**TRANSFER FUNCTIONS FROM REACTIVITY
PULSES GENERATED BY THE REGULATING
ROD -- ENRICO FERMI REACTOR**

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ABSTRACT

This report describes the measurement of reactor power and temperature responses to reactivity pulses generated by a single, trapezoidal movement of the regulating rod. Data obtained at three power levels are reduced by Fourier analysis of their time derivatives. Results are presented in terms of transfer functions between reactivity and power and between power and outlet temperatures.

The advantages and disadvantages of this technique with respect to an alternate oscillator rod technique are examined.

FOREWORD

This report is one of a series of reports on the low-power (up to 1 Mwt) and high-power (up to 200 Mwt) nuclear testing of the Enrico Fermi reactor. The Nuclear Test Program is planned, directed and evaluated by Atomic Power Development Associates, Inc. (APDA). The tests are conducted by Power Reactor Development Company (PRDC). The reactor proper is owned and operated by PRDC. The steam generators and electrical generating facilities are owned by The Detroit Edison Company (DECo).

Many individuals have contributed to the nuclear testing of the Enrico Fermi reactor. Listed below are those, exclusive of the authors, who have made significant contributions to the work described in this report.

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SUMMARY

The dynamic characteristics of the Enrico Fermi Atomic Power Plant were measured by Fourier analysis of power and temperature responses to a reactivity pulse generated by movement of the regulating rod. The results are in the form of transfer functions from reactivity to power and from power to outlet temperatures. Measurements were made from three pulses of different durations at each of three power levels: 0.05 Mwt, 56 Mwt, and 88 Mwt. The 0.05-Mwt and 88-Mwt runs were three-loop operation; the 56-Mwt run was two-loop operation. The dimensions of the reactivity pulses were controlled by generating velocity-demand signals for the automatic controller from an analog computer. Data were recorded on magnetic tape and, after transposition to cards, were analyzed on a digital computer.

The transfer function between power and reactivity obtained from pulse measurements compared very well with that obtained from oscillator rod measurements. However a small, consistent, frequency-dependent difference was present between these two techniques; this tended to put the pulse measurement in better agreement with theory than oscillator measurements. The conclusion was reached that the regulating rod pulse technique is satisfactory for measuring the reactivity transfer function. This technique has the advantage that it uses the regulating rod which is present in the reactor rather than the special oscillator rod mechanism but has disadvantages in that it is not satisfactory for frequencies greater than 0.5 Hz and it is not useful in the evaluation of the automatic mode of reactor operation.

The transfer function from power to reactor outlet temperature gave a value of 2.0 sec for the time constant of the outlet temperature detector and indicated a time delay of 0.4 sec for three-loop operation and 1.0 sec for two-loop operation.

The transfer function from power to plenum outlet temperature indicated a time delay of 30 sec for three-loop operation. Reactor scram transient analysis was 10 sec for this delay. Although the accuracy from the pulse measurement was low, this discrepancy was greater than the probable error in the measurement.

I. INTRODUCTION

Confirmation of the stability of a nuclear system requires measurement of its dynamic characteristics. This must be done at several power levels because instabilities are functions of power levels. In fast, sodium-cooled reactor systems, the most important dynamic characteristic is the response of power to a reactivity perturbation.

The most direct method for determining the dynamic reactivity characteristic is to obtain the reactivity to power transfer function by varying the reactivity by a small known amount and measuring the response of reactor power. Previous work at the Fermi plant has accomplished this by driving an eccentric, rotating poison cartridge at a variety of frequencies.¹ The reactivity variation from such a device is almost a pure sine wave (i.e. single frequency) and the reactor power at that frequency is the response. This method is called the oscillator technique.

The work reported here varies the reactivity in a single, trapezoidal pulse caused by movement of the regulating rod. Recordings are made of both the pulse and the power response, and Fourier analysis of the data is made on a digital computer. The ratio of reactor response to reactivity input so computed as a function of frequency is the reactivity transfer function.

The Fourier analysis of such a pulse indicates all frequencies are present. Thus, theoretically, the entire spectrum of the transfer function can be obtained from a single pulse. However, from a practical standpoint, the power contained in a given pulse at frequencies outside a certain band is too small to be accurately measured over noise levels. By recording several pulses varying in length (i.e., pulse duration), different frequency bands can be covered. An experimental study was made to reduce this technique to practice. One object of this study was to establish both the useful frequency band obtained from a specific pulse and the optimum assortment of pulse lengths. Another object was to establish the frequency limits of this technique.

The pulse method has one major advantage over the oscillator method in that the reactivity variation is caused by the normal regulating rod rather than by the special oscillator equipment.

The report presents the results of a feasibility study of the reactivity pulse technique. A set of data was obtained at each of three power levels: 0.05 Mwt, 56 Mwt and 88 Mwt. Recordings were made of the regulating rod position, reactor power, and reactor outlet temperatures. Fourier analyses

of these recordings were made on a digital computer. The success of the method was evaluated by comparing the results with oscillator results at similar power levels. Comparison was also made with theoretical predictions for the results at the 0.05-Mwt power level.

II. DESCRIPTION OF THE ENRICO FERMI REACTOR

The Enrico Fermi reactor and its associated structures are shown in perspective in Fig. 1. The reactor is contained in a stainless steel reactor vessel sealed at the top by a rotating shield plug which supports the control mechanisms, the holddown mechanism, and the fuel handling mechanism. The reactor vessel is surrounded by boronated and plain graphite neutron-shielding material which is contained inside the primary shield tank. The reactor is of the fast breeder type, cooled by sodium, and operated at essentially atmospheric pressure. The maximum reactor power with the first core loading (Core A) is 200 Mwt.

The core and blanket consist of square subassemblies arranged to approximate a cylinder about 80 in. in diam and 70 in. high. The core, contained in the central portion of the subassemblies, approximates a right cylinder 31 in. in diam and 31 in. high; it is axially and radially surrounded by breeder blankets. The fuel consists of zirconium-clad pins containing U-10 w/o molybdenum alloy with the uranium enriched to 25.6 w/o U-235. A core section of a subassembly consists of 140 fuel pins containing a total of 4.75 kg of U-235. The blanket is depleted U-3 w/o molybdenum alloy. More specific information is given in Table 1.

The reactor cross section, shown in Fig. 2, indicates the placement of individual components within the reactor vessel. The 149 central lattice positions are occupied by core and inner radial blanket subassemblies, the neutron source, and the 10 control rod and safety rod channels. These positions are cooled with sodium flowing upward from the high-pressure plenum which is fed through 14-in. lines from the three primary pumps.

The lattice positions surrounding the inner radial blanket comprise the outer blanket area and form an annular region whose top and bottom are at the same elevation as the top and bottom of the inner radial blanket. Surrounding the outer radial blanket are lattice positions for stainless steel subassemblies used to provide thermal and neutron shielding. The outer radial blanket and shielding lattice positions are cooled with sodium flowing upward from the low-pressure plenum which is fed through 6-in. lines from the three primary sodium pumps. The sodium mixes in the upper plenum with the sodium from the core and then flows to three intermediate heat exchangers to the suction side of the primary pumps.

The reactor is controlled by two control rods and seven safety rods by means of electromechanical drives mounted on the rotating plug. The rods are of the poison type, containing boron carbide enriched in boron-10. One of the two control rods is for regulating and the other is for shimming. The

FIG. 1 PERSPECTIVE VIEW OF REACTOR

TABLE 1 - DIMENSIONS AND COMPOSITION OF
CORE AND BLANKET REGIONS

<u>Subassembly Dimensions</u>	<u>Core Section</u>	<u>Axial Blanket Section</u>	<u>Inner and Outer Radial Blanket Section</u>
Cross Section	Square	Square	Square
Outside Dimension*, in.	2.646	2.646	2.646
Wall Thickness (stainless steel), in.	0.096	0.096	0.096
Space Between Subassemblies, in.	0.047	0.047	0.047
Subassemblies Or Sections [†] , number of	103	206 [‡]	533
<u>Element Dimensions</u>			
Shape	Round Pin	Round Rod	Round Rod
Clad Outside Diameter, in.	0.158	0.443	0.443
Clad Thickness and Material, in.	0.005(Zr)	0.010(S.S.)	0.010(S.S.)
Uranium Diameter, in.	0.148	0.395	0.395
Uranium Length, in.	30.5	14	61.75
Pitch (square), in.	0.199	0.483	0.483
Pins or Rods Per Subassembly, number of	140	32 [‡]	25
<u>Section Composition</u>			
Uranium, v/o	27.3	25.6	40.0
Molybdenum, v/o	5.5	1.4	2.3
Zirconium, v/o	4.6	--	--
Stainless Steel, v/o	17.4	16.5	18.6
Sodium, v/o	45.2	56.5	39.1
Heat Transfer Surface, sq ft	1545	455 [‡]	7923
Uranium Alloy Composition	U-10 w/o Mo	U-3 w/o Mo	U-3 w/o Mo
U-235 Enrichment, w/o	25.6	0.35	0.35

* Does not include the spacer pads.

† There are 103 core subassemblies, 34 inner radial blanket subassemblies,
and 499 outer radial blanket subassemblies.

‡ Total for both axial blanket sections.

FIG. 2 REACTOR CROSS SECTION

seven safety rods are used only to provide shut-down reactivity and are held immediately above the axial blanket during operation of the reactor. Upon a scram signal, each safety rod is delatched from its drive and is fired into the core with a compressed spring. Additional information concerning the reactor design may be found in Reference 2.

III. DESCRIPTION OF APPARATUS AND DATA COLLECTION TECHNIQUES

A. PULSE GENERATION APPARATUS

The reactivity pulse was generated by withdrawing the regulating rod from its critical position a specified increment, holding this position for a specific period of time and then returning the rod to its initial position. This movement could be made manually but it is difficult to attain desired pulse lengths and return the rod exactly to the initial position. However, perfect pulses can be generated with the regulating rod if it is driven by the automatic control system, in conjunction with an analog computer circuit. The automatic control system was modified such that the velocity-demand signal for the regulating rod was generated with an analog computer.

The analog computer velocity-demand circuit, diagrammed in Fig. 3, is essentially a step-demand servo with position feedback in which the size and duration of the step are variable parameters. The voltage to the velocity demand is set by potentiometers across batteries. The analog circuit can be easily modified to generate a train of positive and negative reactivity pulses, but in all work reported here only single, positive pulses were used.

B. INSTRUMENTATION

The rod position signal is obtained from a potentiometer directly coupled to the rod drive. The d-c voltage across the potentiometer gives a rate of change of 28.8 mv per in. of rod movement.

The location and specifications of recorded neutron and temperature sensors are listed in Table 2.

C. DATA RECORDING

Data were recorded on a Sangamo magnetic tape recorder for future transformation and analysis and also on a Sanborn thermal oscillograph for a "hard" copy.

The tape recorder can record and reproduce up to 14 channels of information in FM or direct mode on 1-in. tape at speeds from 7-1/2 to 60 ips. All data reported here were recorded in FM mode on even-numbered channels at 7-1/2 ips.

TABLE 2 - SPECIFICATIONS OF NEUTRON DETECTORS AND TEMPERATURE SENSORS

<u>Parameter</u>	<u>Sensor Identification</u>	<u>Detector</u>	<u>Location</u>
Reactor Power	ND1	Reuter-Stokes Model RSN-15A (Compensated, B-10 Lined) No. F-774, Connected To Keithley Model 415 Picoam- meter. (3.76×10^{-13} amp/watt)	Located In Well, Approx- imately 88 in. From Core Center
	ND2	Reuter-Stokes Model RSN-36A (Uncompensated, B-10 Lined) No. F-793, Connected To Operational Amplifier (2.99×10^{-13} amp/watt)	Located In Well, Approx- imately 95 in. From Core Center
Core Outlet Temperature	TE 115-26	Iron-Constantan Thermocouple Encased In 0.125-in. OD Stainless Steel Sheath. Re- sponse Time Approximately 1 sec.	In Holddown Finger Over Element Location N02-P04 (see Fig. 2)
Upper Plenum Outlet Temperature	TE 201-1	Platinum Resistance Thermom- eter Feeding Bridge Circuit With d-c Amplifier. Response Time Approximately 6 sec.	In 30-in. Outlet Pipe, Loop 1. Sheath In Direct Contact With Sodium

The rod position signal was first fed to the analog computer, offset and amplified, and then fed to the recorders as shown in the circuit diagram, Fig. 3. The other signals were fed directly to the oscillograph for initial offset and amplification; the oscillograph galvanometer signal was passed through fractional-gain operational amplifiers and then to the tape recorder. All signals were recorded with no filtering except for the rod position signal which had a 0.1-sec time constant.

After plant conditions were stabilized at the desired power level, the recorders were started, the reactor operation was switched into the automatic mode, and the reactivity pulse circuit was activated. Approximately five pulse durations later, recorders were stopped and the operation mode was returned to manual.

D. DATA TRANSFORMATION

The data were transformed from magnetic tape to cards so that they could be analyzed on a digital computer. The required equipment was made available to APDA by Argonne National Laboratory, Idaho Division. This equipment consisted of (1) a tape recorder compatible with APDA recordings, (2) analog amplifiers to drive the signals down the 100-yd cables to their computer facility, (3) a multiplexing digital voltmeter feeding a digital magnetic tape recorder and, (4) an IBM 1620 computer to read the digital tape and punch the readings on cards. Each channel of data was punched on a separate deck of 110 serially labeled cards at 10 values per card. The sample spacing was chosen so that the total recording of each pulse would be covered in the 1100 points.

To minimize errors caused by high-frequency noise, the data were passed through a 1.2-sec time-constant filter and rerecorded on adjacent, unused channels before digitization. The filtered data were digitized rather than the data on the original recordings.

The original recordings had a semblance of absolute calibration. However, through rerecording and digitizing, the calibration was lost, for all practical purposes. Consequently, no attempt was made to report results in absolute units.

IV. TECHNIQUES OF DATA ANALYSIS

The fundamental plan for data analysis consisted of Fourier analysis of the data recordings and determination of the transfer function between the various parameters by ratioing their amplitudes and subtracting their phases at corresponding frequencies. Because of the large amount of data, analyses were performed on a digital computer.

A. FOURIER ANALYSIS

To perform a Fourier analysis on a pulse, the data must have an initial value of zero and must return to this value as the effect of the pulse decays. These requirements are usually met by subtracting the initial value from all data. However, in no case did the end conditions exactly equal the start conditions in the data collected here. Consequently, these requirements could not be met by the subtracting technique so an alternate technique was developed. This performs the Fourier analysis on the time derivative of the data.

The derivative of the signal at time, t_n , was computed from the difference between the two adjacent data points:

$$\frac{dX(t_n)}{dt} = \frac{X(t_{n-1}) - X(t_{n+1})}{2 \Delta t}$$

Fourier analysis was performed on this derivative (which is a function of time) and in-phase and quadrature components, absolute amplitude and phase were computed. Results were printed-out and were also punched on cards.

B. TRANSFER FUNCTION

The amplitude of a transfer function is the ratio of amplitudes of output and input; the phase of transfer function is the difference between output and input phases. If the portion of the input signal at frequency, f , is of the form $I(f) \sin [2\pi ft + \phi(f)]$, the corresponding output signal is of the form $O(f) \sin [2\pi ft + \phi(f) + \theta(f)]$. However, before the Fourier analyses were performed on these data, they were differentiated for reasons discussed above. By so doing, the input signal becomes $2\pi f I(f) \cos [2\pi ft + \phi(f)]$ and the output signal becomes $2\pi f O(f) \cos [2\pi ft + \phi(f) + \theta(f)]$. From these expressions it is seen that the values for the ratio of amplitudes and the difference between phases are unaltered by Fourier analysis of the derivatives rather than the original signals.

Because of the large quantity of data, the transfer functions were computed on the digital computer using the cards containing the results of the Fourier analyses and instructions to define which sets were "output" signals and which were "input" signals. Since data of outlet temperatures were collected as well as data for reactivity and core power, transfer functions were computed between core power and outlet temperature, in addition to reactivity and core power.

C. DETERMINATION OF TIME LAGS

Nearly every physical system which has a frequency-dependent gain also has a frequency-dependent phase shift. In the case of a simple time constant, T , the phase is $-\arctan 360 fT$, where f is frequency.

In many systems, the travel of information takes a finite amount of time. Such is the case for sodium temperature information in the Enrico Fermi plant. The travel time, or lag time, L , manifests itself as an additional term in the phase equation:

$$\text{Phase} = -(360fL + \arctan 360fT)$$

For cases of relatively simple systems, values for T can be determined from the amplitude variation of the transfer function. Using these values in the above equation, a value for L can be determined from the phase variation.

D. SELECTION OF MEANINGFUL VALUES

For the data sets of 56 Mwt and 88 Mwt, recordings were made of both ND1 and ND2 signals and transfer functions were computed between them. These results clearly indicated that the data were unreliable whenever the amplitude of either was small (less than 0.0008 volt). On this basis, the only values used were those of transfer functions derived from amplitudes greater than 0.0008 volt.

V. EXPERIMENTAL CONDITIONS

A. PLANT CONDITIONS

Sets of data were taken at three power levels: 0.05 Mwt, 56 Mwt, and 88 Mwt. The conditions of the primary system as indicated on control room instrumentation are listed in Table 3 for each of the runs.

B. PULSE DIMENSIONS

The following limiting criteria were placed on the pulse shape so that plant technical specifications would not be exceeded.

- The reactor power shall not deviate by more than 4 per cent from the pulse start level.
- The regulating rod velocity shall not exceed 10 in. per min for either withdrawal or insertion.

Rod velocities of 10 in. per min (second criterion) were used throughout, to have as much high-frequency power in the pulse as possible. The first criterion was met by controlling the stroke or height of the pulse.

Three pulse lengths were used at each power level and at least two recordings were made of each length. Not all data were successfully carried through the digitizing process. The dimensions of the pulses which were successful and used in this analysis are listed in Table 4; also listed are the card-deck identifying numbers for each parameter and the data spacing.

The regulating rod has a sensitivity of 3.4 cents per in. at the critical positions for these measurements. Since the pulses used had regulating rod strokes that varied from 0.25 to 0.5 in., the reactivity pulses varied from 0.85 to 1.7 cents.

TABLE 3 - PRIMARY SYSTEM CONDITIONS

	0.05 Mwt (May 12, 1966)	56 Mwt (June 28, 1966)	88 Mwt (August 1, 1966)
Ion Chambers:			
IR-1, cpm	5.7×10^5	4.7×10^8	8.2×10^8
IR-2, cpm	5×10^5	4.2×10^8	7.2×10^8
IR-3, cpm	4×10^5	3.8×10^8	7.8×10^8
ND1 amps	1.7×10^{-8}	2.1×10^{-5}	3.3×10^{-5}
ND2 amps	--	1.6×10^{-5}	2.6×10^{-5}
Regulating Rod Critical Position, in. withdrawn	4.56	6.96	7.065
Reactor Inlet Temperatures, F:			
TE 209-1	521.4	540.0	535.6
TE 209-2	521.8	-	-
TE 209-3	521.8	-	551.6
Reactor Outlet Temperatures, F:			
TE 115-9	521.4	737.0	748.4
TE 115-31	521.3	719.5	675.1
TE 115-33	521.2	673.8	731.0
Upper Plenum Outlet Temperatures, F:			
TE 217-Loop 1	524.3	651.6	660.5
TE 217-Loop 2	522.2	656.3	657.1
TE 217-Loop 3	520.5	-	659.4
Sodium Flow Through 14-in. Reactor Inlet Pipes, 10^6 lb/hr:			
FE 201-Loop 1	2.2	2.4	2.3
FE 201-Loop 2	2.1	2.5	2.2
FE 201-Loop 3	1.8*	-0.4	2.4
Sodium Flow Through 6-in. Blanket Inlet Pipes, 10^6 lb/hr:			
FR 202-Loop 1	0.30	0.26	0.38
FR 202-Loop 2	0.31	0.25	0.38
FR 203-Loop 3	0.31	0.25	0.39
Pump Speed, rpm:			
Primary, Loop 1	373	357	463
Primary, Loop 2	377	370	463
Primary, Loop 3	387	0	490
Secondary, Loop 1	0	353	393
Secondary, Loop 2	0	350	370
Secondary, Loop 3	347	0	373

* Flow was oscillating between 1.6 and 2.0×10^6 lb/hr on 30-min period due to temperature controller on liquid rheostat.

TABLE 4 - PULSE DIMENSIONS AND IDENTIFICATION

Reactor Power, Mwt	Pulse Length, sec	Pulse Amplitude, in.	Total Recording Time, sec	Data Sample Spacing, sec	Card-Deck Number for Each Parameter				
					ND1	ND2	Reg. Rod	TE 115-26	TE 201-1
0.05	9.6	0.50	29	0.06	2066		2067		
	9.6	0.50	25	0.06	2064		2065		
	15	0.50	29	0.06	2066		2067		
	29	0.50	143	0.32	2068		2069		
56	9	0.25	59	0.10	2033	2039	2032	2038	
	26	0.36	177	0.20	2029	2035	2028	2034	
	85	0.25	298	0.32	2031	2037	2030	2036	
88	8	0.50	47	0.20	2055	2047	2062	2054	2046
	103	0.25	319	0.32	2051	2043	2058	2050	2042
	103	0.25	414	0.48	2053	2045	2060	2052	2044

VI. ANALYSIS OF TESTS

A. TRANSFER FUNCTION, REACTIVITY TO POWER

The reactivity to power transfer function for each of the three data sets is shown in Figs. 4, 5 and 6. These data show the upper frequency limit of the technique and the band of frequencies obtained from each pulse.

The highest frequency obtained from these data was 0.15 Hz. The limiting parameter is regulating rod speed. If shorter pulses are programmed, the rod total movement does not generate a power perturbation sufficiently greater than the noise level. Some improvement (to perhaps as great as 0.5 Hz) could be realized by using a group of pulses; further improvement could be made by changing the technical specifications to permit higher rod speeds.

The power contained in the single pulse used in these measurements attains maximum amplitude at a frequency of $2/D$, where D is the duration of the pulse. The results indicate that useable data are obtained for a band of frequencies extending from $0.8/D$ to $5/D$. Thus, to obtain a reasonable amount of overlap between the various data sets, pulse durations should be separated by a factor of 3 or 4. A good combination of pulse durations is 100, 25, and 8 sec for measurements at the Enrico Fermi plant.

One of the main objectives of this work was comparison of reactivity transfer functions measured by the pulse technique with those measured by the oscillator rod technique. This comparison is summarized in Table 5. The 0.05-Mwt data listed in this table indicate a trend in the difference between the two methods, in both amplitude and phase. The quotient of the amplitudes from the pulse measurements divided by the oscillator measurements, when normalized at 0.1 Hz, changes from 0.95 at 0.007 Hz to 1.0 at 0.1 Hz. Over this same frequency band, the phase from the pulse measurement changes by 2 deg more than the oscillator measurement, with a total change of 30 deg.

A similar trend is apparent in the amplitude comparison at 88 Mwt. The phase comparison for this case indicates that the pulse measurement has a smaller phase shift than the oscillator measurement.

The trend is not apparent in the data for 56 Mwt. Here, however, the direct comparison between the two methods is not as valid for the data which were obtained at different power levels, i.e., 56 Mwt for the pulse data and 60 Mwt for the oscillator data. Due to this, the ratio would be expected to be greater than unity.

TABLE 5 - COMPARISON OF REACTIVITY TO POWER TRANSFER FUNCTIONS
AS MEASURED BY PULSE AND OSCILLATOR TECHNIQUES

Power Level	Transfer Function Parameter	Measurement Technique	Units	Frequency, Hz									
				0.005	0.007	0.01	0.02	0.03	0.04	0.05	0.07	0.1	0.2
0.05 Mwt (Three-Loop)	Amplitude	Pulse	None		4.15	3.52	2.54	2.14	1.90	1.75	1.60	1.50	
		Oscillator	$\$^{-1}$	4.63	3.82	3.21	2.28	1.93	1.70	1.58	1.42	1.32	1.17
		Pulse÷Osc.	*		0.95	0.96	0.98	0.98	0.98	0.97	0.99	1.00	
		Theoretical	$\$^{-1}$	4.19	3.50	2.95	2.16	1.80	1.60	1.49	1.38	1.28	1.12
	Phase	Pulse÷Theory	*		1.01	1.02	1.00	1.01	1.01	1.00	0.99	1.00	
		Pulse	deg		50	46	38	33	30	28	24	20	
		Oscillator	deg	53	48	44	37	34	30	28	24	20	14
		Pulse-Osc.	deg		2	2	1	-1	0	0	0	0	
56 Mwt (Two-Loop)	Amplitude	Pulse	None	8.30	7.00	5.90	4.38	3.92	3.73	3.55	3.24	2.92	
		Oscillator	$\$^{-1}$	3.00	2.63	2.37	1.83	1.63	1.47	1.36	1.27	1.19	1.09
		Pulse÷Osc.	*	1.13	1.09	1.02	0.98	0.98	1.04	1.07	1.04	1.00	
	Phase	Pulse	deg	32	30	27	26	22	19	16	12	8	
		Oscillator	deg	30	29	28	27	25	24	22	19	16	10
		Pulse-Osc.	deg	2	1	-1	-1	-3	-5	-6	-7	-8	
	Amplitude	Pulse	None	12.8	10.4	9.10	7.23	6.47	6.00	5.75	5.33	5.00	
		Oscillator	$\$^{-1}$	3.17	2.73	2.33	1.86	1.64	1.48	1.38	1.26	1.18	1.08
		Pulse÷Osc.	*	0.95	0.90	0.92	0.92	0.93	0.96	0.98	1.00	1.00	
88 Mwt (Three-Loop)	Phase	Pulse	deg	31	26	24	22	21	20	19	16	11	
		Oscillator	deg	35	33	30	28	26	24	22	19	16	11
		Pulse-Osc.	deg	-4	-7	-6	-6	-5	-4	-3	-3	-5	
	Amplitude	Pulse	None										

* Normalized to 1.00 at 0.1 Hz

FIG. 4 TRANSFER FUNCTION, REACTIVITY TO POWER-0.05 Mwt

FIG. 5 TRANSFER FUNCTION, REACTIVITY TO POWER-56 Mwt

FIG. 8 TRANSFER FUNCTION, POWER TO REACTOR OUTLET TEMPERATURE-88 Mw

FIG. 9 TRANSFER FUNCTION, POWER TO PLENUM OUTLET TEMPERATURE-88 Mw

Also listed in Table 5 are the results of calculations of the amplitude of the zero-power transfer function. No trend is present between the pulse measurements and the calculations.

The pulse and oscillator techniques generally give the same results within $\pm 5\%$. It is impossible at this point to determine which is the more accurate but the superior agreement between theoretical predictions and the pulse technique tends to give weight to the pulse technique.

B. TRANSFER FUNCTION, POWER TO REACTOR OUTLET TEMPERATURE

The reactor outlet thermocouple, TE 115-26, is located in the finger of the holddown fixture at core location N02-P04. A hole in the handling head of the fuel element at this location is such that some sodium from the fuel element flows upward into the finger and across the thermocouple. The transfer function between core power and the thermocouple should be constant until the time constants of the thermocouple and the fuel element come into effect. The time constant of the thermocouple is expected to be about 1 sec; the time constant of the fuel element is much less. Since the data are limited to 0.15 Hz, only the time constant of the thermocouple should be detected. Thus, for the frequency range of the data, the amplitude and phase of the transfer function between core power and TE 115-26 should have the form:

$$\text{Amplitude} = \frac{K}{(1 + i \omega T)}$$

$$\text{Phase} = -(\text{arc tan } \omega T + \omega L)$$

Where T and L are the thermocouple time constant and sodium transport times, respectively, and K is a normalizing factor.

This transfer function was measured at both 56 Mwt and 88 Mwt. The results are shown in Figs. 7 and 8. These results were analyzed and it was found that the 56-Mwt data gave 2.0 sec and 1.0 sec for T and L, respectively; the 88-Mwt data gave 1.8 sec and 0.4 sec for T and L, respectively.

The values for T are somewhat greater than anticipated but they are not unreasonably so; the difference is probably due to the conduction of the holddown finger. The lag times are more difficult to explain but could be indicative of a low flow rate through the handling-head hole. There is a possible error of 0.1 sec on each of these lag times due to the technique of starting the digitizer. (These data were digitized on different playback passes.)

C. TRANSFER FUNCTION, POWER TO PLENUM OUTLET TEMPERATURE

The power to plenum outlet temperature transfer function should contain the same factors as the power to reactor outlet temperature, e.g., temperature-detector and core-time constants, plus a time-constant factor reflecting the degree of mixing in the upper plenum. If no mixing occurs in the upper plenum, the time constant will be zero; if complete mixing occurs, the time constant will be the plenum volume (1143 cu ft) divided by the total sodium flow.³

The static time constant for the temperature detector used for the work reported here (TE 201-1) was found to be 6 sec.⁴ This was determined by plunging it into a hot, stagnant pool of sodium. The core time constant, as before, is too small to affect these measurements. Thus, the amplitude and phase of the transfer function between power and plenum outlet temperature should have the form:

$$\begin{aligned}\text{Amplitude} &= \frac{K}{(1 + i \omega T)(1 + i \omega P)} \\ \text{Phase} &= -(\text{arc tan } \omega T + \text{arc tan } \omega P + \omega L)\end{aligned}$$

where T, L, and P are the temperature-detector time constant, the lag-time time constant and the plenum-mixing time constant, respectively.

L and P are not mutually independent. At zero mixing, P is zero and L is the plenum volume divided by the flow, V/F; at complete mixing, exactly the opposite applies. Without developing the theory further, it seems reasonable to expect that the sum of P and L would always equal V/F regardless of the degree of mixing.

The outlet plenum temperature response from pulse experiments were recorded at 88 Mwt only. The transfer function from power to plenum outlet temperature is shown in Fig. 9. Unfortunately, the amplitude data are so rough that values for T and P cannot be measured. However, the phase data are quite definite, yielding a value for V/F of 30 sec. The expressions above will fit the measured phase curve only when T = 12 sec, P = zero, and L = 30 sec. Thus, the data indicate that no mixing is occurring in the upper plenum.

The time response of the plenum outlet-temperature detector following a scram has been studied for a variety of power and flow conditions.⁵ These experiments measured a lag time of 10 to 11 sec for TE 201-1 and a major time constant of 30 sec for three-loop operation and 48 sec for two-loop operation.

The phase curve for $L = 10$ sec and $T = 30$ sec, the values measured by rod-drop experiments, is also plotted in Fig. 9. This curve obviously does not describe the data. An examination of the original oscillograph recordings of the pulse experiments confirms the 30-sec lag; the temperature indication from TE 201-1 did not change until 30 sec after the pulse. The pulse data are not irrefutable, as evidenced by the scatter of points on the amplitude curve. However, the data are sufficiently consistent to warrant more detailed measurements to resolve the discrepancy.

VII. COMPARISON OF PULSE AND OSCILLATOR TECHNIQUES

There are definite advantages and disadvantages of the pulse technique compared with the oscillator rod technique for measuring reactor transfer functions. These are summarized in the following:

Advantages of Pulse Technique

- Measurement of transfer function without the complicated mechanisms and electronics of the oscillator rod system
- No special core lattice position required
- Coverage of the spectrum more completely, ensuring that no resonances are overlooked
- Shortened time for accumulation of data
- Recordings of more than two parameters, enabling cross-checking and measurement of other transfer functions

Disadvantages of Pulse Technique

- High-frequency limitation due to present limitation of regulating rod speed (some improvement in these measurements is possible using a chain of pulses rather than single pulses, but the reliability is doubtful beyond 0.5 Hz)
- Impossibility of measuring the transfer function of the reactor under automatic control

The pulse method currently requires off-line data reduction with the use of special equipment and a digital computer. The delay which occurs between the recording of data and the final results can probably be no less than several weeks if the procedure outlined here is repeated. This delay could be reduced to several days if a tape-to-card converter were available at the plant, or it could be further reduced to several hours if the data were recorded directly on a digital computer at the plant.

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VIII. CONCLUSIONS

The technique of measuring the reactivity transfer function from a prescribed movement of the regulating rod has been successfully developed. The initial measurements made at 0.05 Mwt, 56 Mwt, and 88 Mwt compare favorably with both oscillator results and theoretical predictions.

The capability of this technique to determine core outlet temperature time constants and time lags as well as reactivity transfer function from the same data set has been demonstrated.

The technique can currently cover a frequency range from 0.001 to 0.15 Hz.

REFERENCES

1. Klickman, A. E., et al, "Oscillator Tests in the Enrico Fermi Reactor," APDA-NTS-11, August, 1967.
2. Power Reactor Development Co., "Technical Information and Hazards Summary Report, Enrico Fermi Atomic Power Plant," Vol. 1-7, Revised March, 1964.
3. Schultz, M. A., Control of Nuclear Reactors and Power Plants, p.280, McGraw-Hill Book Co., New York, New York, 1961.
4. Head, G. F., "Time Response Tests For an L and N Resistance Thermometer," APDA-TM-8, November 4, 1959.
5. Ziniuk, M. A., "Scram Test to Determine Shutdown Transient Characteristics of the Enrico Fermi Reactor and Associated Heat Transport System," APDA-NTS-15, (to be published).