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CURIUM II ROD WITHDRAWAL TEST

INTRODUCTION

During the power ascension of the K-14 Curium-II cycle on September 17, 1966, a rod withdrawal test was performed as described in Reference 1. The objective was to obtain temperature data for fuel assemblies surrounding a septifoil from which a control rod was withdrawn. Temperatures were measured by monitor pin thermocouples in adjacent assemblies and by special thermocouples in a Mark XII test assembly described in Reference 2.

A preliminary report of the test results was included in Reference 3. This report contains a final summary of the results of the rod withdrawal test.

SUMMARY

Results of withdrawal of a fully inserted full rod worth 180 microbucks from cluster 8 of the K-14 charge were as follows:

- Reactor power increased from 950 MW to 1250 MW (32% increase)
- Powers of Mark XII assemblies adjacent to cluster 8 increased between 43% and 48%.
- Coolant channel hot spot factors and assembly hot channel factors indicated by on-line computer data were essentially unchanged. (Discrepancies were noted from data recorded by the on-line computer and by a Midwestern recorder; the computer data are considered valid.)

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- The ratio between maximum monitor pin ΔT and hex average ΔT was essentially unchanged.

- High level flux monitor signals increased between 32% and 47%, in good agreement with measured power increases.

- The plenum inlet temperature increased 2°C and the pump suction temperature increased 9°C.

Results of the test indicate that the constants used in calculations of Mark XXX effluent temperature limits for inadvertent withdrawal of a control rod are probably slightly conservative.

DISCUSSION

Background

If a single control rod is unintentionally withdrawn from the reactor, power in the adjacent region will increase more than the total reactor power. Automatic scram action for this malfunction depends primarily on the Radial Power Monitor; protection prior to the scram is provided by RPM and temperature monitor alarms and automatic rod reversal from the temperature monitor on-line computer. Additional protection against local flux increases is provided by the power density monitor that is set to give an alarm and rod reversal for a local flux increase of about 10%.

The effluent temperature limit for this accident is calculated by the following equation (Reference 4):

$$T_L = T_{in} + \frac{T_{sat} - T_{in}'}{R(HCF)'}$$

where:

T_L = effluent temperature limit, °C

T_{sat} = minimum saturation temperature in assembly, °C

T_{in} = plenum inlet temperature before rod withdrawal, °C

T_{in}' = maximum plenum inlet temperature during rod withdrawal, °C

HCF' = maximum hot subchannel factor during rod withdrawal = $B(HCF)$

$$R = \frac{\text{maximum } \Delta T \text{ in hex after withdrawal}}{\text{maximum } \Delta T \text{ in hex before withdrawal}} = \gamma P_r$$

HCF = hot subchannel factor before withdrawal

$$P_r = \frac{\text{hex power after withdrawal}}{\text{hex power before withdrawal}}$$

$$\gamma = \left[\frac{\text{max. } \Delta T \text{ in hex}}{\text{hex avg. } \Delta T}\right]_{\text{after}} \div \left[\frac{\text{max. } \Delta T \text{ in hex}}{\text{hex avg. } \Delta T}\right]_{\text{before}} = \frac{\alpha'}{\alpha}$$

Rod withdrawal tests are performed to measure changes in HCF and R resulting from inadvertent rod driveout. Results of previous tests in Mark V-B, Mark V-E, and Mark VI-B charges are described in Reference 5.

Curium II Rod Withdrawal Test

The Curium II rod withdrawal test was performed in cluster 8 of the K-14 charge. The normal power ascension was interrupted at 85% of nominal reactor power after normal work had been completed at all levels. The power was then reduced to 60% of predicted operating power and maintained at 60% (950 MW) for one hour prior to the test.

The test consisted of measuring temperatures in adjacent assemblies before, during, and after a single full rod, worth 180 microbucks to the hex or 5 microbucks to the reactor, was driven out of the septifoil from the fully-inserted position. The location of control rods in cluster 8 prior to the withdrawal is shown in Figure 1. A 0.45-inch cadmium full rod was removed from channel A of the septifoil in about seven minutes and the data for the rod-out condition were taken rapidly to minimize the effects of power changes other than those caused by the test. No other rod motion to compensate for these changes occurred while the test rod was being withdrawn. During the time that the rod was in the full-out position (before it was re-inserted), control rods in other clusters were used to maintain constant power. When the test rod was re-inserted, in about six minutes, control rods in other clusters were used to prevent reactor power from decreasing to less than 950 MW.

Temperatures were measured in a special thermocouple assembly in position 32-60 adjacent to cluster 8. This special assembly is described in Reference 2. Signals from the special thermocouples were processed by the on-line computer and by special amplifiers connected to a high-speed Midwestern recorder (Reference 6). An annular monitored Mark XII test assembly was located in position 29-63 adjacent to cluster 8.

Test Results

The chronology of the rod withdrawal test is summarized in Table I. Reactor power increased 32% from 950 MW to 1250 MW when the rod was withdrawn. Power increases in Mark XII assemblies in the charge were between 48% in the hex adjacent to cluster 8 and 21% on the opposite side of the reactor. The average Mark XII power in the hex increased by 45% (P_r = 1.45). Mark XII assembly power increases are shown in Figure 2.

Monitor pin thermocouples indicated ΔT increases between 13° and 16°C in Mark XII assemblies adjacent to cluster 8. The ΔT's indicated by the auxiliary recorders and the on-line computer agreed well as shown in Table II. Small differences between the computer and auxiliary recorder data probably result from the effects of flow variations; thermocouple inputs to the computer are essentially instantaneous but recorder signals indicated a range of ±0.5°C and were averaged over several minutes.

The orientation between the hottest monitor pin thermocouple in assemblies adjacent to the control cluster and the cluster was random. Monitor pin thermocouples in the annular monitored test assembly indicated larger ΔT increases in the three inner channels (monitored by thermocouples A, B, and C) than in the outer channel. The ratio between the maximum monitor pin ΔT and the average monitor pin ΔT in the hex, α, was essentially unchanged by the rod withdrawal. The measured α was 1.054 before the test and 1.058 after the rod withdrawal. Thus, $\gamma = 1.004$. Monitor pin responses are summarized in Table III.

Responses of the special thermocouples in the Mark XII test assembly in position 32-60 are summarized in Table III. Two thermocouples in this assembly became inoperative prior to the test. The ΔT's recorded by the on-line computer before and after rod withdrawal and recorded continuously by the special Midwestern recorder during the rod withdrawal agree well except for the responses from thermocouples 7 and 15. The reason for the discrepancy between maximum ΔT's indicated by the computer and the Midwestern recorder is not known. Because the ΔT increases indicated by the Midwestern recorder for TC's 7 and 15 are not consistent with the changes in other subchannels, computer data are believed to be more reliable although subsequent calibration of the recorder revealed no deficiencies.

Coolant channel hot spot factors and assembly hot subchannel factors before and after the rod withdrawal are compared in Table IV. Computer data indicate no significant change of hot spot factor or hot subchannel factor resulting from the rod withdrawal (B = 1.00). Factors calculated from Midwestern recorder data and average factors measured during full-power operation of the K-14 cycle (Reference 2) are also included in Table IV for comparison. The anomalous behavior of Midwestern data for thermocouples 7 and 15 causes calculated factor increases that are unbelievably large. Hot subchannel factors before the rod withdrawal are within 2-3 standard deviations of the average factors at full power; this agreement is adequate, considering the differences between 60% and 100% power.

Locations of hot subchannels in the Mark XII test assembly are shown in Figure 3. Hot subchannels are randomly oriented relative to the control cluster and their location is not changed by rod withdrawal.

Response of the high level flux monitors is summarized in Table V. As anticipated, the largest signal increase (47%) was indicated by HLFM 4 located in the quadrant nearest cluster 8. Monitors on the opposite side of the reactor indicated increases of about 32%. Responses of the HLFM's agreed well with measured local and average reactor power increases.

The rod withdrawal caused the average plenum inlet temperature to increase about 2°C and the pump suction temperature to increase about 9°C. The largest increases occurred in systems 1 and 6, nearest cluster 8. Effects of the rod withdrawal on plenum inlet and pump suction temperatures are summarized in Table VI.

The axial flux shape, measured by APM 2, adjacent to cluster 8 was the same after rod withdrawal as it had been prior to rod withdrawal. The rooftop ratio indicated by APM 2 decreased about 0.06 units during the withdrawal; the ratio for the other APM rods decreased about 0.02 units.

Comparison of Measured and Recommended Limits Data

Constants used to calculate the effluent temperature limit (Reference 4) are compared with measured values below:

Constant	Recommended (DPSTM-110)	Measured
B	1.01	1.00
γ	1.01	1.004

Although there is some doubt concerning the measured value of B because of discrepancies between data recorded by the on-line computer and a Midwestern recorder, continued use of the recommended values is reasonable and probably slightly conservative.

JWJ:gvb

REFERENCES

1. Joseph, J. W., Temporary Procedure Under TA 1-1558 - K Area. SP-1467 (TA 1-1558)-K, September 2, 1966.

2. Joseph, J. W., Mark XIII Hot Subchannel Factors. DPSP-66-1669, RTR-917, to be issued (Secret).

3. "K-14 Cycle Rod Withdrawal Test", Works Technical Department Progress Report - September 1966. DPSP-66-1-9, p 135 (Secret).

4. Technical Manual on Effluent Temperature and Surface Heat Flux Limits for Fuel and Target Assemblies. DPSTM-110, Revised June 1966 (Secret).

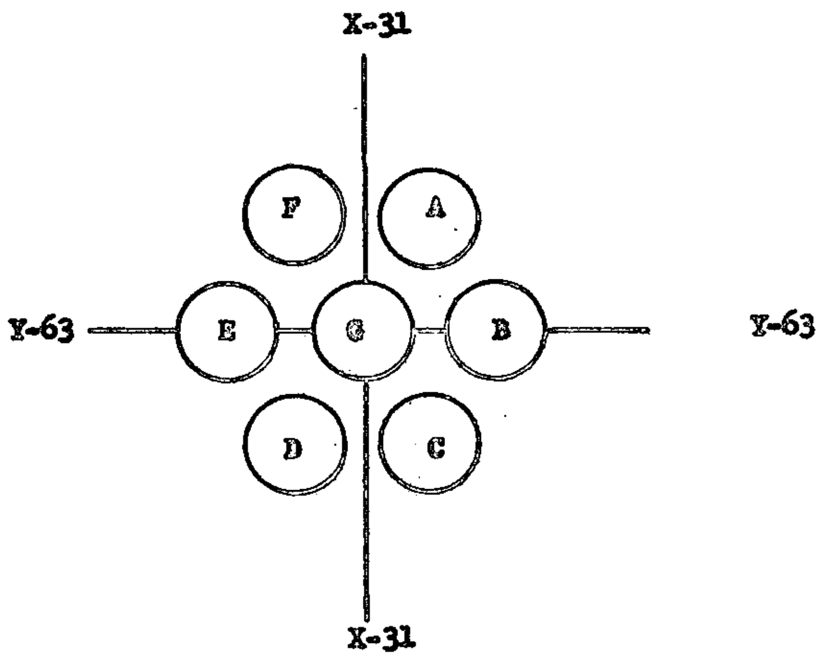
5. Baker, W. H., Analysis of Control Rod Withdrawal Tests. DPST-64-522, November 25, 1964 (Secret).

6. Clayton, J. D., Temperature Measurement for Rod Withdrawal Test. Memorandum to L. W. Fox, October 19, 1966.

[redacted]

Figure 1

Control Rods in Cluster 8
Prior to Rod Withdrawal



Channel	Control Rod
A	0.45 in. Cd. Full Rod (Test Rod)
B	0.35 in. Cd. Full Rod
C	Strong (0.35 in. Cd.) Partial Rod
D	Empty
E	0.27 in. Cd. Full Rod
F	Weak (Co) Partial Rod
G	Empty

Figure 2
Mark XII Relative Power Increase (%) Caused By Control Rod Withdrawal in Cluster 8 of K-14 Curium Charge

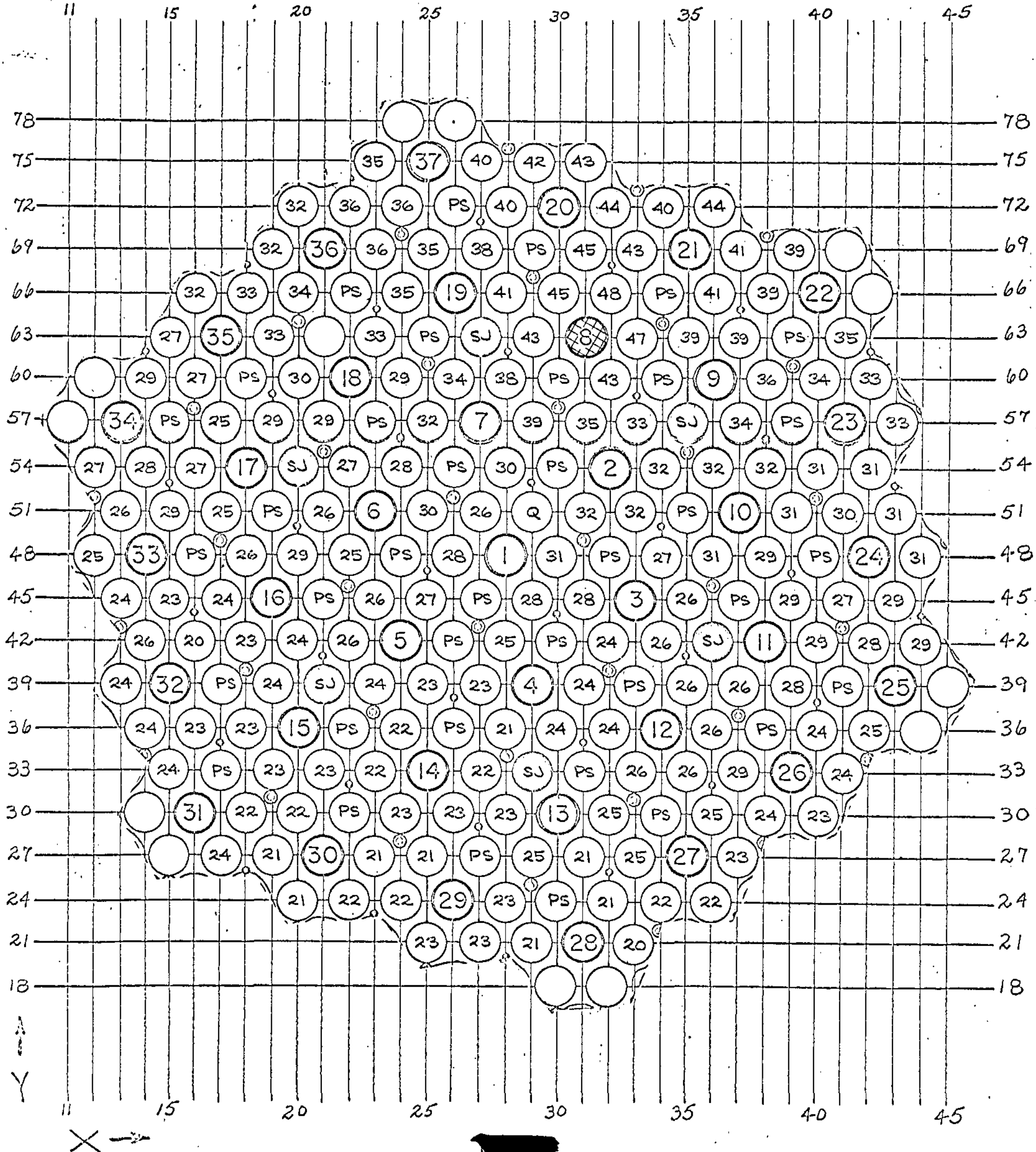
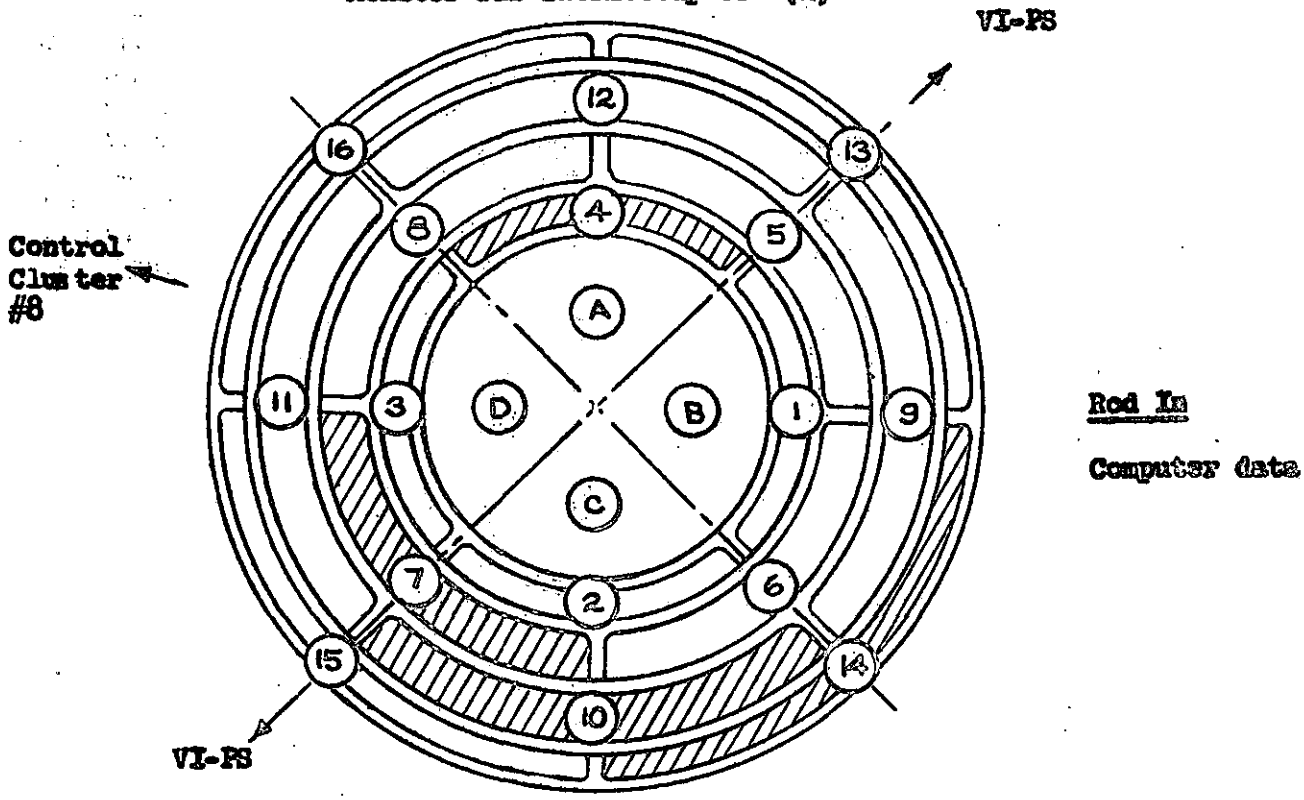


Figure 3
Location of Hottest Subchannel in Mark XII Thermocouple Assembly (Shaded)

Special Thermocouples (1) ...

Monitor Pin Thermocouples (A) ...



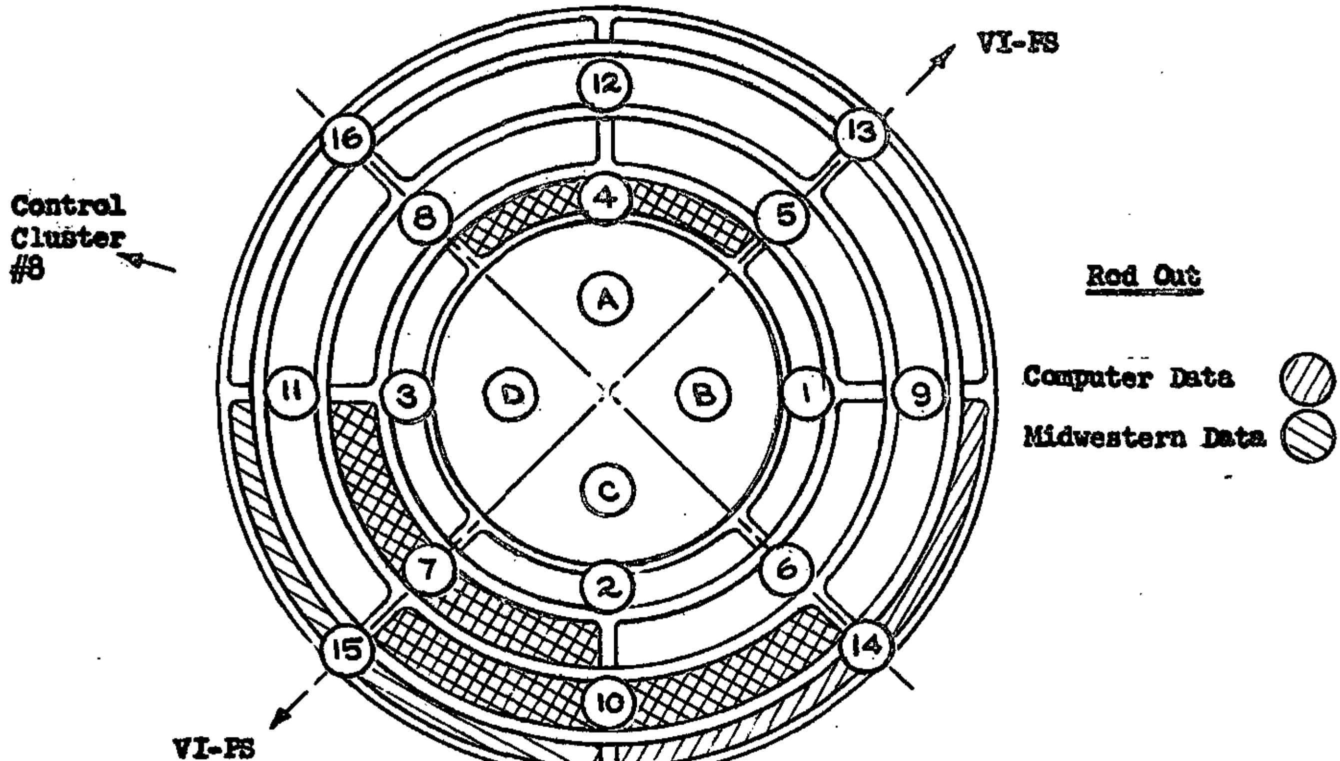


Table I

**Rod Withdrawal Test
Chronology
September 17, 1966**

Time	Reactor Power, MW	Comments
10:30 AM	1300	Normal power ascension to 85% SOP
10:45	1300	
11:00	1300	
11:15	1300	
11:30	1300	
11:45	1250	Reducing power to 60% prior to test
12:00	1050	
12:15 PM	930	
12:30	950	
12:45	950	
1:00	950	
1:15	950	
1:30	950	
1:35	950	Rod withdrawal begun
1:42		Rod withdrawal complete
1:45	1250	Data collection in progress
1:57		Rod reinsertion begun
2:00	1030	
2:03		Rod reinsertion complete
2:15	950	
2:30	950	
2:45	950	
3:00	950	
3:15	1160	Normal power ascension resumed. [redacted]

Table XI

Monitor Pin Thermocouple Response - Cluster 8

			ΔT from Computer, °C			ΔT from Aux. Recorder, °C		
Position[a]	Assy.	Pin TC	Rod In	Rod Out	Change	Rod In	Rod Out	Change
33-63	XII	A	30.5			30.0	45.5	15.5
		B	29.8			29.9	45.7	15.8
		C	29.0			28.2	43.4	15.2
		D	28.8			28.5	44.0	15.5
32-60	XII-TC[b]	A	29.3	41.4	12.1	25.6	38.2	12.6
		B	28.8	41.4	12.6	28.9	42.6	13.7
		C	30.3	43.8	13.5	30.2	45.0	14.8
		D	30.4	44.1	13.7	30.2	45.2	15.0
30-60	VI-FS	A	9.6			8.5	13.6	5.1
		B	7.9			7.1	11.2	4.1
		C	10.1			8.1	12.9	4.8
		D	9.1			0.0	0.0	0.0
29-63	XII-AM[c]	A	32.6			32.5	48.7	16.2
		B	33.5			34.2	50.2	16.0
		C	34.3			34.8	51.1	16.3
		D	28.8			28.8	42.2	13.4
30-66	XII	A	30.9			31.0	46.5	15.5
		B	30.8			31.1	47.1	16.0
		C	30.0			30.1	45.5	15.4
		D	30.2			30.2	45.2	15.0

Notes: (a) Response of Mark XII assembly in position 32-66 not recorded.

(b) Special thermocouple test assembly.

(c) Annular-monitored test assembly.

Table III

**Special Thermocouple Response
Mark XII Test Assembly in
Position 32-60**

Channel	TC	Temperature Rise (ΔT) °C — Computer: Rod In	Rod Out	Change	Midwestern Change[(a)]
Inner	1	23.2	34.5	11.4	14.1
	2	23.2	34.1	10.9	13.4
	3	26.6	39.5	12.9	13.2
	4	29.1	43.2	14.2	12.4
Small Intermediate	5	24.9	36.8	12.0	11.7
	6	27.1	39.5	12.4	9.3
	7	28.5	41.9	13.5	22.8
	8	26.4	38.7	12.3	9.7
Large Intermediate	9	24.9	37.1	12.2	15.0
	10	27.5	40.6	13.1	14.4
	11	25.3	38.5	13.2	13.5
	12	-	-	-	-
Outer	13	-	-	-	-
	14	26.3	38.0	11.7	9.0
	15	24.8	36.2	11.4	18.6
	16	21.6	34.2	12.6	9.0

Note: (a) Change of ΔT indicated by Midwestern recorder is corrected for 2.4 °C increase in inlet temperature caused by rod withdrawal.

[redacted]

Table IV

Hot Spot Factors and Hot Subchannel Factors in Mark XII Test Assembly in Position 32-60

Factor	Channel	Computer Rod In	Computer Rod Out	Midwestern Rod Out	Cycle Avg.[a] Rod In
Hot Spot Factor (H_t)	Inner	1.139	1.142	1.070	1.096
	Small Intermediate	1.066	1.069	1.279	1.065
	Large Intermediate	1.061	1.049	1.042	1.055
	Outer	1.087	1.052	1.192	1.054
Hot Subchannel Factor (HCF)	Inner	1.094	1.087	1.044	1.078
	Small Intermediate	1.073	1.055	1.290	1.089
	Large Intermediate	1.036	1.022	1.054	1.051
	Outer	≤ 1[b]	<1[b]	1.091	<1[b]

Notes: (a) Average factor at full reactor power during K-14 cycle (Reference 2).

(b) ΔT of hottest subchannel in outer channel was less than normalized ΔT of hottest monitor pin thermocouple.

[redacted]

Table V

High Level Flux Monitor Response (%)

HLFM	Rod In	Rod Out	Change
1	59.8	79.0	19.2
2	60.5	79.8	19.3
3	60.8	83.5	22.7
4	58.8	86.5	27.7

HLFM Locations

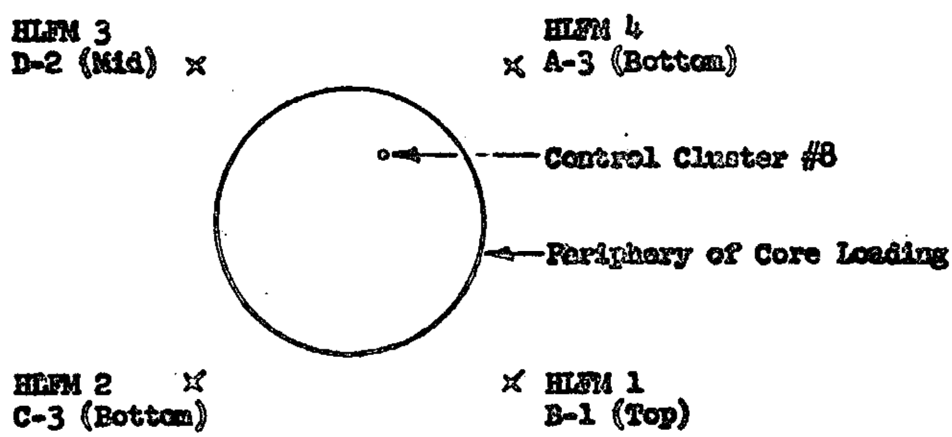


Table VI

Effect of Rod Withdrawal on Reactor Inlet and Effluent Temperatures

Temperature	System	Temperature, °C Rod In	Rod Out	Change
Plenum Inlet	1	29.0	30.9	1.9
	2	28.7	30.4	1.7
	3	29.0	30.4	1.4
	4	28.4	29.8	1.4
	5	27.7	29.2	1.5
	6	28.5	30.3	1.8
	Avg.	28.5	30.2	1.7
Reactor Effluent	1	54.0	64.1	10.1
	2	53.5	61.6	8.1
	3	52.1	59.7	7.6
	4	52.1	59.9	7.7
	5	53.2	61.8	8.6
	6	52.4	62.4	10.0
	Avg.	52.9	61.6	8.7

[redacted]