10 MW on November 3. Plant temperatures were reduced to 660°F and 500°F with the reactor operated at 10 MW to measure the sodium temperature effect on reactivity.

A brief outage for fuel surveillance and refueling cell maintenance was begun. At this time it was found that the reactor outer head back-up seal was again leaking. It was decided to calibrate the sub-prompt transient poison slug and perform core rearrangements for installation of the Core II Instrumented Fuel Rods (IFR) prior to seal repair.

On November 18, 1971 the fuel moves were completed, the Refueling Cell purged to air, and the outer head backup seal leakage located with the USON leak detector. The outer head was untensioned and the backup seal components removed for inspection. All elastomer components were again found to exhibit permanent deformation. After attempting to improve the seal design by a change in shape and material of the elastomer components, the original shape had to be retained before a successful seal was achieved. This was finally completed on November 27. Concurrently, three IFR's were prepared and moved into the Refueling Cell. The Refueling Cell was closed and purged back to argon on November 28. Cell purity sufficient to permit reactor operation was achieved on December 2 and testing resumed with fine reflector segment and sub-prompt FRED slug calibrations. The Core II sub-prompt transient tests began on December 3, 1971, and were completed on December 6.

The before-super-prompt transients fuel surveillance was conducted on December 7 and 8 using a rapid cooldown and heatup technique when reinstalling the rods such that the backup seal was not compromised. IFR installation and FRED slug change-out (super-prompt installed; sub-prompt removed) took place on December 9. Reactor operation began again on December 10 with fine reflector segment and FRED slug calibrations. The Core II super-prompt transient tests began on December 11, 1971.

On December 16, 1971 the reactor was made available for one shift for operator licensing examinations and then testing resumed. The last Core II super-prompt transient was completed on December 17 and fuel surveillance was begun immediately.

Reactor operation resumed on December 19, 1971 with the beginning of Core II power ascension from 10 MWt to 20 MWt. On the way up the plant was stabilized and static tests were conducted every 2 MWt increase. Flow oscillation testing was conducted at 15 MWt and the WRM's were calibrated at 18 MWt. Finally, 20 MWt was reached on the evening of December 20, 1971. The plant static test data was taken at 20 MWt and the reactor was then shutdown to investigate a malfunction in the Refueling Cell purification loop compressor.

From December 21 through December 31, 1971 the plant was shutdown for repairs to the purification loop compressor and cleanup of the purification loop and Refueling Cell where they had become contaminated with oil from failed seals in the compressor.

Reactor operation was resumed on January 1, 1972 with an extended high power run to irradiate the fission to capture ratio measurement foil holder rod for Core II. A 90 MWt-day irradiation of this rod was completed on January 4 and the reactor was shutdown to prepare the rod for shipment to VNC. On January 7 and 8 while leak checks were being conducted on the foil holder and a guinea pig rod, which was also going to VNC, the reactor was operated for several hours for neutron source and rod drop measurements in support of the SEFOR Follow-On Program. The foil holder and guinea pig rods were loaded into the fuel shipping cask on January 9, 1972. This completed the SEFOR Experimental Program. Preparations for plant decommissioning commenced immediately and were in progress at the end of the report period.

A total of 223 equipment malfunctions were corrected, distributed as follows:

Mechanical	59
Electrical	67
Instrumentation	83
Computer	14
Total	223

The more significant malfunctions included:

Main Secondary Pump Induction Voltage Regulator drove past its low limit switch and stopped at ~200 gpm flow. A new larger low limit automating device was manufactured and placed in the IVR to prevent a recurrence.

Main IHX level switch had an erratic current output due to a faulty variable transformer. Transformer and level switch were replaced.

Relay K9 in safety system chassis B3 failed the monthly license test procedure. K9 was replaced with a new relay. The monthly license test procedure was repeated to ensure the proper functioning of the K9 relay.

No. 2 Nitrogen Blower Suction Damper operator failed due to a broken pneumatic supply line. The copper supply line to the suction damper operator was replaced with a flexible stainless steel line.

The main 26.5 volt charger failed due to the loss of three diodes. They were replaced and the charger returned to service.

The reflector drive circuit for reflector 2 failed due to a faulty contact on a CR 120 series relay. The relay was replaced and similar relay contacts were cleaned. The system functioned properly.

During tests, involving mercury-wetted relays, a contact protection failed causing excessive current in Bus "A". All mercury-wetted relays in "A" Bus were replaced.

Reflector T/C 6-4 failed. T/C 6-4 was replaced, in the safety system, by T/C 6-5.

Reactor outer head backup seal was replaced.

Argon compressor gas oil seals failed and a rotor "froze". The compressor was overhauled at the vendors repair shop. After overhaul, the compressor was returned to service.

A total of 38 plant and equipment modifications including the following significant items:

A. Electrical

- Manual Automatic Transfer Switch Main Sodium Pump
- Fuel Rod Inspection and Distillation Station Lighting
- Fuel and Half-Ton Grapple Overload Protection Features
- Containment Isolation Valves 8217-1-4,-5-6 Key Lock for Containment Isolation
- Installation of Additional Criticality Alarm Siren
- Ball Joint for Level Probes Electrical Box Support Pipes
- Safety Enclosures for Man Access Flowmeters
- Conductive Cooling Capabilities for Main Secondary Pump
- Additional Contact Protection Rx Safety System
- Installation of Additional Klaxon (Evacuation Alarm)
- Modification to increase output voltage from 26.5 volt chargers
- Instrumented Fuel Rod Instrumentation Installation
- 2.4 KV Switchgear
- Crane Mercury Vapor Light Relocation and Protection

B. Mechanical

- Hinged Cover for Vaults
- Refueling Cell Crane Bridge Motor
- Instrument Shop Air Line
- Man Access System Flowmeter
- Shield Plugs for Through head ports
- Emergency Air Lock Pressure Test
- No. 2 Nitrogen Blower Suction Damper
- Tightener Rod Storage Rack
- Adapter Rod Extension
- Total Modifications completed equaled 38.

Gamma ray spectrometry measurements of fission gas components of the reactor covergas were made routinely during the transient testing. The results continue to indicate levels of Xenon and Krypton commensurate with tramp uranium in the system. Routine environmental surveys were conducted to verify that no environmental radioactivity increase attributable to reactor operation occurred.

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