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REACTIVITY AND EFFICIENCY TRENDS VS.
OPERATING TRENDS FOR C, H, KE, AND KW REACTORS
1956 THROUGH 1960

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REACTIVITY AND EFFICIENCY TRENDS VS. OPERATING TRENDS
FOR C, H, KE, AND KW REACTORS - 1956 THROUGH 1960

INTRODUCTION

Changes in operation and corresponding changes in the reactivity status of Hanford reactors are the result of a continuing effort to improve operating efficiency. Trends data related to these changes in operation and reactivity have been published previously for the periods from 1950 through 1959. The purpose of this report is to include trends data for 1960. All included data were selected from the sources listed in references on page

Bar graphs in the first part of the report show yearly averages of selected data, and the line graphs in the second part show the interrelationship of some of the yearly averages depicted in the first part. The tables in Appendix I show maximum, average, and minimum values. This document presents trends data for C, H, KE, and KW reactors. A second document, HW-72855, presents trends data for B, D, IR, and F reactors.

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Page 2

Since splines have come into full-scale usage, the graphs showing the number of temporary poison columns used per startup requiring temporary poison are no longer applicable and have been excluded from this document.

Notice that all reactivity values are listed in the unit percent excess k.

SUMMARY AND CONCLUSIONS

The graphs indicate that in most instances, the trend in operating and reactivity variables leveled off some in 1960, thus tending to make accurate reactivity predictions more straightforward; increases in power levels, not shown in the graphs, did continue to complicate predictions. Because of increased usage of enrichment and supplemental poison to improve flattening, a trend toward more difficult predictions will probably continue. Prediction accuracy has not changed significantly in most cases in 1960. Maintaining prediction accuracy is in some part due to increased accuracy of metal and graphite temperature coefficient calculations and modifications in calculating techniques. Studies and data gathering to improve the accuracy of calculating these reactivity coefficients will continue.

Startup efficiency showed a marked improvement in the form of lower nonequilibrium losses. This improvement was due primarily to the increased use of poison splines.

DISCUSSION

The Shutdown Data Sheets, authored by the area physicists for the respective reactors, are essentially a running account of reactor startups, shutdowns, and the associated reactivity conditions; and were therefore the main source of data for this report. New methods of calculating some of the reactivity and operating variables have changed the average values of the respective variables significantly in some cases. However, these are noted and explained in the descriptive discussion accompanying each graph.

The graphs and tables in this report present summaries of information used in making criticality predictions and operational efficiency studies and for historical purposes. The data are not absolutely accurate but for the purpose here intended are quite adequate. The graphs are presented in the order given on the following page. References, appendix, and tables follow the graphs.

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Operational Physics Sub-Section
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TABLE OF CONTENTS

Part I

Page Number

I. OPERATING TRENDS

I-A	Uranium Discharge Size	4
I-B	Uranium Exposure Level	6
I-C	Effective Full Power Days	8
I-D	Operating Period Duration	10
I-E	Outage Duration	12
I-F	Total Outage Time	14
I-G	Number of Outages	16
I-H	Average ECT	18
I-I	Number of Scrams	20
I-J	Average Scram Recovery Time	22

II. TRENDS IN REACTIVITY VARIABLES

II-A	Reactivity in Control Rods	24
II-B	Reactivity from Temperature Coefficients	26
II-C	Reactivity in Flattening	28
II-D	Fringe Poison and Enrichment Columns	30
II-F	Enrichment Reactivity	32
II-G	Enrichment Discharged	34

III. STARTUP CRITICAL PREDICTION TRENDS

III-A	Startup Pile Periods	36
III-B	Average Prediction Error	38
III-C	Spread of Prediction Errors	40

IV. OPERATING EFFICIENCY TRENDS

IV-A	Nonequilibrium Losses per Startup	42
IV-B	Potential Equilibrium Gains	44

Part II

I. LINE GRAPHS

C	Reactor	47
H	Reactor	48
KE	Reactor	49
KW	Reactor	50
	Summary of Eight Reactors	51

PART I

I. OPERATING TRENDS

The first 10 graphs show variations in selected operating variables which directly or indirectly affect reactivity predictions and efficiency while operating.

I-A. Uranium Discharge Size

Figure I-A shows the average percent of the pile discharged per outage based on flux-squared reactivity weighting. Outages where no discharge was taken or where the size of the discharge was negligible were not considered in determining the averages given here. Note that reactivity weighted percentages are presented rather than the weight or number of tubes per outage; however, the values are very close to but slightly higher than weight or number of tubes per outage.

Longer operating periods increase the percent of the uranium reaching goal exposure and therefore the size of the discharge increases accordingly. It is significant that the discharge size has generally increased despite a marked increase in goal exposure which tends to reduce the effects of higher power levels and longer operating periods.

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FIGURE I-A - AVERAGE PERCENT OF PILE DISCHARGED EACH OUTAGE

I-B Uranium Exposure Level

The exposure level of discharged fuel is primarily a function of the established goals. For 1956 through 1958, the data shown are for natural uranium only, while for 1959 and 1960, exposure levels of enriched uranium were included with the natural uranium exposure levels to determine the average. The higher exposure with the I&E fuel element used as the primary production fuel element in 1959 and 1960 has reduced the operating reactivity loss associated with the transition from solid to I&E elements.

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FIGURE I-B - AVERAGE EXPOSURE OF DISCHARGED URANIUM

I-C. Effective Full Power Days

The value of effective full power days for 1956 is defined as annual pile production divided by the average pile power level at shutdown. For 1957 through 1960 the value was redefined as total number of days operated minus the annual nonequilibrium loss in equivalent equilibrium days. (The actual nonequilibrium losses are shown in Figure I-F.)

The 1957 value for H reactor reflects outage time for tube replacement and CG-558 (Water Plant Expansion) project. The values for KW in 1958 and for KE in 1959 reflect extended outages for RTD and gas seal replacements.

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FIGURE I-C - EFFECTIVE FULL POWER DAYS IN YEAR (SEE TEXT FOR DEFINITION)

I-D. Duration of Operating Period

This graph shows the average number of days of operation between outages for the respective reactors. The marked decrease in H pile values in 1960 was due mainly to an increase in rupture and water leak shutdowns. The increase in 1959 is the result of longer operating periods, which were made possible at least partly by high goal exposures and decreases in ruptures and spurious scrams. It is of note that the 1959 increase occurred concurrently with the full-pile loading of I&E fuel elements.

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HW-72856
Page 11

FIGURE I-D - AVERAGE NUMBER OF DAYS OPERATED BETWEEN OUTAGES

I-E. Duration of Outage

Figure I-E shows the average duration of outages in hours. The average does not include scrams or the extended outages listed in Appendix I. Notice the average outage time has decreased in all cases except H pile for 1960.

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FIGURE I-E - AVERAGE OUTAGE DURATION

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I-F. Figure I-F shows the total number of days down for the year. This includes the long outages in Appendix I but does not include the time down for scrams.

Nonequilibrium losses in equivalent equilibrium days are shown at the top of each bar graph for 1957 through 1960. The sum of outage time, non-equilibrium losses, and effective full power days (see Figure I-C) should be approximately equal to the number of days in the year. Since outage time for scrams was not included, the summation will be slightly less than the number of days in the year.

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FIGURE I-F - TOTAL TIME DOWN (NOT INCLUDING SCRAMS AND POISON DISCHARGE OUTAGES) AND TOTAL NONEQUILIBRIUM LOSSES

*Nonequilibrium losses

I-G. Number of Outages

The number of outages shown in Figure I-G is restricted to all outages of 10 or more hours duration in order to exclude scrams. The term "scrams" is used here to refer only to those outages where a recovery was made in less than 10 hours. Note the marked increase in H Pile's number of outages.

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Page 17

FIGURE I-G - NUMBER OF OUTAGES MORE THAN 10 HOURS DURATION

I-H. Average ECT

ECT (Effective Central Tubes) is defined as follows:

$$\text{ECT} = \frac{\text{Total reactor power in megawatts}}{\text{Total maximum tube power in megawatts*}}$$

*For the 10 most productive tubes in the reactor.

Values shown in Figure I-H for 1956 to 1958 are arithmetic averages of data presented in monthly Reactivity Balance Reports. Values for 1959 and 1960 are arithmetic averages of data included in Pile Physics Monthly Reports. Data from the Reactivity Balance Reports are best values for a given date, whereas data from the Pile Physics Monthly Reports are monthly average values for normal equilibrium operation. To give a more exact comparison, the annual averages from the Pile Physics Monthly Reports for the past four years are given below:

<u>Reactor</u>	<u>1957</u>	<u>1958</u>	<u>1959</u>	<u>1960</u>
C	1580	1600	1640	1697
H	1530	1580	1595	1625
KE	2400	2405	2445	2515
KW	2420	2420	2455	2495

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FIGURE I-H - AVERAGE EFFECTIVE CENTRAL TUBES

I-I. Number of Scrams

Figure I-I shows the total number of scrams per year whether recoveries were made or not. Available scram recovery time has decreased while operational difficulty following a scram recovery has increased as the result of higher pile power levels. Therefore, the reduction in number of scrams is particularly important to the maintenance of high operating efficiency.

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FIGURE I-I - NUMBER OF SCRAMS PER YEAR

I-J. Average Scram Recovery Time

Scram recovery time in this report refers to that amount of time after a scram (from equilibrium operating conditions) within which a recovery can be successfully accomplished before the pile goes subcritical. The general decrease in available scram recovery time has resulted from increased pile power levels.

Due to the negligible probability of recovering from an equilibrium scram and the risk involved, scram recoveries were discontinued at the K reactors early in 1959. Therefore, no values are given for the K reactors during 1959 and 1960.

The average values shown in the graphs were calculated from data submitted by the area physicists in their respective monthly reports.

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FIGURE I-J - AVERAGE SCRAM RECOVERY TIME

II. TRENDS IN REACTIVITY VARIABLES

This group of graphs shows the reactivity contributions of relevant variables, and also presents quantitative values of selected variables associated with the reactivity of a reactor.

II-A. Reactivity in Control Rods

Data in Figure II-A show the average reactivity in percent excess k , held in horizontal control rods just before shutdown. These data are based on the results of rod calibration tests. The most recent rod calibration test for C pile was in February 1958; for H pile in January 1957; and for K piles in May 1957 at KW. Compared to original calibrations the latest calibrations showed that horizontal rods absorbed approximately 40 per cent more reactivity at C pile, approximately 65 per cent more at H pile, and approximately the same at the K piles.

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FIGURE II-A - AVERAGE REACTIVITY HELD IN RODS AT SHUTDOWN

II-B. Reactivity from Temperature Coefficients

Figure II-B shows the average reactivity contribution from the over-all effect of metal and graphite heating. The over-all reactivity of the temperature coefficients is obtained by algebraically summing a negative metal temperature effect and a positive graphite temperature effect of a reactor just before shutdown. The relatively higher values for 1959 and 1960 are the result of higher pile power levels, higher uranium fuel exposures (in 1959) for the pile and the smaller negative uranium temperature coefficient of I&E fuel elements compared to solid fuel elements.

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FIGURE II-B - AVERAGE VALUE OF REACTIVITY FROM OVER-ALL TEMPERATURE COEFFICIENT

II-C. Reactivity Absorbed by Flattening

Figure II-C shows average effective reactivity absorbed by non-power tubes in the respective reactors. Fringe poison tubes for shield protection at H Reactor were excluded; all other non-power tubes were included. Special irradiations tubes and tubes out of service pending replacement absorbed a portion of the reactivity included here.

The relatively high values for H pile reflect use of the PCCF to absorb long-term reactivity gains which accompany long periods of operation at high power levels. Since C and the K piles do not have the PCCF, needed flattening flexibility is provided by the horizontal control rods and poison splines.

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FIGURE II-C - AVERAGE REACTIVITY ABSORBED BY FLATTENING AND OTHER NONURANIUM COLUMNS IN PILE

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HT-72856
29

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II-D. Fringe Poison Columns and Compensating Enrichment

Biological shield damage at H reactor increased with higher pile power levels. To reduce shield temperature and thus prolong the life of the shield, fringe poison columns were introduced. Enrichment columns were also charged to compensate for the reactivity loss associated with the fringe poison.

This graph shows the average numbers of fringe poison columns and compensating enrichment columns for H pile beginning with their charge dates in 1957 through the end of the year and the annual averages for 1958, 1959 and 1960.

C pile and the K piles have water-cooled biological shields and consequently do not need fringe poison for shield protection.

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FIGURE II-D - FRINGE POISON COLUMNS AND COMPENSATING ENRICHMENT

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II-F. Enrichment Reactivity

Figure II-E shows average monthly reactivity inventories of enrichment in the respective reactors. Most of this enrichment was in the form of natural uranium enriched with U-235 (E-metal). During 1956 and 1957, however, part of the enrichment was in the form of U-235 - Aluminum alloy (C-metal). By the end of 1957 essentially all of the "C" columns were replaced by "E" columns. Reactivity-wise, one "C" column is equal to about 3 "E" columns.

In-pile inventories of enrichment were increased to compensate for decreases in pile reactivity associated with the change-over from solid to I&E fuel elements in 1957 and 1958.

Values for 1959 reflect use of the one-group diffusion theory as described in HW-60439/9/ for enrichment evaluation during the last half of 1959. The flux-squared weighting method used previously, although still valid for determining small changes in reactivity it overevaluates the reactivity effect of the large amounts of radial enrichment at C, H, KE, and KW reactors.

The graphs for 1960 are divided into two parts; the top of each bar signifying "spike" enrichment and the bottom of each bar depicting "E" ring enrichment.

NOTE: This graph does not include enrichment charged for fringe poison compensation (see Figure II-D).

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HW-72856
Page 33

FIGURE II-F - AVERAGE ENRICHMENT REACTIVITY - EXCLUDING FRINGE POISON COMPENSATION

II-G. Enrichment Discharged

This figure shows the total number of enrichment columns discharged per year including fringe enrichment and production test enrichment. "E" columns were not charged in significant quantity until 1957 and it was not until 1958 that all "C" columns were replaced with "E" columns. With the elimination of "C" columns came an increase in enrichment throughput since a "C" column is three times as strong as an "E" column and can remain in the pile three times as long and is therefore essentially equal to nine "E" columns.

The high value for C pile for 1957 reflects enrichment columns used in production tests.

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FIGURE II-G - TOTAL NUMBER OF ENRICHMENT COLUMNS DISCHARGED EACH YEAR

III. STARTUP CRITICAL PREDICTION TRENDS

The graphs in this section, except for Figure III-A, show the trend in criticality prediction accuracy. Predictions are based on the ability to calculate the reactivity of the pile when startups are being attempted. Reactivity calculating methods are included in the Discussion for III-B.

III-A. Startup Pile Periods

Figure III-A shows the average magnitude of reported startup periods in reactivity units of percent excess k.

It is desirable to maintain a reasonably slow rising period for cold startups, and therefore the average value of the rising periods should not be increasing or decreasing as pile power level, exposure, outage time or any other related factor varies. Prediction accuracy and instrument sensitivity are two main factors which provide greatest assurance of starting up on a reasonable rising period; improvements in both have permitted less conservative rod withdrawal procedures. This, combined with the use of subcritical monitoring, should show a continued trend to leveling out of the average startup period.

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HW-72856

Page 37

FIGURE III-A - AVERAGE COLD STARTUP RISING PERIOD

III-B. Average Prediction Error

Startup reactivity can be calculated either as a difference between the hot operating reactivity preceding shutdown and the cold reactivity after shutdown, or as the change in cold reactivity from startup to startup. Calculated differences by the first method are large and highly sensitive to exposure, whereas the calculated changes by the second method are relatively small and independent of exposure. Since the dependence on exposure (with its associated inherent uncertainties) is essentially eliminated from the calculation, the results by the second method should be more reliable. This method has been used increasingly through 1959 and 1960.

Figure III-B shows the arithmetic average of prediction errors that were reported in the Shutdown Data Sheets (2-3). Large negative errors caused by excessive water in the pile from tube leaks were not included since it is virtually impossible to evaluate in advance the reactivity loss caused by the water.

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FIGURE III-B - ARITHMETIC AVERAGE OF PREDICTION ERRORS

III-C. Spread of Prediction Error

This graph shows the scatter of prediction errors about zero. The values are determined by the root mean square method, which is as follows:

$$\text{Root Mean Square} = \sqrt{\frac{\sum_{i=1}^N E_i^2}{N}}$$

Where E is the magnitude of the prediction error and N = total number of predictions made. Large negative errors caused by excessive water (from leaking process tubes) in the moderator were not included in the averages.

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FIGURE III-C - ROOT MEAN SQUARE VALUE OF PREDICTION ERRORS

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IV. OPERATING EFFICIENCY TRENDS

The graphs in this section indicate the trend of startup efficiency and flattening efficiency as shown by nonequilibrium losses and potential equilibrium gains respectively. These data were not routinely collected until late 1956 and are therefore not shown for 1956.

IV-A. Nonequilibrium Losses per Startup

Nonequilibrium losses can be simply defined as the number of days of full production lost because the pile could not be started up to full power level immediately. Thus one day of nonequilibrium loss as defined here is equivalent in production lost to one full day of shut-down time.

The increase in nonequilibrium losses in 1959 is the result of higher pile power levels and longer periods of transient operation. The marked decrease in nonequilibrium losses in 1960 reflects the increased use of poison splines for supplementary control.

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FIGURE IV-A - AVERAGE NONEQUILIBRIUM LOSS PER STARTUP

IV-B. Potential Equilibrium Gains

The data in Figure IV-B for 1957 through 1959 are based on analyses of temperature maps where a flattened zone is assumed for the respective reactor and the difference between the observed flattening and theoretical flattening is called the potential equilibrium gains. In other words, it is the gain in power level which could be achieved with perfect flattening flexibility in the central zone. Reactivity changes can adjust the relative level of fairly small groups of tubes in respect to other groups of tubes but still have little effect on the relative difference in powers between tubes within one to three lattice units of each other. This theory was applied in the analysis of temperature maps to find the potential gains.

The average results from temperature map analyses were found to be low in comparison to more exact analyses of tube power data found on factor maps. The values for 1960 reflect the use of zoned factor maps instead of temperature maps for calculation of potential gains. The size of the zones was taken to be approximately the size of the region controlled by a spline - about six to seven tubes square.

The bottom portion of the bar gives the average values calculated from zoned factor maps. The entire bar gives the potential gains if the entire flattened zone operates at the same tube power.

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FIGURE IV-B - AVERAGE POTENTIAL EQUILIBRIUM GAIN PER OPERATING PERIOD

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Part II

LINE GRAPHS

The first four of the following five figures depict the inter-relationship between theoretical potential gains, gains by control zones, monthly average effective central tubes, and nonequilibrium loss averages by month.* The 1959 and 1960 averages for effective central tubes and nonequilibrium losses for the respective reactors are shown at the left of each graph.

The fifth figure shows the over-all average values for all eight reactors. The values for KE and KW reactors for these averages were counted twice since their production is approximately double that of each of the other six reactors. The over-all 1959 and 1960 averages for ECT and NEL are shown at the left of the graph.

*NOTE: For further explanation of values, refer to the respective bar graph explanatory notes in Part I.

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KW Reactor

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All references listed on page 48 of HW-64933 plus Shutdown Data Sheets for each reactor:
C - HW-62999; H - HW-63004; KE - HW-63005; KW - HW-63006.

1. HW-63753B - "Monthly Record Report, Irradiation Processing Department, Research and Engineering," O. H. Greager, January, 1960
2. HW-64122B - "Monthly Record Report, Irradiation Processing Department, Research and Engineering," O. H. Greager, February, 1960
3. HW-64555B - "Monthly Record Report, Irradiation Processing Department, Research and Engineering," O. H. Greager, March, 1960
4. HW-65013B - "Monthly Record Report, Irradiation Processing Department, Research and Engineering," O. H. Greager, April, 1960
5. HW-65527B - "Monthly Record Report, Irradiation Processing Department, Research and Engineering," O. H. Greager, May, 1960
6. HW-65924B - "Monthly Record Report, Irradiation Processing Department, Research and Engineering," O. H. Greager, June, 1960
7. HW-66296B - "Monthly Record Report, Irradiation Processing Department, Research and Engineering," O. H. Greager, July, 1960
8. HW-66685B - "Monthly Record Report, Irradiation Processing Department, Research and Engineering," O. F. Greager, August, 1960
9. HW-66970B - "Monthly Record Report, Irradiation Processing Department, Research and Engineering," O. H. Greager, September, 1960
10. HW-67286B - "Monthly Record Report, Irradiation Processing Department, Research and Engineering," O. H. Greager, October, 1960
11. HW-67681B - "Monthly Record Report, Irradiation Processing Department, Research and Engineering," O. H. Greager, November, 1960
12. HW-68039B - "Monthly Record Report, Irradiation Processing Department, Research and Engineering," O. H. Greager, December, 1960

APPENDIX I

LIST OF LONG OUTAGES NOT INCLUDED IN OTHER LISTINGS

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C Pile

Except for 1955 outages, all outages for C pile listed on page 49 of HW-64932, plus:

February, 1960	63.75	Stuck rupture
April, 1960	147.7	Scheduled maintenance
September, 1960	101.11	Scheduled outage
October, 1960	106.57	Scheduled outage
November, 1960	88.333	Rupture
December, 1960	113.333	Scheduled outage

H Pile

Except for 1955 outages, all outages for H pile listed on page 49 of HW-64932, plus:

March, 1960	67.15	Water leak
March, 1960	84.217	Rupture removal
June, 1960	156	Tube replacement and Ball 3X work
July, 1960	72.67	Rupture removal
August, 1960	95.53	Rupture removal
October, 1960	165	Scheduled outage

KE Pile

Except for 1955 outages, all outages listed for KW pile on page 50 of HW-64932, plus:

July, 1960	73.90	Rupture and maintenance work
November, 1960	71.38	Rupture and maintenance work

KW Pile

Except for 1955 outages, all outages listed for KW pile on page 50 of HW-64932, plus:

February, 1960	61.4	Rupture
March, 1960	64.8	Rupture
July, 1960	70.2	Rupture, charge-discharge and maintenance
November, 1960	71	Rupture and maintenance

Refer to HW-64932, pages 51, 52, 53, 54 for data for the years 1955, 1956, 1957, 1958, and 1959 of maximum, average, minimum values. Following is the maximum, average, minimum values for 1960.

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HW-72856
Page 54

TABLE OF MAXIMUM - AVERAGE - MINIMUM VALUES

CALENDAR YEAR REACTOR		1960			
		C	H	KE	KW
Uranium Discharge	Max.	50.48	81.56	39.3	46.8
Size in Per	Avg.	17.2	13.6	16.3	22.3
Cent of Pile	Min.	6.0	2.82	5.3	4.4
Uranium Exposure	Max.	759	862	722	720
Level in Megawatt	Avg.	628	674	667	678
Days Per Ton	Min.	456	539	539	629
Effective Full Power Days ^{/1/}		281.4	278.5	293.1	207.3
Duration of	Max.	30	28	25	33
Operating Period	Avg.	9.5	9.06	8.75	13.65
in Days	Min.	1	1	1	1
Duration of Outage	Max.	60.43	58.1	58.583	60.17
in Hours ^{/2/}	Avg.	36.3	38.1	37.8	40.2
	Min.	15.65	26.33	24.217	20.5
Total Outage Time ^{/3/}		72.98	82.78	65.96	59.25
Number of Outages ^{/3/}		33	35	35	26
Reactivity in Control	Max.	1.342	1.420	1.011	.946
Rods in Per Cent	Avg.	.963	1.038	.738	.862
Excess k	Min.	.320	.340	.613	.778
Reactivity from	Max.		1.491	1.423	1.268
Temp. Coefficients	Avg.	1.517	1.294	.997	1.027
in Per Cent Excess k	Min.		1.016	.552	.869
Flattening Reactivity	Max.		1.471	.815	.489
in Per Cent Excess k	Avg.	.153	.941	.309	.213
	Min.		.743	.127	.009
Enrichment Reactivity in	Max.	<u>1.58</u>	<u>1.70</u>	<u>.840</u>	<u>1.053</u>
Per Cent Excess k ^{/4/}		.583	.080	.502	.509
	Avg.	<u>1.24</u>	<u>1.22</u>	<u>.74</u>	<u>.92</u>
		.49	.04	.44	.43
	Min.	<u>1.87</u>	<u>.848</u>	<u>.63</u>	<u>.856</u>
		.404	.02	.32	.330
Pile Period at Startup	Max.	.125	.157	.114	.130
in Per Cent Excess k	Avg.	.079	.079	.054	.065
	Min.	.016	.047	.024	.034

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TABLE OF MAXIMUM - AVERAGE - MINIMUM VALUES
(Continued)

CALENDAR YEAR REACTOR		1960			
		C	H	KE	KW
Prediction (+/-) Error in Per Cent Excess k	Max.	.186	.700	.364	.336
	Avg.	.005	-.021	.021	.029
	Min.	-.171	-.360	-.147	-.187
RMS Prediction Error		.085	.232	.111	.152
Nonequilibrium Loss in Equivalent Equilibrium Days/57	Max.	1.0392	.611	1.4150	.996
	Avg.	.404	.321	.330	.366
	Min.	.1605	.147	.1130	.150
Equilibrium Gain in Per Cent Equilibrium Power Level/67	Max.	$\frac{13.2}{5.6}$	$\frac{13.7}{6.6}$	$\frac{11.1}{5.7}$	$\frac{13.7}{7.3}$
	Avg.	$\frac{8.40}{3.26}$	$\frac{10.43}{3.351}$	$\frac{8.98}{3.35}$	$\frac{10.50}{4.68}$
	Min.	$\frac{6.7}{2.6}$	$\frac{9.0}{2.3}$	$\frac{6.9}{2.2}$	$\frac{8.5}{2.3}$

DATE

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7/15/94

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