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IDO-17011

December 1964

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TRANSIENT TESTS OF THE FULLY ENRICHED, STAINLESS STEEL PLATE-TYPE, P CORE IN THE SPERT I REACTOR: DATA SUMMARY REPORT

A. P. Wing

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ATOMIC ENERGY DIVISION

**NATIONAL REACTOR TESTING STATION
US ATOMIC ENERGY COMMISSION**

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IDO-17011
AEC Research and Development Report
Reactor Technology
TID-4500 (35th Ed.)
Issued: December 1964

TRANSIENT TESTS OF THE FULLY ENRICHED,
STAINLESS STEEL PLATE-TYPE, P CORE IN THE SPERT I REACTOR:

DATA SUMMARY REPORT

BY

A. P. WING

PHILLIPS
PETROLEUM
COMPANY

Atomic Energy Division

Contract AT(10-1)-205

Idaho Operations Office

U. S. ATOMIC ENERGY COMMISSION

ABSTRACT

This report presents the data obtained from the transient test series performed on the Spert I stainless steel plate-type P core. The tests consisted of step insertions of reactivity under varying conditions ranging from ambient temperature to $\approx 97^{\circ}\text{C}$ and resulted in asymptotic reactor periods ranging from 6.0 sec to 4.0 msec. The experimental data obtained from each test are presented in both tabular and graphical form. The graphs include time-history plots of reactor power, fuel plate surface temperature, and pressure. Time-history composite graphs displaying fuel plate surface temperature as a function of reactor core position are included. Correlated graphs displaying test data as functions of asymptotic reactor period also are included.

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I. INTRODUCTION

This report is a detailed summary of the experimental data obtained during the P core transient test series performed in the Spert I reactor facility from October 1958 through August 1959.

The primary objective of this test series was to determine the kinetic response of this reactor system to step insertions of reactivity. Similar studies have been carried out in this facility using a variety of heterogeneous cores, including both highly enriched, aluminum or stainless steel, plate-type fuel elements [1-4] and low enriched uranium oxide, rod-type fuel elements [5].

The purposes of this report are (a) to present a complete set of graphs and tables of the experimental data taken in these tests, (b) to describe the methods used in processing the data, and (c) to provide information on the instrumentation used for the transient test measurements of reactor power, temperature, and pressure.

The content and organization of this report are as follows: Section II consists of a general description of the Spert I facility and brief descriptions of the reactor fuel elements and core configuration used in the P core test series. Section III is a description of the static characteristics of the reactor. Section IV gives a description of the various tests performed. In Section V, details of reactor power, temperature, and pressure measurements are discussed. Section VI consists of a summary of the data processing procedures and the inherent errors contributed to the data by these procedures. Section VII contains a tabular summary of the test data and a description of the detailed data plots presented in the appendices. Section VIII contains a list of references pertaining to the P core transient test series.

II. REACTOR DESCRIPTION

The Spert I reactor [6, 7] is a pool type, light water moderated and reflected reactor facility constructed for the purpose of performing various types of experimental studies to determine the dynamic behavior of different reactor cores. A cutaway view of the reactor configuration used for the P core test series is shown in Figure 1.

The reactor vessel used for the P core test series was an open tank 4 feet in diameter and 15 feet high. The vessel was filled with water to a height of two feet above the core during all transient test operations described in this report. There was no provision for heat removal. Coolant circulation was effected only by natural convection.

The P core configuration is shown in Figure 2. This core was designated the P 18/19 core because it consisted of 19 fuel assemblies each capable of containing 18 fuel plates. In the P core, 14 fuel assemblies each contained 18 fuel plates and the 5 fuel assemblies associated with the control rods (CR-1, -2, -3, -4) and the transient rod (TR) each contained 16 fuel plates.

The fuel plates were mounted in 34-inch-long stainless steel cans with square cross sections, approximately three inches on a side. A pair of grooved sideplates were permanently brazed into each can to provide guides for the fuel plates. The water channel thickness between fuel plates was ≈ 0.127 inch. The P core fuel assembly (Army Package Power Reactor type) is illustrated in Figure 3, and the characteristics of these assemblies are given in Table I.

The meat section of each fuel plate consisted of highly enriched uranium dioxide in stainless steel, contained ≈ 29 g of U-235, and was ≈ 0.02 inch thick by 2.5 inches wide by 22 inches long. The meat section was clad with type 304L stainless steel alloy to make a fuel plate ≈ 0.03 inch thick by 2.844 inches wide by 33.625 inches long. An 18 plate fuel assembly contained ≈ 520 g of U-235.

Shutdown and control of the reactor were achieved through the use of four control rods and one centrally located transient rod operated by means of motor drive systems suspended on a bridge above the core. Each control rod consisted of a fuel section and a poison section. The lower fuel section consisted of a sixteen plate P core assembly and had a fuel loading of ≈ 420 g of U-235. The upper poison section was made up of a hollow box constructed of B₄C-bearing iron, clad with stainless steel. Flux suppressors 1.25 inches high by 0.188 inch thick, fabricated of stainless steel containing 1.35 weight percent of boron-10, were installed in the water gap between the fuel and poison section. Figure 4 is an illustration of a P core control rod.

The blade-type transient rod, used to initiate power excursions, consisted of a cadmium sheet, 24 inches long by 2.09 inches wide by 0.02 inch thick, centered in a flattened aluminum tube, 87.5 inches long by 2.5 inches wide by 0.27 inch thick. The center assembly of the core was modified by the removal of two center fuel plates to permit insertion of the transient rod.

Fig. 1 Reactor cutaway Spert I P 18/19 core.

Fig. 2 Spert I P 18/19 core configuration.

Fig. 3 Spert I P 18/19 fuel assembly.

TABLE I

PHYSICAL CHARACTERISTICS OF THE P CORE FUEL ASSEMBLIES

	<u>Fuel Assembly</u>	<u>Control Rod Assembly</u>
Overall length - in.	33.625	33.625
Overall width - in.	2.844	2.624
Overall thickness - in.	2.863	2.619
Meat length - in. (nominal)	22.0	22.0
Meat width - in. (nominal)	2.5	2.281
Meat thickness - in. (nominal)	0.020	0.020
Clad thickness - in. (nominal)	0.005	0.005
Clad material	Stainless steel type 304L	Stainless steel type 304L
Fuel	UO ₂ Stainless steel cermet	UO ₂ Stainless steel cermet
Enrichment - wt% U-235	93.2	93.2
Meat composition wt%		
U-235	18.8	18.8
UO ₂	22.88	22.88
Boron Carbide	0.12	0.12
Stainless steel	77.0	77.0
U-235/plate - g (nominal)	28.65	26.1

Fig. 4 Spert I P 18/19 core control rod.

III. STATIC CHARACTERISTICS

The transient test series was preceded by a series of static measurements. These measurements included control rod calibrations, transient rod calibrations, temperature coefficient measurements, void coefficient measurements, and neutron flux distribution measurements [8, 9, 10]. The physical constants of the P 18/19 core are summarized in Table II.

The differential rod worth was determined by control and transient rod calibrations using the period method over the entire range of rod travel. Boric acid was added to the moderator to adjust the critical position. The integral rod worth curve derived from these data is shown in Figure 5.

TABLE II
PHYSICAL CONSTANTS OF THE P 18/19 CORE

Critical mass (U-235)	7.8 kg
Total mass (U-235)	9.3 kg
Metal-to-water ratio	0.3
Hydrogen-to-uranium ratio	120
Excess reactivity (clean - 20°C)	4.9\$
Temperature Defect 20 - 94°C	1.48\$
Temperature coefficient at 20°C	$-0.25 \times 10^{-2} \text{ } \$/^{\circ}\text{C}$
Temperature coefficient at 95°C	$-3.4 \times 10^{-2} \text{ } \$/^{\circ}\text{C}$
Average void coefficient at 20°C	$-9.9 \times 10^{-4} \text{ } \$/\text{cm}^3$
Reduced prompt neutron generation time $\frac{\Lambda}{\beta}$	$2 \times 10^{-3} \text{ sec}$

The temperature coefficient was determined over the range of 13 to 95°C using both a heating cycle and a cooling cycle. The reactivity loss for various temperatures during the heating cycle was found by using the critical position of the control rods and the rod worth curve, while for the cooling cycle the change in reactivity was found from period measurements as well as from the rod worth curve. Figure 6 shows the temperature defect plotted from data obtained from both heating and cooling the water. A plot of the temperature coefficient obtained from period measurements and from differentiation of the temperature defect curve is shown in Figure 7.

Void coefficient measurements were made by using 0.11- by 0.5- by 23-inch strips of high purity magnesium (0.2 percent manganese) to simulate voids. The amount of moderator displaced by magnesium was varied from

Fig. 5 Control rod calibration.

zero to 10.5 percent of the moderator volume. Figure 8 shows the reactivity loss versus void volume for uniformly distributed voids.

Measurements of the thermal neutron flux distribution were made by using gold foils, 5/32-inch diameter and 5-mil thickness, mounted on plexiglass strips. The placement of these strips is shown in Figure 9. The vertical flux profiles with 11-3/4 inches of control rod fuel in the core are shown in Figures 10 through 12. Vertical flux profiles in the reflector are shown in Figure 13. Horizontal flux profiles at three vertical positions are shown in Figure 14.

Fig. 6 Reactivity temperature defect.

Fig. 7 Temperature coefficient of reactivity.

Fig. 8 Reactivity defect as a function of the volume of moderator voided.

- ▲ 3 FOILS PER STRIP
- 13 FOILS PER STRIP
- 17 FOILS PER STRIP
- ◊ 11 FOILS + 2 Cd COVERED FOILS PER STRIP

Fig. 9 Gold foil placement.

Fig. 10 Vertical flux profiles.

Fig. 11 Vertical flux profiles.

Fig. 12 Vertical flux profiles.

Fig. 13 Vertical flux profiles.

Fig. 14 Horizontal flux profiles.

IV. TRANSIENT TEST PROCEDURE

The transient tests were performed by inserting a known excess reactivity in the reactor and observing the dynamic response of the system as indicated by the measurement of the time histories of power, pressure, and temperature. The inserted reactivity was essentially a step change and was accomplished by the rapid ejection of the transient rod located in the center of the core. The test sequence was as follows: With the transient rod below the core, the reactor was made critical by the partial removal of the control rods. The reactor was then made subcritical by drawing the transient rod into the core. The control rods were then further withdrawn such that upon removal of the transient rod the desired excess reactivity would be obtained. The test was initiated by the rapid ejection of the transient rod from the core, producing an exponential rise in the reactor power.

During testing of the P core, step transients were performed with periods ranging from ≈ 6 sec to ≈ 5 msec [11, 12]. The initial power level for all tests discussed in this report was approximately two watts. The initial system temperature was approximately 20°C. However, in order to study the effect of initial temperature on the reactor's kinetic response, a few step transients were performed with an initial system temperature of approximately 97°C.

V. INSTRUMENTATION

During the P core test series, measurements were made of reactor power, fuel plate surface temperature, and pressure [13]. A block diagram of the transient instrumentation is shown in Figure 15. The following is a description of the techniques used for measurement of each variable.

Fig. 15 Spert I transient instrumentation block diagram.

1. POWER

Reactor power data were obtained by measurement of the neutron leakage from the core using four Spert-designed, boron-lined ionization chambers. The range of chamber sensitivities to core flux required to provide adequate coverage of the expected transient power range ($\approx$ six decades) was obtained by locating several chambers at different distances from the core. Three of these chambers were connected to linear-amplifier circuits and one to a logarithmic-amplifier circuit. (All power data reported in this report are from the linear-amplifier circuits.) The data were transmitted from the amplifiers at the reactor to optical recording oscillographs half a mile away in the control center.

The bandwidth of the linear amplifiers ranged from 100 cps for ion-chamber currents of about 10^{-9} amps to 10 kc for ion chamber currents of about 10^{-5} amps or larger [14]. However, the bandwidth of the oscillograph galvanometers limited the overall response of the system to 5 kc. For the data presented in this report, the chamber current at peak power was never less than 9×10^{-8} amps.

Each chamber and its associated circuitry were subjected to a three-stage calibration procedure. First, the chambers were placed in a high neutron

flux field in the thermal column of the Materials Testing Reactor. Measurements were made of the linearity of the chamber current as a function of neutron flux, the value of the current at a given neutron flux, and the operating voltage range for current saturation (ie, the domain where the current is independent of the applied voltage).

Second, the gain, linearity, and dynamic range of the electronic circuitry associated with each chamber were measured using a calibrated current source in place of the chamber. A relationship was then determined between the input current of the source and the magnitude of the resultant deflection of the galvanometer trace on the oscillograph record. This instrument calibration procedure was repeated weekly in order to offset the effects of drift in the electronic amplifiers. The sensitivity or gain values obtained from the calibrations had a probable error of less than one percent. The dynamic range of each Spert boron-lined ion chamber as coupled with the linear amplifier circuits was determined to be approximately two decades.

Third, the reactor power corresponding to a given current output from each chamber was determined. With the reactor operating at some arbitrary power level, the rate of increase in the bulk system temperature was measured, along with the deflections of the galvanometers connected to the outputs of the ion chamber circuits. From the measured rate of temperature rise and a calculated value for the system heat capacity, the thermal power of the reactor was determined. The power, the deflections of the galvanometers connected to the outputs of the ion chamber circuits, and the results of the instrument calibration were then used to determine the chamber calibration constants in terms of power per unit current for each ion chamber.

2. TEMPERATURE

Fuel plate surface temperature was measured by the use of 10-mil-diameter, chromel-alumel, fiber-glass insulated thermocouples spot-welded onto the outer surfaces of selected fuel plates. These thermocouples had a bandwidth of approximately 25 cps. Calibration of the circuitry associated with the thermocouples was carried out in the same manner as for the ion chamber electronic circuitry.

The location of the thermocouples involved a three-dimensional coordinate system as illustrated in Figure 16. The northwest corner of the reactor core was used as the point of origin of the coordinate system. The first coordinate given was the lattice position in the core (Figure 16a). The second coordinate was the plate position (Figure 16b). The plates in the fuel assemblies were numbered 1 through 18 with plate number 1 being the northern-most of the assembly. The thermocouples were located on the outer surfaces of plates 1 and 18. The third coordinate was the vertical distance in inches from the reactor core midplane (Figure 16c).

For example: (55-01 +3) indicates a transducer located in lattice position 55, on the first fuel plate, and three inches above the core midplane.

Fig. 16 Specification of transducer location.

3. PRESSURE

To measure transient pressure, two variable reluctance and two strain gauge type pressure transducers were used. These transducers were located in the lower ends of the fuel assemblies in core positions 33, 35, 53, and 55. They gave an approximate measure of the average pressure developed within the water channels of the fuel assemblies during transient operation. All pressure transducers used had a range of 0 to 100 psig. Calibration of the electronic circuitry associated with the pressure transducers was carried out in the same manner as for the ion chamber electronic circuitry.

The implications of the pressure measurements are discussed in detail in Reference 15.

VI. DATA PROCESSING PROCEDURES

Signals from the transducers at the reactor area (neutron-detecting ion chambers, pressure transducers, thermocouples, etc) were amplified and transmitted to high speed recording oscillographs located one-half mile away in the control center. Data from 52 different channels were recorded on the oscillographs.

The analog data recorded on the oscillographs were processed through an analog-to-digital conversion system. The conversion system consists of a manually operated analog curve follower, coupled to an analog-to-digital converter having tabular and punched card outputs. The converter is constructed in such a way that appropriate scale factors can be incorporated in the system so as to yield the digital reduced data in the desired physical units. The reduced data were plotted on a digital X-Y plotter to obtain curves representing the time variation of reactor power, temperature, pressure, etc.

The errors introduced by the data processing procedures were as follows: the analog curve follower introduced an estimated error of $\pm 1/2$ mm (or about 0.7 percent of the full scale deflection of 76 mm) due to the parallax encountered by the operator in attempting to position a movable index precisely on a point of the analog curve. The estimated error introduced in the analog-to-digital conversion was $\pm$ one unit in the least significant digit of the converter's output which ranged from ± 001 to ± 999 . The estimated error introduced in setting the scale factors for the digital plotter was ± 0.02 inch (0.2 percent of the full scale deflection of 10 inches on the digital plotter). There was also an inherent error of ± 0.015 inch (0.15 percent of full scale) contributed by the servo-plotting mechanisms which locate the data points on the graph paper.

All of these errors combine to give an overall error from the data reduction process of less than five percent provided the original deflection of the analog curve was approximately 10 mm or more. No data with maximum deflections less than 10 mm and no power data with peak deflections less than 50 mm are included in this report.

VII. TEST DATA

The principal data obtained from the transient tests of the Spert I P 18/19 reactor are summarized in tabular form in this section and graphical form in the Appendices. Table III gives the nomenclature used in the tabular data and graphs.

TABLE III

NOMENCLATURE

<u>Notation</u>	<u>Units</u>	<u>Definition</u>
τ	msec	Asymptotic reactor period.
α	sec ⁻¹	Inverse period.
θ_i	°C	Initial temperature
θ_{max}	°C	Maximum temperature
$\theta(t_m)$	°C	Temperature at peak power
$\phi(t_m)$	MW	Peak power
$E(t_m)$	MW-sec	Energy release at peak power

In Table IV, the tests are ordered first by the initial temperature conditions and then in order of decreasing asymptotic reactor period. Table IV gives the initial test conditions, the asymptotic reactor period, the peak reactor power, the energy release to time of peak reactor power, the fuel plate surface temperature at time of peak power, the maximum fuel plate surface temperature, and the maximum transient pressure.

Appendices A, B, and C consist of graphs of the data recorded during the test series. Each test is represented by a figure indexed according to both the initial asymptotic reactor period and the initial reactor temperature. In Appendix A, the figures consist of curves showing the time-history of the reactor power, the hottest measured fuel plate surface temperature, and the transient pressure (when significant) in the end box of assembly 33. Appendix B consists of curves showing the behavior of the fuel plate surface temperature rise at four vertical positions in the reactor. Appendix C consists of curves showing behavior of the fuel plate surface temperature rise at three horizontal positions in the reactor. Time of peak power is marked on all of the plots in Appendices A, B, and C.

Appendix D consists of a set of correlative plots showing the variation with the inverse asymptotic reactor period of the values at (a) the peak reactor power, (b) the energy release to time of peak power, and (c) the maximum fuel plate surface temperature. This series also includes a plot of the reactor power behavior at several asymptotic reactor periods to illustrate the change in burst shape with decreasing asymptotic reactor period.

TABLE IV

EXPERIMENTAL DATA OF THE P 18/19 CORE SERIES

Transient Number	τ (msec)	α (sec ⁻¹)	θ_i (°C)	$\phi(t_m)$ (MW)	$E(t_m)$ (MW-sec)	$\theta(t_m)$ (°C)	θ_{max} (°C)	P_{max} (psig)
08522	6000	0.17	20	0.215	2.50	48	88	0
08527	2500	0.40	20	0.450	2.60	60	97	0
08531	1300	0.77	20	0.730	2.30	64	100	0
08535	670	1.49	21	1.30	1.90	81	112	0
08538	260	3.85	19	2.80	1.70	77	128	0
08617	110	9.09	18	6.20	1.30	61	110	0
09417	61	16.4	14	15.0	1.50	70	107	0
08621	42	23.8	17	28.0	2.00	98	120	0
09326	38	26.3	13	38.0	2.13	83	120	0
09420	26	38.5	15	62.0	2.57	109	128	0
08613	21	47.6	17	91.0	2.77	118	136	0
08623	20	50.0	18	110	2.92	120	156	0
08631	16	62.5	20	144	3.30	142	192	2
08722	14	71.4	15	230	3.61	124	210	2
08725	9.3	108	16	340	4.80	140	270	4
08760	6.7	149	17	650	6.10	150	370	13
08796	6.0	167	18	830	6.70	160	440	24
08815	5.0	200	17	1050	7.20	190	500	31
10223	76	13.2	97	2.00	0.190	101	102	0
10230	23	43.5	97	15.0	0.401	103	113	0
10233	11	90.9	97	89.0	1.20	116	126	6
10235	5.0	200	97	390	2.81	174	233	21
10241	4.0	250	97	560	3.45	195	275	27

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APPENDIX A

REACTOR POWER, FUEL PLATE SURFACE TEMPERATURE,
AND PRESSURE AS FUNCTIONS OF TIME

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A1. Transient 08522, initial conditions: 6.0-sec reactor period at 20°C .

A2. Transient 08527, initial conditions: 2.5-sec reactor period at 20°C .

A3. Transient 08531, initial conditions: 1.3-sec reactor period at 20°C.

A4. Transient 08535, initial conditions: 670-msec reactor period at 21°C.

A5. Transient 08538, initial conditions: 260-msec reactor period at 19°C .

A6. Transient 08617, initial conditions: 110-msec reactor period at 18°C .

A7. Transient 09417, initial conditions: 61-msec reactor period at 14 $^\circ\text{C}$.

A8. Transient 08621, initial conditions: 42-msec reactor period at 17 $^\circ\text{C}$.

A9. Transient 09326, initial conditions: 38-msec reactor period at 13°C .

A10. Transient 09420, initial conditions: 26-msec reactor period at 15°C .

A11. Transient 08613, initial conditions: 21-msec reactor period at 17°C .

A12. Transient 08623, initial conditions: 20-msec reactor period at 18°C .

A13. Transient 08631, initial conditions: 16-msec reactor period at 20°C.

A14. Transient 08722, initial conditions: 14-msec reactor period at 15°C.

A15. Transient 08725, initial conditions: 9.3-msec reactor period at 16°C .

A16. Transient 08760, initial conditions: 6.7-msec reactor period at 17°C .

A17. Transient 08796, initial conditions: 6.0-msec reactor period at 18°C.

A18. Transient 08815, initial conditions: 5.0-msec reactor period at 17°C.

A19. Transient 10223, initial conditions: 76-msec reactor period at 97°C.

A20. Transient 10230, initial conditions: 23-msec reactor period at 97°C.

A21. Transient 10233, initial conditions: 11-msec reactor period at 97°C.

A22. Transient 10235, initial conditions: 5.0-msec reactor period at 97°C.

A23. Transient 10241, initial conditions: 4.0-msec reactor period at 97°C.

APPENDIX B

FUEL PLATE SURFACE TEMPERATURE RISE AS A FUNCTION OF TIME
WITH VERTICAL POSITION AS A PARAMETER

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B1. Transient 08527, initial conditions: 2.5-sec reactor period at 20°C.

B2. Transient 08535, initial conditions: 670-msec reactor period at 21°C .

B3. Transient 08538, initial conditions: 260-msec reactor period at 19°C.

B4. Transient 08617, initial conditions: 110-msec reactor period at 18°C.

B5. Transient 08621, initial conditions: 42-msec reactor period at 17°C .

B7: Transient 08631, initial conditions: 16-msec reactor period at 20°C .

B8. Transient 08760, initial conditions: 6.7-msec reactor period at 17°C.

B9. Transient 08815, initial conditions: 5.0-msec reactor period at 17°C.

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APPENDIX C

FUEL PLATE SURFACE TEMPERATURE RISE AS A FUNCTION OF TIME WITH HORIZONTAL POSITION AS A PARAMETER

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C1. Transient 08527, initial conditions: 2.5-sec reactor period at 20°C.

C2. Transient 08535, initial conditions: 670-msec reactor period at 21°C.

C3. Transient 08538, initial conditions: 260-msec reactor period at 19°C.

C4. Transient 08617, initial conditions: 110-msec reactor period at 18°C.

C5. Transient 08621, initial conditions: 42-msec reactor period at 17°C.

C6. Transient 08623, initial conditions: 20-msec reactor period at 18°C.

C7. Transient 08631, initial conditions: 16-msec reactor period at 20°C.

C8. Transient 08760, initial conditions: 6.7-msec reactor period at 17°C.

C9. Transient 08815, initial conditions: 5.0-msec reactor period at 17°C.

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APPENDIX D

CORRELATIVE PLOTS

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D1. Reactor power as a function of inverse asymptotic reactor period.

D2. Energy at time of peak power as a function of inverse asymptotic reactor period.

D3. Maximum fuel plate surface temperature as a function of inverse asymptotic reactor period.

D4. Power burst shape as a function of asymptotic reactor period.

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