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ATTENUATION EFFECTIVENESS OF THE HANFORD REACTOR IRON MASONITE SHIELDS

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ATTENUATION EFFECTIVENESS OF THE HANFORD REACTOR
IRON MASONITE SHIELDS

INTRODUCTION

The masonite in the iron-masonite biological shields of the Hanford reactors is deteriorating with time due to the removal of the hydrogen from it. It has been shown that the rate of masonite deterioration increases rapidly with increases in the temperature to which it is subjected; 1/ deterioration of masonite due to radiation damage effects in the Hanford shields is a much smaller factor. The result of this loss of moderating material from the shield is an increase in the radiation leakage through the shield in excess of that due simply to higher power levels. 2/

In order to determine deterioration rates and the dependence of these rates upon temperature conditions, shield monitoring facilities were installed during the CG-558 outages in 1956 and 1957 at the B, D, DR, F, and H reactors. In the far side shields thermocouples were placed for measuring the temperatures of the various shield layers, and foil activation equipment was constructed for measuring the neutron flux leaking out through the bulk shield. Thermocouples were also installed in the

/1/ "Hanford Shield Masonite Deterioration Studies," HW-35202 (), L. A. Wilson, 8-8-55.

/2/ "The Effect of Masonite Burnout on Shield Attenuation Properties," HW-38418 (), W. L. Bunch, 5-23-56.

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INTRODUCTION (Continued)

top shields of these reactors at this time. Thermocouples were originally installed in the C reactor shields.

Status reports on the iron masonite shield attenuation characteristics have been issued following CG-558 project completion./3,4/ This report up-dates information based upon shield temperatures and neutron leakages measured at these reactors during the past three years to show:

1. Observed deterioration rates to date.
2. Present and predicted attenuation effectiveness of the iron-masonite shields.

(The top shield at the C reactor and all of the K reactor biological shields are constructed of concrete and are, therefore, not considered here.)

CONCLUSIONS

// For anticipated conditions of reactor operation during the next ten years radioactive leakage escaping the reactor shields will not present any significant problems. However, the rate of increase in leakage through the top shields will be such that in subsequent years additional measures will be required for protection of personnel around the areas adjacent to the tops of some of the reactors. (See Figure 1.)

/3/ "Interim Report No. I, Development Test - IP-102-C, Biological Shield Data - Use of Neutron Detector Facility," HW-54358 (██████), W. L. Bunch, 1-3-58.

/4/ "Biological Shield Data - Use of Neutron Detector Facility, Interim Report Number II, Development Test IP-102-C," HW-57373 (██████), W. L. Bunch, 8-29-58.

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FIGURE 1
TEN YEAR PREDICTION OF NEUTRON LEAKAGE RATES
FOR TWO SELECTED SHIELD CASES

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SUMMARY

Neutron flux leakage through the far side shields of the five old reactors has been measured routinely during the past two to three years. Also the operating temperatures of the various shield layers at these locations as well as in the C reactor far side shield have been taken routinely during this period. The leakage increased rates and the approximate maximum operating temperatures were found to be:

Maximum Side "B" Shield Temperatures and Normalized Leakage Increases

<u>Reactor</u>	<u>Maximum Temperature</u>	<u>Neutron Leakage</u>
F	130°C	57 per cent increase in 2 years
H	120°C	35 per cent increase in 2-1/2 years
B, D, DR	110°C or less	No significant increase
C	125°C	No data

The above data would seem to indicate a very simple relationship between maximum shield temperatures and neutron leakage rates. Actually, however, it is difficult to associate a particular leakage increase rate with a given shield temperature. The shield operating temperatures have varied considerably at times from those shown above, and the major part of the deterioration taking place is in the innermost masonite layers. Also measurements under constant conditions of neutron leakages have not continued for a period long enough to establish definite trend values.

Thermal deterioration has previously been demonstrated to be exponential with temperature precluding existence of a damage "threshold." However, the above results do indicate that at a maximum side-shield operating temperature of about 110°C masonite burnout rates have an insignificant effect on iron-masonite shield attenuation properties and that at temperatures greater than about 110°C masonite deterioration sufficient to reduce shield attenuation properties noticeably is to be expected. A facility for measuring neutron leakage through the top bulk shield is currently planned for installation at the F reactor; however, no such data have been available in the past. It would be expected, though, that damage rates would become evident in the top shields at approximately the same temperature (110°C) as in the side shield. Top shield deterioration rates will increase faster with increases in maximum operating temperatures because of radiation streaming through the VSR penetrations causing a greater depth of the top shield to be near the maximum biological shield temperature.

The present attenuation effectiveness of the shields and that predicted for the coming ten years is as follows (the predictions are based upon certain assumptions outlined in the discussion section of this report):

1. Far Side Shields

The following absolute dose-rate values have been computed corresponding to measured neutron leakage through the H reactor far side shield. These numbers are believed to represent the right order of magnitude for all of the six old reactors:

SUMMARY (Continued)

<u>Neutron Leakage - H Reactor Far Side</u> <u>1700 MW Power Level</u>	
<u>Neutron Energy</u>	<u>Dose Rate</u>
Thermal	.06 mrem
Intermediate	.06
Fast	.40
Total	.52 mrem

In all cases for the next ten years the far side shield temperatures can be held to a maximum of 130°C or less by the use of fringe poison loadings in row #96. At this rate the leakage from these shields will not increase by more than about a factor of ten in the ten-year period.

2. Near Side Shields

Deterioration of the near side shields, which have not been protected to date by fringe poison, is estimated to have been less than that of the far sides at the B, C, D, DR, and F reactors and about the same as that of the far side at the H reactor. Over all the neutron leakage through the near side bulk shields is at present considered to be insignificant in relation to the leakage through the HCR penetrations.

A larger leakage can be tolerated through the near side because of the additional shielding afforded by the inner rod room walls. However, some fringe poison protection will be required for the near side shields during the next ten years.

3. Top Shields

At the B, D, DR, and F reactors the operating temperatures of the top shields have been somewhat higher than those of the side shields; therefore, the deterioration rates of the top shields have probably been from three to four times those of the side shields. Due to the high operating temperatures of the H reactor top shield it has probably, over the past three years, suffered a burnout rate on the order of five times that of the other top shields. Even so the neutron leakage through any of the top bulk shields is considered to be small compared to the leakage through the VSR penetrations (estimated 10 mrem through the H pile top shield bulk as compared with an average of about 250 mrem due to leakage around the VSR's).

For the next ten years the D and F reactor top shields can be held to maximum temperatures of 130°C or less by use of a fringe poison blanket. However, with a full blanket of fringe poison in row #46 the maximum temperatures may reach 140°C in the B top shield and 150°C in the DR and H top shields. These temperatures indicate a possible increase in bulk neutron leakage, normalized to constant power, of a factor of ten for D and F, a factor of 30 for B, and a factor of 100 for DR and H over the ten year period. This means that ten years from now at the top of the DR and H reactors the component of neutron dose due to bulk shield leakage will perhaps exceed that component due to leakage out through the VSR channels.

SUMMARY (Continued)

Projecting these higher top shield burnout rates to subsequent years clearly points out the desirability for conservatism in establishing maximum allowable shield temperatures and for aggressive administration of the fringe poison program for shield protection.

4. Inlet and Outlet Shields

The inlet and outlet shields operate at temperatures approximately that of the water in the process tubes which penetrate them. The inlet shields, therefore, run at relatively very low temperatures. The outlet shields with maximum operating temperatures in the range of 90 to 100°C are estimated to suffer deterioration of the same order of magnitude as the side shields at maximum temperatures of 130°C. During the next ten years the neutron leakage through the outlet shields will not become large enough to create problems due to activation of components in the discharge area and the leakage of radioactivity through these shields will not be large enough to cause problems of personnel exposure outside the secondary shielding walls.

DISCUSSIONA. Background

The attenuation effectiveness of the iron-masonite shields in the Hanford reactors is being reduced with time due to the loss of hydrogen from the masonite. The causes of masonite deterioration and the methods used in measuring deterioration effects are discussed in two previous reports./3,4/

It is shown in reference No. 4 that the increase in normalized neutron flux leakage through an iron-masonite shield during an operating period of t days at a fixed temperature distribution may be determined by the relation:

$$(1) \quad L = L_0 e^{bt}$$

where L_0 = original normalized leakage rate

L = final normalized leakage rate

$$b = (\mu_b x_b / 6) A \sum_{i=1}^6 \exp - B/T$$

and μ_b = attenuation coefficient of the masonite

x_b = total masonite thickness

A and B = constants determined by out-of-pile experiments

T = operating temperature of i^{th} masonite layer in K°.

The above expression considers only temperature as the deterioration parameter, since the effects of radiation damage in the Hanford shield are relatively small.

It is also shown in reference No. 4 that the exponential increase in shield neutron leakage should be reflected in the count rate of a foil activated in a neutron detector facility, the increase in count rate being expressed by:

$$(2) \quad R = R_0 e^{at}$$

where R_0 = original normalized count rate

DISCUSSION (Continued)

R = final normalized count rate

t = time in days

$$a = (\mu_b x_b / 6) A^* \sum_{1}^6 \exp - B/T$$

If a in equation (2) is the same as b in equation (1) then the value of A* determined by the foil data substantiates the value for A as determined by Wilson's out-of-pile data (Wilson computed A = 3730). If a ≠ b and the constant B is assumed to be correct, the empirical foil data can be used to evaluate A* by the relation

$$(3) \quad A^* = (a/b) A = (a/b) 3730$$

In other words, the measured rate of increase of neutron leakage can be used to re-evaluate the rate predicted as a function of shield temperature based on the out-of-pile data.

B. Source of Neutron Leakage Data

The neutron detector facilities mentioned above were installed in the far side shields of the B, D, DR, F, and H reactors during the CG-558 outages. They provide a means of measuring neutron leakage through the bulk shield by the method of foil activation. At this time thermocouples were placed in these same shields to allow measurement of operating temperatures of each steel layer in the shield. (The temperature of a particular masonite layer is then taken as the average of the temperatures of the two adjacent steel layers.) Sketches of the neutron and temperature detection facilities are shown in Figures 16 and 17. With this equipment routine neutron leakage and shield temperature data have been taken by the processing groups during the past two to three years.

Charts 1 through 5 show the normalized count rates of the gold foils irradiated in the neutron detector facilities of the B, D, DR, F, and H reactors plotted against the power days (days in which production exceeds 1000 MW) for those reactors. The sets of data are fitted with curves by the least squares method, the solid line indicating the best fit to the data and the dotted lines showing the 90 per cent confidence limits of the slope. The vertical bars indicate the 90 per cent confidence limits of the intercept. Also plotted on these charts are some of the highest temperatures reached by the masonite in the reactor far side shields during this period.

C. Discussion of Observations to Date1. B Reactor

Referring to chart No. 1 one might infer that the B reactor shield was improving with age. However, such a situation is not believed plausible. It can, however, be concluded from the available data that there has been no significant leakage change due to deterioration of this shield and that the apparent slight increase in neutron attenuating properties can be attributed to inaccuracies in the data and/or the methods of analysis. Note that the highest recorded operating temperatures of the masonite in

DISCUSSION (Continued)

this shield have been about 110°C since the charging of fringe poison was accomplished in March, 1957. The original far side fringe poison loadings consisted of nine tubes of depleted uranium. This material had reached goal concentration and was replaced with five tubes of mint in July, 1959. Since shield leakage trends are meaningful only for constant fringe column loadings, only the data recorded for the period between these two loading changes were used in the analysis.

2. D Reactor

From the D reactor plot shown on chart No. 2 one might also falsely infer improved attenuation with time. Here again it is assumed that no significant deterioration has occurred to the shield and that the statistical limits of the data at the low counting rates involved are too wide to draw any conclusions on trends. The highest recorded operating temperatures of the masonite in this shield have also been about 110°C. In this case, however, these relatively low temperatures were experienced without the use of fringe poison protection; the D reactor is the only one of the five older piles that does not contain fringe poison in the far side and top at the present time.

3. DR Reactor

Much of the foil count data taken at the DR reactor is seen on chart No. 3 to be badly scattered. This effect has been attributed to scattered neutrons originating at the neutron spectrometer which is located above the neutron detector facility. A series of fairly consistent data was taken at DR during the period from December, 1958 to May, 1959; this interval was used in evaluating a leakage trend for that reactor. No significant increase in neutron leakage was noted for this period, the leakage trend line being almost exactly horizontal. No foil data have been taken at DR since May, 1959, as installation of the gas-loop facility has permanently blocked access to the neutron detector facility. Again in this case the maximum recorded masonite temperature in the side shield has been about 110°C.

4. F Reactor

Data taken at the F reactor are shown on chart No. 4. Here the neutron leakage trend has a definite upward slope showing an increase in average leakage of approximately 57 per cent during the approximate two-year period for which data are available; no foil data were taken at F during the period from September, 1959 to January, 1960 because of the presence of a high background of scattered neutrons at the X-level location. (This leakage problem has since been corrected.) It is interesting to observe that in this case the maximum recorded masonite temperatures for this side shield have been about 130°C. The first portions of fringe poison blankets for the far side and top F reactor shields were charged in December, 1959.

5. H Reactor

Chart No. 5 shows that at H reactor there has been a significant and consistent trend of increased leakage through the far side shield. Here the average

DISCUSSION (Continued)

neutron leakage has increased by about 35 per cent in approximately two and one-half years. During this time the maximum recorded masonite temperatures were in the range of 120°C.

It was decided during 1959 to charge some extra fringe poison columns in row #96 at H pile because:

- a. The maximum operating temperature of the far side shield had been relatively high.
- b. There is additional incentive for maintaining this shield in good condition as there are personnel working on the X-1 level a large portion of the time.

The data have, therefore, been analyzed in two portions covering periods during which the conditions of shield protection were constant.

D. Present and Predicted Future Attenuation Effectiveness of the Iron-Masonite Shields

1. Assumptions

For the iron-masonite shields the present attenuation properties and those predicted for the next ten years are discussed below. The predictions are based upon the following assumptions:

- a. Shield burnout would be governed by a temperature dependent deterioration factor which has been evaluated from the accumulated shield temperature and neutron leakage data from the F reactor, this being the worst case observed to date. Using equation (3) and substituting the values for a and b as determined from the F pile data, the value of the deterioration factor was found to be

$$A^* = 1930$$

- b. The six older reactors would operate at current power levels for the next two years, at 120 per cent of current levels for the following two years, and at 150 per cent of current levels for the next six years.
- c. The helium concentrations in these reactor atmospheres would be maintained at percentages at least as high as those of December, 1960.

2. Expected Deterioration Rates

The following discussion of attenuation characteristics will divide the shields of the B, D, DR, F, and H reactors into four groups:

a. Far Side Shields

The neutron detector facility at the H reactor was used during November and December, 1959, to evaluate the absolute neutron

DISCUSSION (Continued)

leakage through the H pile far side bulk shield. This was done by irradiating two bare gold foils, one cadmium covered gold foil, and six sulphur wafers in the third (from the inside) slot of the foil holder during an operating period of about three weeks duration. The average neutron flux was then computed for this location by E. G. Peterson, Hanford Laboratories Shielding Engineer, using counting equipment calibrated to absolute values to measure the activities of the above materials and then using that data as input to an IBM-709 program for calculating fluxes. The resulting flux values along with the corresponding biological dose values are listed in Table #1. (The average neutron energies were taken as 0.025 ev for thermal, 0.24 ev for resonance and 0.13 Mev for fast neutrons. Conversion ratios developed by Snyder and Neufeld /5/ were used between flux and dose.)

Table No. 1

Neutron Leakage Measured in H Reactor Neutron Detector Facility

	<u>Flux in Neutrons/ cm²/sec/MW</u>	<u>Biological Dose mrem/1700 MW</u>
Thermal neutrons	9.44×10^{-2}	0.60
Intermediate neutrons	9.46×10^{-2}	0.64
Fast neutrons	1.20×10^{-2}	0.80

These values were taken at a position about six inches into the shield from the outside surface. Extrapolating to the outside of the shield we would expect these thermal and resonance fluxes to be reduced by about a factor of ten and the fast flux to be reduced by at least a factor of two. Flux leakage computed in this manner at the outside surface of the shield is shown in Table No. 2.

Table No. 2

Approximate Neutron Leakage Through H Reactor Far Side Bulk Shield Power Level - 1700 MW

Thermal neutrons	0.06 mrem
Intermediate neutrons	0.06 mrem
Fast neutrons	0.40 mrem
Total neutrons	0.52 mrem

The count rates of these materials - particularly the sulphur - were not appreciably above background; thus accuracy of the calculations may be limited. However, the numbers are believed to represent the right order of magnitude for the side shields of all of the six old reactors.

/5/ "Fundamental Aspects of Reactor Shielding," Herbert Goldstein, Addison-Wesley Publishing Company, Inc., 1959, page 30.

DISCUSSION (Continued)

For similar conditions of power level, flattening and gas composition, the DR and H far side shields require somewhat more fringe poison protection than that required at B, D, and F. (Current fringe poison loadings are shown on Charts 11 through 14.)

Although the C reactor side shields are also constructed of iron-masonite laminations they are water cooled and are, therefore, considered to be in a different category from those of the five older reactors. The far side shield at C pile has been running at maximum temperatures of about 125°C. Extrapolation of this value for higher power levels indicates that fringe poison protection will be required for this shield by the time the C reactor is operating at 120 per cent of current power levels.

However, for conditions anticipated for the next ten years it appears that in all cases the far side shield temperatures can be held to a maximum of 130°C or less by the use of fringe poison loadings in row #96. Assuming the deterioration rate observed at the F reactor for temperatures in this range the leakage rate from these shields should not increase by more than about a factor of ten in the ten-year period. Therefore, based on the absolute leakage observed at the H reactor we would not expect a leakage rate greater than about five mrem through any of the far side bulk shields by 1970.

b. Near Side Shields

Because of the near side entry of the HCR's the near side shields will ordinarily operate at a temperature 10°C to 20°C lower than those on the far side. This ratio depends in large part upon the amount and location of enrichment and fringe poison loadings contained by the reactor. In the days before spike enrichment was used, the near side shields were running at least 20°C lower in temperature rise than the far sides. (Enrichment was first used routinely in the B, D, DR, and F piles in 1957. The H pile has contained some enrichment since late 1952.) The regular crescent shaped enrichment patterns changed the relationship so that the near sides were running only about 10°C cooler than the far sides. The ratio was changed again when fringe poison was used for protection of the far side shields. For the reactors containing from 10 to 15 fringe poison columns in row #96 it is estimated that the near side shields are now running at temperatures from 20°C to 30°C higher than those on the far side. Based on these various considerations it is concluded that at the B, C, D, DR, and F reactors the near side shields have suffered less deterioration than the far side shields. At H reactor it is probable that the near side shield has deteriorated as much and maybe more than the far shield. However, the fact must be taken into account that a larger radiation leakage can be tolerated through the near side because of the additional shielding afforded by the inner rod room walls. Over-all the neutron leakage through the near side bulk shields is at present considered to be less than that through the far shields and insignificant in relation to the leakage through the HCR penetrations.

DISCUSSION (Continued)

Projecting ahead, it is seen that fringe poison protection for the near side shields will most likely be required during the next ten years. There has not been any neutron detection equipment for use with any of the near shields and there is a need for measured data at this location. Therefore, installation of a neutron detector in one of the inner rod rooms and/or temperature measuring devices in a near side shield are being considered; near side shield temperatures may also be estimated from adjacent fringe tube powers. At any rate, there appear to be no appreciable problems connected with near side shield deterioration. Fringe poison columns in row #51 will afford ample protection as needed for anticipated operating conditions. Some near side protection will probably be required at power levels of 120 per cent of current levels.

c. Top Shields

No neutron detector facilities have been available for measurement of top shield leakage. (Plans are currently under way for installation of equipment at the top of the F reactor similar to that provided in the various reactor side shields.) Thermocouples were installed in the B, D, DR, F, and H top shields during the CG-558 outages. The deterioration rates assumed here are those inferred from use of routinely observed top shield temperatures with the temperature-deterioration rate ratio indicated in the F reactor side shield.

Charts No. 6 through 10 show the maximum temperatures recorded in the masonite of the top shields during the past two and one-half years. Also shown are the helium concentrations and power levels corresponding to these temperatures. Because of the VSR penetrations the heat distribution within these shields is different from that in the side shields. In the top more of the heat-producing reactions take place further "into" the shield; therefore, the second and third masonite layers (going toward the outside) run hotter in proportion to the first. In some cases, presumably because it is better insulated, the second layer actually runs hotter than the first. Also, the maximum temperature in the top shield is generally higher than the maximum in the sides; therefore, the top shields require the most fringe poison protection. This total effect of greater top shield maximums plus less favorable gradient has produced a burnout rate in the B, DR, and F top shields of perhaps three to four times that of the side shields. The temperatures in the D reactor top shield have run consistently low; therefore, that shield has most likely not deteriorated appreciably. However, due to the high operating temperatures of the H reactor top shield that shield has probably, over the past three years, suffered a burnout rate on the order of five times that of the other top shields (or fifteen to twenty times that of the H pile side shields). Even so, the neutron leakage through any of the top bulk shields as of the present time is considered to be small compared to the leakage through the VSR penetrations (estimated ten mrem through the H pile top shield as compared with an average of about 250 mrem due to leakage around the VSR's).

DISCUSSION (Continued)

Representative maximum top shield temperatures and the corresponding helium concentrations and number of tubes of top fringe poison protection for the B, D, DR, F, and H reactors are shown in Table 3. (See also charts 6 through 14.)

Table No. 3Representative Maximum Temperature Ranges
For the Reactor Top Shields

<u>Reactor</u>	<u>Max. Top Shield</u> <u>Temp. Range</u>	<u>No. Top Fringe</u> <u>Poison Tubes</u>	<u>Avg. He</u> <u>Percentage</u>
B	90°C	19	55
D	100	0	75
DR	110	20	70
F	70	11	80
H	150	30	40

Looking ahead for the next ten years and considering the anticipated conditions of helium concentrations and power levels it is probable that the D and F reactor top shields can be held to maximum temperatures of 130°C or less by use of a fringe poison blanket. However, with a full blanket of fringe poison in row #46 the maximum temperatures may reach 140°C in the B pile top biological shield and 150°C in the DR and H top shields. These temperatures indicate a possible increase in bulk neutron leakage, normalized to constant power, of a factor of ten for D and F, a factor of 30 for B, and a factor of 100 for DR and H over the ten year period. This means that ten years from now at the top of the DR and H reactors the component of neutron dose due to bulk shield leakage may equal or exceed that component due to leakage out through the VSR channels.

Projecting these higher top shield burnout rates to subsequent years clearly points out the need for conservatism in maximum allowable shield temperatures whenever possible.

d. Inlet and Outlet Shields

The inlet and outlet shields operate at temperatures approximately that of the water in the process tubes which penetrate them. The inlet temperatures are therefore relatively very low and effectively no depreciation is expected for that shield. The outlet shields operate in the range of temperatures up to about 100°C. This value represents a fairly uniform temperature throughout the shield and results in an over-all shield deterioration rate of perhaps the same order of magnitude as a side shield with a maximum temperature of 130°C. However, a greater leakage can be tolerated through the rear shields as they are backed up by secondary shielding walls. No problems are anticipated with respect to outlet shield leakage in the next ten years either concerning personnel exposure through the secondary shielding walls or activation of components in the discharge area.

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Research and Engineering Section
IRRADIATION PROCESSING DEPARTMENT

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FIGURE 5
F-1 REACTOR
NORMALIZED NEUTRON LEAKAGE TREND THROUGH FAR SIDE SHIELD
AND MAXIMUM SHIELD MASONITE OPERATING TEMPERATURES
(LEAKAGE TREND 90% CONFIDENCE LIMITS SHOWN BY DOTTED LINE)

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FIGURE 8

D-REACTOR

MAXIMUM TOP SHIELD MASONITE TEMPERATURES AND CORRESPONDING
HELIUM CONCENTRATIONS AND POWER LEVELS

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FIGURE 10
F REACTOR
MAXIMUM TOP SHIELD MASONITE TEMPERATURES AND CORRESPONDING
HELIUM CONCENTRATIONS AND POWER LEVELS

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FIGURE NO 12

B - REACTOR FRINGE POISON LOADINGS
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FIGURE NO 13

DR REACTOR FRINGE POISON LOADINGS

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FIGURE NO 14

F REACTOR FRINGE POISON LOADINGS
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FIGURE NO 15

H REACTOR FRINGE POISON LOADINGS
AS OF FEBRUARY 1960

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Far Side View of Reactor Showing Approximate Location
of the Neutron Detector Facility

FIGURE 16

NEUTRON DETECTOR FACILITY - LOCATION AND DETAILS*

* Taken from Reference No. 3.

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FIGURE 17

THERMOCOUPLE ARRANGEMENT
B, D, DR, F, AND H REACTOR TOP AND FAR SIDE SHIELDS

(Installed as part of CG-558 Project)

Note: One group of seven thermocouples as shown here is located at the approximate geometrical center of each of the top and far side shields at the B, D, DR, F, and H Reactors.