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IN-1248

December 1965

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A RE-EXAMINATION OF THE MTR GRAPHITE PEBBLE BED REFLECTOR

E. Fast, V. G. Wheeler and S. Cohen

PHILLIPS
PETROLEUM
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ATOMIC ENERGY DIVISION

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NATIONAL REACTOR TESTING STATION
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A C K N O W L E D G M E N T

Grateful acknowledgment is made to M. L. Griebenow for performing the in-tank irradiation work and pebble instrumentation. Further acknowledgment is expressed for the work performed by MTR Operations personnel in sampling and liner removal. The Machine Shop personnel under L. G. Olsen developed and operated equipment necessary to free the VG liners. Design of special liner handling tools was performed by R. A. McGuire and D. R. Conkling. Analytical work by W. A. Ryder, V. R. Olsen, F. P. Spessard and L. L. Dickerson is also acknowledged.

A B S T R A C T

The MTR graphite pebble bed reflector condition was re-examined. Results show that the pebble bed will not cause excessive structural temperatures or present a fire or radiological hazard because of any credible accident.

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A RE-EXAMINATION OF THE MTR GRAPHITE PEBBLE BED REFLECTOR

by

E. Fast, V. G. Wheeler, and S. Cohen

I. INTRODUCTION

This report presents the results of studies to re-evaluate the condition of the MTR graphite pebble bed reflector. The objectives of this work included studies to determine the stored energy distribution in the pebble bed, thermal performance of the bed, and other properties of the bed that could affect reactor safety.

A continuing surveillance program has provided information about the condition of the pebble bed since the MTR was started. Historically, the pebble bed reflector design was adopted to prevent damaging dimensional distortion of graphite caused by irradiation in the presence of fast neutrons. As additional graphite irradiation data became available from research, reactor operation, and incidents such as Windscale, a greater cause for concern was the buildup and possible undesirable release of stored energy. Although stored energy buildup in the MTR reflector graphite was not expected to be severe, a surveillance program provided for periodic sampling and analysis to obtain stored energy data. Some of this data from previous work is included in this report as reference material.

Based on previous results of the surveillance program, this re-examination of the bed was undertaken to insure the continued safe operation of the MTR under all credible conditions.

II. SUMMARY

Graphite balls sampled from the pebble bed through the MTR VG-12 and VG-20 experimental facilities were examined for stored energy, crystallite spacing change, ignition temperature, hydrocarbon content, and weight loss.

The samples were taken at various levels. A maximum specific stored energy of 70 cal/g was indicated at about 18 in. below reactor center plane. The temperature for self-sustained combustion was about 750°C for the pebble bed samples compared to 820°C for virgin balls. The hydrocarbon content of the pebble bed was found to be insignificant. A statistical analysis of irradiated balls from the central pebble bed region showed a loss in weight of $0.2 \pm .04\%$ per 10^4 MWd. If oxidation is the mechanism, about 3×10^{-8} μc per cm^3 of C^{14} activity is added to the stack effluent. This is not significant as a radiological hazard.

Virgin graphite balls were irradiated in L-52 lattice positions of the MTR as controls to help interpret results and in order to make further tests on the stored energy release mechanism. An energy release was shown to be under control, with but minor overshoot in temperature, in the case of slow anneal with gradual increase in temperature, and in the case where the anneal was interrupted by removing the heat source. Since adequate control was shown for these tank irradiated balls which contain more releasable stored energy than in the reactor pebble bed, control of energy release in the reflector should pose no problem.

The thermal performance of the MTR graphite pebble bed was evaluated semi-quantitatively. Pebble bed thermal tests included pebble transient temperature behavior during a scram and during a coolant flow change. Calculated results based on a simple convective heat transfer model and the transient test data agreed reasonably well with gamma heat measurements.

Pebble bed temperature and gamma heat measurements provided axial profiles that were not completely consistent. Coolant air channeling in the bed was postulated as the reason for the inconsistency. The instrumented pebbles used in temperature measurements now serve as MTR pebble bed monitors.

Reduction in coolant flow and a step increase in reactor power were postulated as two credible accidents which could trigger energy release. At least five minutes are available to the operator to take corrective action before pebble bed temperature would increase to the point where complete stored energy release could not be prevented assuming no power reductions. A maximum hypothetical accident was postulated as causing an adiabatic release of stored energy in the MTR pebble bed. Results indicate a maximum temperature rise of 105°C. This accident results in MTR structure temperatures that are lower than allowable values.

III. CONCLUSIONS

A gradual increase in the temperature of the pebble bed will not cause an uncontrollable release of stored energy. The present releasable stored energy buildup is about half that predicted in 1959. The temperature required to sustain combustion is about 300°C above the maximum possible during an adiabatic energy release. Any credible accident causing a spontaneous stored energy release will not lead to excessive structure temperatures. Even a maximum adiabatic release would not be damaging except possibly to the ionization chambers. A graphite stored energy anneal is not necessary for continued safe operation of the MTR at the present power level until at least 1969.

IV. MTR PEBBLE BED SAMPLING AND MONITORING PROCEDURES

Sampling and monitoring temperature profiles in the MTR graphite pebble bed were required to evaluate bed conditions. The procedures used for sampling and providing temperature monitors are described in the following sections.

A. General

The MTR pebble bed is a random stack of one-inch diameter graphite balls located in the space between the outer surface of the reactor tanks and the stacked blocks of permanent graphite as shown in Figures 1 and 2. The pebble bed is penetrated by several tubes called VG (vertical graphite) facilities.

Previous sampling of the pebble bed was performed by removing the VG-10 facility tube and driving a sampling case with a conical tip into the pebble bed. After driving the case to the desired bed elevation, the case was opened allowing a pebble to enter. Using this method, an axial sample profile was obtained for the VG-10 location (some results have been included in this report for reference).

B. New Procedures

Since additional samples were needed at locations removed from VG-10 to adequately cover the entire bed, a new method was developed to permit both sampling and insertion of instrumented pebbles at the same time. The method required the following procedural sequence:

- (1) Instrumented pebble preparation
- (2) VG facility liner removal
- (3) Sampling and instrumented pebble insertion method
- (4) Safety precautions.

The new locations chosen to supply representative data for the entire pebble bed were VG-12 and VG-20 (see Figure 2). Since liner removal destroys the usefulness of a VG facility, the number of locations chosen for sampling represents a compromise. The tests made on these balls are described in Section VI of this report.

1. Instrumented Pebble Preparation

Spare MTR graphite pebbles were machined as shown in Figure 3 for thermocouple attachment. These machined pebbles were irradiated in the MTR lattice. The irradiation is described in Section V of this report. After irradiation, nine of the pebbles were fitted with 0.062 in. metal clad (type 304 stainless steel) chromel-alumel thermocouples 30 ft. long. The thermocouples were checked before and

FIGURE 1

MTR REACTOR VERTICAL CROSS SECTION

DATE 1 6 64
F. L. H. 6 B 5

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FIGURE 2

MTR REACTOR STRUCTURE PLAN VIEW AT REACTOR CENTERLINE

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ASSEMBLY
SCALE 3" = 1"

4 BALL
MATL - GRAPHITE
REQD - 1
SCALE - 3" = 1"

3 COLLAR
MATL - 304 STN. STL.
REQD - 1
SCALE - 8" = 1"

2 PLUG
MATL - GRAPHITE
REQD - 1
SCALE - 3" = 1"

1 THERMOCOUPLE
MATL - NOTED
REQD - 1
SCALE - 8" = 1"

WRENCH
MATL - MILD STL.
REQD - 1
SCALE - 1 1/2" = 1"

ITEM	DWG NO	MATL	DESCRIPTION	QTY
1	THIS DWG	NOTED	THERMOCOUPLE	1
2	"	"	GRAPHITE PLUG	1
3	"	304 SST	COLLAR	1
4	"	GRAPHITE	BALL	1

Fig 3

TOLERANCES UNLESS OTHERWISE SPECIFIED
FRACTIONS: 1/16 DECIMALS: 0.05 ANGLES: 1/2
BREAK ALL SHARP EDGES UNLESS OTHERWISE SPECIFIED
PITTSBURGH STEEL COMPANY
DO NOT SCALE THIS DRAWING

INDEX CODE			
AREA	DRW TYPE	CL	ORIG
531	0603	40	706

531060340706010437

PHILLIPS PETROLEUM COMPANY
ATOMIC ENERGY DIVISION
IDAHO FALLS, IDAHO

MTR
GRAPHITE ANNEALING
GRAPHITE BALL & THERMOCOUPLE
ASSEMBLY & DETAILS

SCALE: 4:1000 DATE: DRAWING NO: MTR-D-6383

REV	BY	DATE	REVISION
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after attachment to the pebbles for continuity and resistance to ground and found to be satisfactory. The nine completed assemblies were also tested for response to temperature change with satisfactory results.

The remaining, irradiated pebbles were used for various tests as described in Section V of this report.

2. VG Facility Liner Removal

a. Description

The MTR VG-12 and VG-20 aluminum liners penetrate the graphite pebble bed to an elevation approximately 20 in. below core centerline. The 8 ft. long tubular liner is fluted on the outside and contains a 1/2 in. thick bottom plate drilled with eight 1/2 in. diameter holes for cooling purposes. The top of the liner is threaded inside and seal welded to a short cylindrical section which in turn is pinned to a stepped steel liner extension tube penetrating the reactor top shield structure. The liners and extension tube slope inward toward the reactor vessel.

b. Removal Procedures

Removal of the VG-12 and VG-20 facility liners was accomplished as follows:

The liner bottom was cut using the tool shown in Figure 4. This cutting tool, powered by a 1/2 in. standard portable drill, contained a hole saw attached to an extension rod. Clips, fastened to a rod inside the hollow extension rod, were attached to the liner bottom plate through the holes permitting retrieval of the plate after completing the cut.

Attempts to break the seal weld between the liner and short cylindrical threaded joint were not successful. A boring tool was fabricated to cut through the cylindrical aluminum joint and steel holding pins. After cutting through the pins, the liner and joint could then be raised through the steel tube and out of the reactor.

The tool used to lift and remove the liner is shown in Figure 5. Two pawls are retracted as the tool is lowered in the liner extension and liner. The liner contains two opposing slots 1/2 in. wide and 2 in. long. When the tool is at the proper elevation, the pawls are extended by means of a drive rod attached to the pawls and located inside the hollow lifting rod. The extended pawls engage the slots allowing the liner to be lifted.

3. Sampling and Instrumented Pebble Insertion Procedure

The method adopted to obtain samples and install instrumented pebbles in the VG-12 and VG-20 locations in the pebble bed consisted of removing the liner bottom and attaching a length of one inch diameter thick-walled "Tygon" tubing to a commercial vacuum cleaner. The free end of the tubing was then inserted down the facility

until bottomed. The vacuum cleaner was then turned on and a pebble, held against the tubing end by atmospheric pressure, was withdrawn. After obtaining the required samples, an instrumented pebble was inserted and bottomed in the facility. The liner removal tool was then inserted in the facility by threading the instrumented pebble lead wire through a hole in the tool. The liner was raised a pre-determined distance allowing the pebble bed to collapse into the hole created by this move. This also fixed the position of the instrumented pebble in the desired location in the bed. The above procedure was repeated until all the required samples were obtained and all instrumented pebbles installed at the desired elevation. The liner was then removed from the reactor.

4. Safety Precautions

Sampling the pebble bed and removal of the liners presents radioactive contamination and direct exposure problems. The MTR ventilation system maintains forced convection air cooling through the pebble bed during reactor operation and shutdown. Exhaust fans produce a negative pressure in the bed and therefore reduce contamination problems such as dusting during sampling and liner removal operations.

The following procedures were adopted to minimize any possible health physics problems during the sampling and liner removal:

- (1) A portable CAM was used to monitor all sample and material removals from the VG facilities.
- (2) Portable beta-gamma survey instruments, operated by Health Physics personnel, monitored all material withdrawn from the facility.
- (3) Catch baskets were provided during the boring operation to collect the cuttings.
- (4) Samples were immediately dropped into labeled plastic bags upon removal from the reactor. A shielded cask was used to store samples during the operation.

No unexpected activity was encountered during the operation. Air activity was negligible. The pebbles ranged in activity rate (combined beta-gamma) from a few mr/hr to 1 R/hr at contact. The liners were removed using the 2-1/2 ton crane. All personnel not required were evacuated from the immediate area. The liner was lifted slowly from the reactor and the activity was continuously monitored using several survey instruments. Maximum liner activity rate at contact was several R/hr.

C. Sample and Instrument Pebble Locations

Figures 6 and 7 show the positions of pebbles sampled and instrumented pebbles inserted with respect to core centerline elevation for VG-12 and VG-20 respectively.

ASSEMBLY
SCALE 1" = 1'

ITEM ① SHANK
MATL STL ONE REQD
SCALE 1" = 1'

ITEM ③ SPRING BASE ASSY
MATL - STL ONE REQD
SCALE 1" = 1'

ITEM ④ SAW DRIVE WELDMENT
MATL - STL ONE REQD
SCALE 1" = 1'

ITEM ⑨ SPRING LATCH
MATL - 1/2 THK SPRING STL - ONE REQD
SCALE 1" = 1'

ITEM ⑧ 2 3/8 DIA HOLE SAW
MATL STL ONE REQD
SCALE 1" = 1'

ITEM	DWG NO	MATL	DESCRIPTION	QTY
1	THIS DWG	STL	SHANK	1
2	COMM	STL	3/8 STD PPE COUPLRS	2
3	THIS DWG	STL	SPRING BASE ASSY	1
4	THIS DWG	STL	SAW DRIVE WELDMENT	1
5	COMM	STL	3/8 LOCK WASHER	2
6	COMM	STL	3/8-16 SOCKET HD BOLT X 3/8 LG	2
7	COMM	STL	3/32 FLAT HD RIVET X 3/8 LG	2
8	THIS DWG	STL	2 3/8 DIA HOLE SAW	1
9	THIS DWG	SPRING STL	SPRING LATCH	1

1. MARVEL HIGH SPEED EDGE 2 3/8 DIA HOLE SAW
ARMSTRONG BLUM MFG CO CHICAGO ILL
STOCK No 38 OR EQUIVALENT

GENERAL NOTES
WHEN CUTTING BOTTOM OUT OF VG LINER,
USE 1/2 CHUCK SLOW SPEED DRILL

REF DWG
BKC-3150 555-1
REACTOR STRUCTURE AREA No 3
MECHANICAL DESIGN VG-1, 3, 5, 6, 7, 10 THRU 14
LINERS & PLUGS

Fig 4

TOLERANCES UNLESS OTHERWISE SPECIFIED FRACTIONS ± .01 UNLESS SHOWN OTHERWISE DECIMALS ± .005 UNLESS SHOWN OTHERWISE HOLE DIA ± .005 UNLESS SHOWN OTHERWISE HOLE DIA ± .005 UNLESS SHOWN OTHERWISE HOLE DIA ± .005 UNLESS SHOWN OTHERWISE		INDEX CODE 531060340706010447	
PHILLIPS PETROLEUM COMPANY ATOMIC ENERGY DIVISION SAND FALLS, MISSOURI		MTR REACTOR VG 7 LINER BOTTOM CUTTING TOOL ASSEMBLY & DETAILS	
SCALE 1" = 1' DATE 12/1/57 DRAWING NO. MTR-E-6393		REVISION NO. 1 DATE 12/1/57

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ITEM	DWG NO	MATL	DESCRIPTION	QTY
1	THIS DWG	STL	PAWL DRIVE WELDMENT	1
2	COMM	STL	1/8" 16 NC 2 HEX NUT	1
3	THIS DWG	STL	HANDLE WELDMENT	1
4	THIS DWG	STL	PAWL HOUSING	1
5	THIS DWG	STL	PIN	1
6	THIS DWG	STL	PAWL	1
7	THIS DWG	STL	PAWL	1
8	THIS DWG	STL	BOTTOM PLATE	1
9	COMM	L	1/8" 16 SOCKET HEAD X 1 3/4" LG	2
10	COMM	STL	LOCK WASHER	2
11	COMM	L	1/8" 16 NC 2 FLAT HEAD SCREW X 3/4" LG	2
12	COMM	STL	NO 8 SASH CHAIN X 6 LG 1/2" C	1
13	COMM	STL	1/8" DA COTTER PIN 2 1/2"	1

GENERAL NOTES
 1. WHEN TOOK TO COMPLETELY ASSEMBLED
 DRILL 5/32" DA HOLE THROUGH HANDLE & PAWL
 DRIVE WITH PAWLS EXTENDED POSITION
 AS SHOWN IN ASSEMBLY DRAWING

REF DWG
 BKC 3150 555 1
 REACTOR STRUCTURE AREA #3, MECHANICAL
 DESIGN, V6-1 3 5, 6 7 10 THRU 14
 16 THRU 20 LNER 4 PLUGS

Fig 5

TOLERANCES (UNLESS OTHERWISE SPECIFIED)
 FRACTIONS 1/16 INCHES 0.05 ANGLES 1/2
 DECIMALS 0.005 INCHES 0.005 ANGLES 1/2
 ALL DIMENSIONS UNLESS OTHERWISE SPECIFIED
 FROM SURFACE UNLESS OTHERWISE SPECIFIED
 DO NOT SCALE FROM DRAWING

INDEX CODE
 53106034070611046

PHILLIPS PETROLEUM COMPANY
 ATOMIC ENERGY DIVISION
 DAKOTA FALLS, DAKOTA

MTR REACTOR V6 7 HOLE
 ALUMINUM LNER
 REMOVAL TOOL
 ASSEMBLY & DETAILS

SCALE: DRAWING NO. MTR E 6407

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FIGURE 6

SAMPLE AND MONITOR LOCATIONS - VG-12

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FIGURE 7

SAMPLE AND MONITOR LOCATIONS - VG-20

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The location of samples and instrumented pebbles for the VG-20 facility were not located as originally planned. The catch basket stuck following the boring operation and attempted removal resulted in raising the liner contrary to procedure.

The samples were prepared in the MTR hot cell for analyses by boring approximately 1/2 in. deep holes using a #60 bit. These holes were used to attach thermocouples to the pebbles for stored energy and ignition tests.

The instrumented pebble lead wires were routed to the MTR data logger using the readout points shown in Figures 6 and 7.

V. AUXILIARY STUDIES ON GRAPHITE BALLS IRRADIATED IN THE MTR CORE

To aid in interpreting results of measurements on graphite balls from the MTR pebble bed, a program of testing was planned on virgin graphite balls. Forty-five balls were loaded into two B baskets and irradiated in the MTR L-55-NE and -NW positions during MTR Cycle 193 in contact with the process water at about 40°C. The balls were loaded as shown in Figure 8 which is included for reference in subsequent discussion. The fast flux (> 1 MeV) exposure at centerline was 0.21×10^{20} nvt. Part of these balls have been reinserted into the pebble bed zone of the MTR reflector each with an imbedded thermocouple as has been described in Section IV. The remainder were used for calibrating the stored energy of the instrumented balls and for studying the conditions and rate of release of stored energy. Other measurements included the effect of induction heating in stored energy release, measurement of C_0 crystallite spacing, and ignition temperature. This section describes the tests made and results obtained on these irradiated graphite balls.

A. Stored Energy Studies

The usual procedure used in annealing irradiated graphite at 200°C is given in this section together with results of measurements obtained from the in-tank irradiated balls. Results are also given for several other anneal tests designed to show how readily the rate of release can be controlled.

1. Procedure

The normal procedure for anneal consisted of heating the irradiated ball in an oven, held at 200°C, and recording the temperature of the sample as a function of time. Imbedded in the center of the ball was a chromel-alumel thermocouple which was connected to a 20 mv strip chart recorder. The measurement was continued until the ball came to temperature equilibrium with the oven. A post-anneal curve was obtained in the same way and was placed on the same chart in juxtaposition for ready comparison and use in calculations. Further details of the procedure and applicable theory for calculating stored energy are given in IDO-16182.^[1]

A typical anneal curve for a graphite ball irradiated in the MTR lattice is reproduced in Figure 9. The point of separation of the anneal and post-anneal curves shows at what temperature the energy release begins. This is usually about 50°C above the irradiation temperature. The energy released produces a sharp rise with an overshoot in temperature of up to several hundred degrees above the oven temperature, which release is essentially adiabatic. When the releasable stored energy is appreciably lower, illustrated in Figure 10, the

FIGURE 8
LOADING CHART FOR IN-TANK IRRADIATIONS

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FIGURE 9

ANNEAL AND POST-ANNEAL TEMPERATURE CURVES FOR IRRADIATED GRAPHITE BALL NO. 13

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FIGURE 10

ANNEAL AND POST-ANNEAL TEMPERATURE CURVES FOR IRRADIATED GRAPHITE BALL No. 2

temperature rise is more gradual so that heat losses, or gains, in the sample energy must be considered. The thermal balance equation relates the rate of stored energy release to the temperature change in the sample and losses to the environment:

$$\frac{dE}{dt} = C(T)M \frac{dT}{dt} - LA\Delta T$$

where $C(T)$ is the specific heat of graphite at temperature T ; M , the mass; t , the time; L , a heat flow coefficient which depends both on temperature and sample geometry; and ΔT , the difference between oven and sample temperatures. The quantities on the right are obtained experimentally. To obtain the stored energy, E , the integration is performed graphically from a plot of $\frac{dE}{dt}$ as a function of t . A typical plot of this type is shown in Figure 11 for data from the curve of Figure 10.

Results obtained from selected graphite balls from basket #62 are summarized in Table I. Given are the temperature at which energy release began, (T_s), maximum release temperature (T_{max}), and the energy released in calories per gram of sample. The calories per gram are shown graphically in Figure 12 plotted as a function of vertical position in the MTR lattice position. The reversal in stored energy near the center reflects the high irradiation undergone by the graphite. A maximum point in stored energy [1] occurs at a fast neutron exposure of about 10^{19} nvt (> 1 MeV). For greater exposures the stored energy released at 200°C decreases. (The total stored energy releasable at higher anneal temperatures or by combustion continues to increase.)

2. Pre-Anneal Samples

The graphite balls irradiated in basket #61 were subjected to a pre-anneal treatment at 110°C. This group of samples included those designed for use as instrumented balls and associated calibration standards. Selected samples from basket #62 were used to study spontaneity of energy release as a function of anneal temperature.

The low temperature anneals of 18 balls, taken 9 in a group, were done by bringing the oven temperature to 100°C slowly with the balls inside. Each ball had a thermocouple imbedded in it which was connected to a multipoint recorder. A maximum overshoot of about 8°C was observed in the first group (Nos. 2, 3, 7, 8, 9, 101, 102, 103, 109) before the balls came to equilibrium temperature with the oven. The second batch (Nos. 1, 4, 5, 6, 104, 105, 107, 108, 110) was heated more slowly and hence showed little or no overshoot.

Following this pre-anneal treatment in which the temperature approximated that of the MTR centerline pebble zone, the calibration samples No. 1-9 were annealed in the usual way by heating to 200°C in a constant temperature oven. The representative temperature-time curve of this type, given in Figure 10, may be compared directly with that of Figure 9 since both samples received about the same irradiation. Because

TABLE I

DATA ON 200°C ANNEAL OF IRRADIATED GRAPHITE BALLS -
IRRADIATED IN MTR-L-55-NE, CYCLE 193

<u>Sample No.</u>	<u>Location Inches from C</u>	<u>T_s °C</u>	<u>T_{max} °C</u>	<u>Energy Released cal/g*</u>
35	15	111	216	27
32	12	105	313	57
29	9	101	389	85
27	7	103	411	93
26	6	89	413	97
25	5	102	414	94
24	4	109	414	93
21	1	62	401	98
18	- 2	91	387	86
14	- 6	105	390	84
13	- 7	101	396	87
11	- 9	99.5	412	94
10	-10	108	409	91

* Energy calculated assuming adiabatic release, based on maximum temperature.

FIGURE 11

ENERGY RELEASE RATE CURVE - BALL NO. 2

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FIGURE 12

STORED ENERGY OF IN-TANK IRRADIATED GRAPHITE BALLS

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it was partially annealed, however, sample 2 of Figure 10 did not attain as high a temperature during final anneal as did sample 13 of Figure 9. The energy release also occurs more slowly. The temperature-time curve of Figure 10 is very similar to those obtained with balls from the MTR reflector of comparable total energy (See Section VI).

The calculated stored energy is plotted in Figure 13 as a function of vertical position. Individual values are summarized in Table II along with the interpolated values for the other balls. The minimum in the curve again is at the position of maximum fast flux, indicating a saturation of the effect. The condition of stored energy of the "instrumented" balls can be read from this curve since they were in alternate positions with the others during irradiation in the MTR.

3. Partial Anneals at Different Temperatures

Annealing at several different temperatures was the subject of study for balls No. 12, 19, 20, and 22. The initial anneal was made with oven temperatures at 100, 120 or 140°C followed by the usual anneal at 200°C for each ball. However, ball No. 20, initially subjected to 100°C anneal was given two intermediate anneals at 120 and 140°C before the 200°C anneal. The data are summarized in Table III giving initial energy release temperatures (T_s), maximum temperatures (T_{max}), and estimated energy released in each case. It appears that an anneal in a 140°C environment is high enough to trigger the release of nearly all the energy normally releasable at 200°C, whereas if the initial release was at lower temperatures only a portion of the energy was released.

It should be emphasized that the release of stored energy is more nearly spontaneous in these balls than in those from the MTR reflector zone because of the lower irradiation temperature. However, since even under these conditions the rate of energy release can be controlled, there should be no serious problem controlling the release of energy from the reflector balls.

4. Interrupted Anneal

Experiments in which normal anneal was interrupted by removing the specimen from the oven were designed to show that the release of energy could be stopped after an anneal had started by controlling the heat source or environment. Sample No. 16 was heated in a 200°C controlled oven to 180°C then removed. Subsequently, it was reinserted and annealed at 200°C. Similarly the anneal of Sample No. 17 was interrupted at 150°C and 200°C before being allowed to anneal completely. Sample No. 23 was withdrawn from the oven at 110°C and at 10 degree intervals up to 210°C. The sample was kept out of the oven less than one minute after each withdrawal. In each case removal of the sample from the oven caused immediate decrease in the rate of temperature rise and only a modest overshoot in temperature before reversing direction. The maximum temperature finally reached in the interrupted anneal is appreciably lower than expected otherwise. Figure 14 is a reproduction of the temperature curves obtained with Sample No. 17 together with the post-anneal curve which followed the same time sequence in and out of the oven.

TABLE II

DATA ON 200°C ANNEAL OF IRRADIATED GRAPHITE BALLS AFTER 110°C
PRE-ANNEAL TREATMENT - IRRADIATION IN MIR-L-55-NW, CYCLE 193

<u>Sample No.</u>	<u>Location Inches from C_E</u>	<u>T_s °C</u>	<u>T_{max} °C</u>	<u>Energy Released cal/g*</u>
9	7	131	318	60
8	5	146	330	66
7	3	146	308	57
6	1	143	330	61
5	- 1	129	314	62
4	- 3	151	300	57
3	- 5	151	280	48
2	- 7	85	297	57
1	- 9	130	345	71

* Energy calculated by "long" method using Equation 1.

FIGURE 13
STORED ENERGY OF IN-TANK IRRADIATED GRAPHITE BALLS

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FIGURE 14

INTERRUPTED ANNEAL AND POST-ANNEAL TEMPERATURE CURVES

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TABLE III

IRRADIATED GRAPHITE BALLS SUBJECTED TO SEVERAL ANNEAL TEMPERATURES

Sample No.	100	120	140	200
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A. Comparison of T_s and T_{max}

	T_s	T_{max}	T_s	T_{max}	T_s	T_{max}	T_s	T_{max}
12	78	107					121	366
19			93	131			139	302
22					93	339	---	200
20	86	107	90	124	128	142	167	241

B. Comparison of Stored Energy Released

				cal/g at 200° anneal
12	10.2			73 ^a
19		15.1		56 ^b
22			70 ^a	
20	8	6 (?)	3 (?)	30 ^b

a. Adiabatic energy release assumed
 b. Long method using equation (1)
 All other values based on relative areas between curves

In another test, Sample No. 15 was placed in the cold oven. The rate of heating was controlled by increasing the temperature set point of the oven 5°C every 5 minutes. The sample temperature lags the oven temperature until energy release begins. Thereafter it leads the oven temperature until the anneal is completed. In no case, however, is the temperature differential as much as 10°C, Figure 15 shows a plot of the temperature differential as a function of oven temperature.

5. Induction Heating Anneal Test

A few irradiated graphite balls were annealed using induction heating. This type of test was desired because the heat generated in the body of the sample is similar to that caused by gamma irradiation, rather than by conduction from the surface. The unit was a 1000 watt "Ther-monic", made by Induction Heater Corporation. The instrument was adjusted to give a sample temperature of about 200°C in an unirradiated ball at equilibrium with normal convection. The temperature transient in an irradiated ball showed that the energy release was essentially the same as with the usual oven anneal procedure.

B. X-Ray Diffraction

Table IV summarizes available data on C_0 lattice spacing obtained by X-ray diffraction. Pre- and post-anneal values indicate that this phenomenon does not anneal completely with anneal of the stored energy. The dip seen in the stored energy calibration curve is not observed here which agrees with previous results [1] that no saturation effect appears in the C_0 lattice spacing in this range of fast neutron exposure. The recovery observed at 200°C anneal is generally less than 50%. The 110°C anneal does not bring about significant recovery in most cases.

C. Ignition Tests

Several unirradiated balls were heated sufficiently with the induction heater to determine the ignition temperature. The test ball, with a chromel-alumel thermocouple imbedded in the center, was centered in a glass tube of 1-1/6 in. inside diameter. Air was drawn through the tube at the rate of ten liters per minute during heating. An average of $830^\circ \pm 10$ was obtained as the ignition temperature.

FIGURE 15
SLOW HEATING TEST OF IRRADIATED GRAPHITE BALL NO. 15

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TABLE IV

CHANGE IN C_0 LATTICE SPACING IN IRRADIATED GRAPHITE BALLS

<u>Sample No.</u>	<u>Irradiated Sample</u>		<u>Annealed at 110°C</u>	<u>Annealed at 200°C</u>
	C_0 (angstroms)	% change*	% Change*	% Change*
1	7.12	5.6	5.0	2.8
2	7.17	6.4	5.9	5.2
3	7.24	7.4	6.8	5.2
4	7.12	5.6	4.7	4.6
5	7.10	5.3	4.7	5.2
6	7.08	5.0	5.2	3.9
7	7.14	5.9	5.2	4.2
8	7.01	4.0	---	2.5
9	7.08	5.0	3.1	2.5
26	6.96	3.3	---	1.9
101	6.96	3.3	3.4	
102	7.07	4.9	4.6	
103	7.10	5.3	6.1	
104	7.07	4.9	4.6	
105	7.26	7.7	6.2	
106	7.19	6.7	6.7	
107	7.11	5.5	5.6	
108	7.14	5.9	4.7	
109	6.98	3.6	3.0	
110	6.90	2.4	1.5	

* A value of $6.74 \overset{\circ}{\text{A}}$ is assumed for unirradiated graphite.

VI. MEASUREMENTS OF MTR PEBBLE BED REFLECTOR GRAPHITE

Stored energy and X-ray diffraction measurements were made on graphite balls retrieved, as previously described, from the MTR reflector through VG-12 and VG-20. The results and pertinent discussion are given below. Also included are the results of measurements of fast flux, hydrocarbon extraction, ignition temperatures and material weight loss.

A. Stored Energy Measurements

Results of 200°C stored energy release measurements are given in Table V for balls retrieved from VG-12 and VG-20 after 112,550 MWd of MTR operation (end of Cycle 200). The location from which a ball was taken is given as the distance from the reactor fuel center plane (given graphically in Figures 6 and 7). In most cases 4 balls were obtained from a level as the liner was being removed. Each measured value is recorded to show how well the results agree among themselves. The vertical distribution of stored energy is shown graphically in Figures 16 and 17 for VG-12 and VG-20, respectively. A maximum value of about 70 cal/g was obtained at 18 in. below center.

A comparison may be made with earlier data taken from VG-10.^[2] The initial retrieval of balls was done after 61,535 MWd of MTR operation. The stored energy results are plotted in Figure 18 to show the vertical distribution at that time. A maximum of about 60 cal/g was obtained at 18 in. below center. Subsequent samplings (not reproduced here) taken after 68,812 and 96,892 MWd show considerably more scatter in the data.

B. X-Ray Measurement of C₀ Spacing

Table V also presents data on change of C₀ crystallite lattice spacing in the graphite from VG-12 and VG-20. The results are given in terms of the percent change in the unirradiated value of 6.74 angstroms. Results are portrayed graphically as a function of vertical position in Figures 16, 17 and 18 for comparison with stored energy data. The variation of C₀ spacing with vertical position is very nearly that of the fast flux, in contrast to the stored energy picture. The post-anneal value is also given in Table V for comparison. In some cases these values differ but little, showing that this type of damage does not anneal very well at 200°C.

C. Flux Measurements

Fast neutron flux (> 1 MeV) measurements were made with 0.020 in. diameter nickel wire in selected graphite reflector positions. A typical vertical distribution is given in Figure 19 for VG-12. The maximum fast flux in several graphite reflector facilities is plotted in Figure 20 as a function of effective distance from the core. An approximate linear relationship is obtained on a semi-log plot, ie, log flux as a function of distance.

TABLE V

STORED ENERGY AND X-RAY C_o SPACING MEASUREMENTS,
MTR REFLECTOR GRAPHITE BALLS

VG-12

<u>Sample</u>	<u>Inches from ϕ</u>	<u>T_{sep}</u>	<u>T_{max}</u>	<u>Stored Energy</u>	<u>C_o ($\text{\AA}$)</u>	<u>% change⁺ in C_o</u>	<u>Post Anneal % change in C_o</u>
12-1-A		68	329	62*	6.83	1.3	0.3**
B	-20	68	329	62*	6.83	1.3	
12-2-A	-14	114	332	64	6.94	3.0	2.4
B	"	110	315	62	7.00	3.9	
C	"	117	285	34*	6.96	3.3	
12-3-A	- 7	131	219	18	7.22	7.1	2.7**
B	"	128	262	41	7.14	5.9	
C	"	144	251	34*	7.12	5.6	5.0
D	"	125	280	45	7.06	4.7	
12-4-A	1	159	211	10*	7.12	5.6	5.6
B	1	137	238	27	7.05	4.6	
C	1	137	260	36*	7.04	4.5	
D	1	136	251	34	7.04	4.5	

VG-20

20-1-A	-20	112	298	51	7.00	3.9	0.6**
B	"	120	341	68	6.88	2.1	
D	"	115	336	64*	6.88	2.1	
C	"	122	343	68	6.92	2.7	2.1
20-2-A	- 3	155	212	13	7.12	5.6	5.3
B	"	110	226	25*	7.14	5.9	
C	"	152	207	7.7	7.14	5.9	
D	"	150	211	12*	7.14	5.9	
20-3-A	3	71	227	17*	6.92	2.7	2.7
B	"	---	201		6.92	2.7	
C	"	127	230	24	6.90	2.4	
D	"	154	219	15*	6.90	2.4	
20-4-A	21	156	207	4.9*	6.76	0.3	0.3
B	"	164	206	6.4	6.79	0.7	
C	"	---	---		6.76	0.3	
D	"	169	202	2.4*	6.76	0.3	

TABLE V (Contd)

STORED ENERGY AND X-RAY C_O SPACING MEASUREMENTS,
MTR REFLECTOR GRAPHITE BALLS

Sample	Inches from C_L	T_{sep}	T_{max}	Stored Energy	C_O (Å)	% change ⁺ in C_O	Post Anneal % change in C_O
20-5-A	33	162	202		6.74	0.0	
B	"	199	203		6.76	0.3	
C	"				6.76	0.3	
D	"				6.76	0.3	
20-6-C	57				6.74	0.0	

* Interpolated from curve relating area measurements between anneal and post-anneal curves with stored energy.

** After induction heating to ignition point.

+ Unirradiated graphite C_O spacing assumed to be 6.74 Å.

FIGURE 16

VERTICAL DISTRIBUTION OF STORED ENERGY IN VG-12

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FIGURE 17

VERTICAL DISTRIBUTION OF STORED ENERGY IN VG-20

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FIGURE 18

VERTICAL DISTRIBUTION OF STORED ENERGY IN VG-10

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FIGURE 19
AXIAL FAST FLUX PROFILE FOR VG-12

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FIGURE 20

FAST NEUTRON FLUX DISTRIBUTION IN THE MTR
GRAPHITE PEBBLE BED

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The values of flux obtained here agree well with those deduced from X-ray measurements of C_0 lattice spacing, using the calibration curve of IDO-16182 (Figure 3). The nvt at 7 in. below center plane is about 1.73×10^{19} based on 112,550 MWd operation and the flux from Figure 19. This, according to the calibration curve, corresponds to about 6% change in C_0 spacing, in good agreement with the value given in Table VI. Similarly, VG-10 had a total fast nvt of about 1×10^{19} at the end of Cycle 119 and the observed change of about 3% in the C_0 spacing (Figure 18) again is in good agreement with that obtained from the previous calibration.

D. Hydrocarbon Extraction

No significant amount of hydrocarbons were found to be absorbed in samples from VG-12 and VG-20 that were tested. Trace indications that appeared were present also in virgin balls and were believed to be the result of human contact in handling.

E. Ignition Temperature

The temperatures at which self-sustained combustion was observed in a number of the graphite balls from the MTR reflector are recorded in Table VI. Ignition tests were made after the balls had been annealed of their stored energy. The balls were heated by induction as was done with the unirradiated balls. Results show an ignition temperature for these balls averaging 70°C below that for the cold balls. The spread in values is also significantly greater, probably due to the non-uniform ball surface contamination. Dust and other foreign matter on the surface as well as irradiation damage are known to catalyze the oxidation reaction. In either case, however, the required ignition temperature of above 700°C is much higher than the normal operating temperature of the graphite (110°C) or even the maximum attained during adiabatic stored energy release (400°C). Thus there is no reason to expect ignition of the MTR graphite during the anneal.

F. Weight Loss

A statistical study of the weights of MTR reflector irradiated and unirradiated balls was made to determine material loss as a function of MWd of reactor operation. A total of 136 virgin balls gave an average weight of $14.78 \pm .031$ grams. Irradiated balls from the reflector were obtained at various times from VG-10, VG-12 and VG-20 as previously mentioned in this report. The average weights are plotted in Figure 21 as a function of MWd of MTR operation. The slope gives the rate of weight change of $-0.20 \pm .04$ percent per 10^4 MWd operation. This low rate of loss is not sufficient to affect the operation of the MTR significantly over its lifetime.

The reason for the small weight loss has not been established. Not enough erosion would be anticipated from the air flow itself to account for the observed effect. Slow oxidation could occur as a result of the neutron and gamma flux fields and the slightly elevated temperature

TABLE VI

IGNITION TEMPERATURE OF GRAPHITE BALLS

<u>Sample Ball No.</u>	<u>Ignition Temp. °C</u>
VG-12-1-A	720
VG-12-1-B	725
VG-12-3-A	817
VG-12-6-	720*
VG-12-6-	673
VG-20-1-B	770
VG-20-1-D	<u>817</u>
Average	748 $\pm$ 50
Virgin ball A	840
Virgin ball B	830
Virgin ball C	<u>820</u>
Average	830 $\pm$ 10

* Hydrocarbon extraction made previously.

FIGURE 21

MTR GRAPHITE PEBBLE BED WEIGHT AS A FUNCTION OF OPERATING TIME

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of MTR operation. Oxidation studies are reported in the literature only for considerably higher temperatures.^[3] Although theory is not good enough to predict oxidation rates at MTR operating temperature, the weight loss rate observed is not necessarily contradictory to what is known.

As a possible check of the above interpretation, calculations of weight loss were made separately on balls coming from the center ± 12 in. and those from outside these limits. The central region has higher fluxes and temperatures. A weight loss rate of 0.24 ± 0.05 percent per 10^4 MWd was obtained for the central region compared to 0.15 ± 0.05 for the other balls. Because of the relatively large uncertainties it is doubtful that a significant difference exists between the two zones. However, the difference is in the direction anticipated if oxidation has occurred.

The rate of graphite loss does not pose a health hazard even if all lost material is discharged to the atmosphere. Calculations showed the present rate of C^{14} release to the atmosphere through the MTR stack to be about 3×10^{-8} μc per cm^3 compared to 10^{-6} μc per cm^3 quoted as a permissible concentration level.^[4]

G. Discussion

The stored energy measured in the several graphite balls from the same location of the VG facilities varies over a considerable range. The range is greater than would be expected due to experimental uncertainties. Several possible causes may be postulated that offer reasonable explanations: (1) that some of the balls came from different levels, having been displaced during the process of retrieving them; (2) partial anneal may have occurred without triggering a general energy release in neighboring balls. This is possible because of the small area of contact between balls and subsequent low direct heat conduction. Evidence of the first postulate comes particularly from the increased scatter in the three VG-10 samplings taken after 61,535, 68,812 and 96,892 MWd of MTR operation. The method of sampling from VG-12 and VG-20 makes this error less likely but still possible. The second postulate is substantiated in that balls from the same level show approximately the same crystallite spacing but differ appreciably in stored energy. Examples may be seen in Table V in the samples from levels VG-12-2 and VG-20-2.

The accumulated stored energy that will be released in an adiabatic anneal at 200°C is a function of both the fast neutron flux and irradiation temperature. As was shown ^[1] the specific energy in calories per gram reached a maximum at about 1×10^{19} nvt > 1 MeV (Fast) when the samples were irradiated in the MTR tank (water contact). Work summarized by Nightingale^[3] shows the apparent maximum or saturation value decreases and occurs at higher exposures when the irradiation

temperature is increased. For constant irradiation temperature formulae of the type

$$S = S_{\infty} (1 - e^{-kE})$$

and

$$S = S_{\infty} (\tanh k'E)$$

were fitted to their data in the range 30 to 450°C irradiation temperatures. Here, S is the stored energy and E , the exposure. The parameter k is a function of irradiation temperature becoming smaller with increased temperature over the range of interest here. Data obtained with MTR graphite are not detailed enough to make further generalizations. It is well known that a decrease in stored energy buildup accompanies a rise in graphite temperature during irradiation at constant flux. Of the data presented in Table V the series VG-12-2 and VG-12-5 were irradiated in about the same fast flux (see Figure 19). The graphite temperatures respectively were about 42 and 66°C. The released stored energy differed by a factor of two for this small temperature differential.

Considering the maxima of stored energy values, conservative results from the point of view of safety, are obtained. Maximum temperatures that might be reached are below those which would initiate combustion or cause structural damage.

The change in C_0 spacing is also dependent to some extent on the irradiation temperature. Again comparing the data for VG-12-2 and VG-12-5 in Table V, it is seen that there is about a factor of two difference, although the flux was nearly the same. Irradiation temperatures were 42 and 66°C, respectively. Conversely the effect at 66°C on C_0 spacing is about the same as at 40°C with only half the flux value. This observation, though of passing interest, has no direct bearing on the safety aspects of MTR operation.

VII. PEBBLE BED THERMAL PERFORMANCE

A. General

The rate of damage by neutrons to graphite is influenced by the irradiation temperature. This effect is especially pronounced with respect to the accumulation and release of stored energy. Therefore, a knowledge of the thermal condition of the pebble bed is necessary to evaluate the possibility of a hazardous release of stored energy.

The MTR graphite pebble bed is heated by the absorption of gamma radiation during reactor operation. This heat is removed primarily by a forced circulation air system as shown in Figure 22. Conduction heat transfer from the bed to the reactor vessel wall is a secondary heat removal mechanism. Although the total air flow through the reactor structure is measured, the several parallel flow paths of the system complicate flow measurements through the bed. A second complicating factor in obtaining adequate coolant (air) flow measurements in a packed bed is the possibility of coolant channeling. Based on these factors and the difficulty and expense involved in developing a comprehensive program for an operating reactor, a modest program that would yield semi-quantitative information concerning the pebble bed thermal characteristics was performed. The program consisted of the following:

- (1) Measurement of axial temperature profiles in the bed
- (2) Measurement of pebble bed axial gamma heat profiles in locations at or near temperature measurements
- (3) Determination of heat transfer rates from pebbles by transient methods.

B. Measurements of Pebble Bed Axial Temperature Profiles

The insertion of instrumented graphite pebbles in the VG-12 and VG-20 locations provided axial temperature profiles in these areas of the MTR graphite pebble bed. Typical readings with the reactor at 40 MW are shown in Figure 23 for the two locations.

C. Measurements of Pebble Bed Axial Gamma Heat Profiles

Gamma heating measurements were made in the VG-13 and VG-19 facilities adjacent to the VG-12 and VG-20 locations respectively. A graphite calorimeter was used for the measurements as described in IDO-16652.^[5] The axial profiles for each facility are shown in Figure 24.

D. Pebble Bed Heat Transfer Transient Tests

Several transient tests were performed to gain information on the overall heat transfer processes in the MTR pebble bed. The tests consisted of measuring pebble and air temperature decay as a function of

time following a scram and measuring temperature as a function of time when the coolant air flow was changed by starting and stopping the standby blower with the reactor at full power.

1. Transient Scram Tests

Of the twelve pebbles that were instrumented with thermocouples during the construction of the MTR, only three appear to be functioning at the present time. One of these thermocouples provides an alarm signal. The other two thermocouples, designated B-3 and B-5, were connected to single point recorders together with a pebble bed air temperature measuring thermocouple, A-3. Temperature-time traces were obtained for the above thermocouples following a scram after the reactor had operated at normal conditions (40 MW) for at least 24 hours prior to the scram. The transient was monitored for approximately one hour.

The normal coolant air flow (two blowers) was maintained during the transient. The results are shown in Figures 25 and 26. The erratic behavior and slow response of the B-5 pebble is believed to be caused by poor thermocouple-pebble contact. Therefore, only the B-3 instrumented pebble data were used for calculations. The location of the B-3 instrumented pebble and A-3 air thermocouple are west of the N-S reactor centerline and at the reactor midplane elevation and approximately 3 in. from the reactor tank outside wall.

Additional scram transient tests were performed using the newly installed instrumented pebbles in VG-12 and VG-20. The thermocouples were connected to the MTR data logger and the results shown for two pebbles in Figures 27 and 28 based on continuous logging of data which provides a readout approximately every 100 sec.

2. Coolant Flow Transient Tests

The same instrumented pebbles and air thermocouple, B-3, B-5 and A-3 and associated recorders, were subjected to a flow transient. With the reactor operating at normal power and air coolant flow (two blowers), the standby air blower was turned on and operated until the pebble and air temperature stabilized (approx. 45 min.). The standby blower was then turned off. The results of the transient are shown in Figures 26 and 29. The B-5 pebble thermocouple behaved erratically in the same manner as previously described. The air flow meter was off scale when three blowers were operated.

3. Heat Transfer Calculations Based on Transient Tests

The gamma energy absorbed by the graphite pebbles is transferred by convection to the air coolant and conduction through the bed to the reactor tank wall. These mechanisms are inter-related by the complex air and heat flow paths through the bed. Since this work made no attempt to obtain the detailed data necessary to separate the various mechanisms of heat and mass flow, a heat transfer rate, assuming only transfer from the pebbles to the air, was calculated.

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FIGURE 22

MTR REACTOR AIR FLOW SCHEMATIC

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FIGURE 23

MTR PEBBLE BED AXIAL TEMPERATURE PROFILES

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FIGURE 24

AXIAL GAMMA HEAT PROFILES IN THE MTR PEBBLE BED

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FIGURE 25

MTR GRAPHITE PEBBLE BED TEMPERATURE -
TIME BEHAVIOR DURING A SCRAM

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FIGURE 26

MIR GRAPHITE PEBBLE BED TEMPERATURE - TIME BEHAVIOR

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FIGURE 27

MTR GRAPHITE PEBBLE BED TEMPERATURE - TIME BEHAVIOR - VG-12

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FIGURE 28

MTR GRAPHITE PEBBLE BED TEMPERATURE - TIME BEHAVIOR - VG-20

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FIGURE 29

MTR GRAPHITE PEBBLE BED TEMPERATURE -
TIME BEHAVIOR RELATED TO COOLANT AIR FLOW

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The rate of temperature change of the graphite pebbles was obtained from the initial slope of the time-temperature traces shown in Figure 25. The slopes at the start of the transients were used to approximate steady state power conditions. The results of the calculations show a heat transfer rate of 4 Btu/hr-pebble (h convection = 2.3 Btu/hr-ft²-°F) or 0.08 watts/gram.

E. Discussion of Results

The MTR pebble bed temperature profiles shown in Figure 23 do not exhibit the same slope as expected based on the gamma heat profiles shown in Figure 24. Several possible explanations could account for this discrepancy in results:

- (1) Inadequate pebble-thermocouple contact
- (2) Incorrect instrumented pebble position in the bed
- (3) Air flow channeling through the bed.

The instrumented pebble pre-insertion checkout coupled with good transient response data as shown in Figures 27 and 28 tend to rule out inadequate pebble-thermocouple contact. Improper location of the instrumented pebbles is considered unlikely because measurements of the thermocouple lead lengths after insertion substantiated the locations. Air flow channeling through the bed appears to offer the most likely explanation for the discrepancy. Unfortunately data is not available to evaluate this factor.

The heat transfer rate calculated from the transient test data agrees with measured gamma heat values for comparable reactor location.

VIII. ACCIDENT ANALYSIS

The MTR graphite pebble bed can potentially release stored energy accumulated by fast neutron exposure during its operating lifetime if a reactor accident causes the bed temperature to increase. This section of the report presents analyses of two credible reactor accidents that would cause the pebble bed temperature to increase:

- (1) Decrease in coolant air flow
- (2) Increase in reactor power.

A previous report^[2] has presented the results of a hypothetical maximum accident based on stored energy accumulation in the MTR pebble bed. This accident was re-examined with respect to the more recent data presented in this report.

A. Decrease in Coolant Flow Accident

Decrease in coolant flow could be caused by flow blockage of the air ducts, stack or pebble bed. The size of the respective channels involved makes this type of accident very unlikely. Partial blockage of the graphite bed is possible by graphite dusting, erosion and radiation damage effects. This is a long term effect and would be detected by a general rise in bed temperature over a long time interval.

A more likely cause of decreasing air flow is the loss of one of the two operating blowers. This accident has been chosen as the limiting accident for analysis for the following reasons:

- (1) The mechanical loss of two blowers together with safety circuit failure is not considered credible;
- (2) Loss of power to the blowers causes a reactor scram.

The MTR safety circuitry employs a fast setback when the air coolant flow decreases below a fixed set point. The circuit is backed up by a slow setback when the blower ΔP decreases below a fixed set point.

A stored energy release curve shown in Figure 30 was used in the analysis. The pebble used in obtaining this data contained the maximum stored energy of all pebbles previously sampled from the VG-10 location. Pebbles of higher stored energy have been sampled from VG-12, but the operating temperatures are correspondingly lower. Figure 31 shows the stored energy release rate based on Figure 30 as a function of temperature. The initial bed temperatures used in the analysis are high for the stored energy curve shown in Figure 30 leading to conservative results. The assumptions used in the analysis are as follows:

- (1) The heat transfer coefficient is constant over the transient temperature range. The variation of air properties with temperature was analyzed. Neglect

FIGURE 30

MTR GRAPHITE STORED ENERGY RELEASE CURVE

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FIGURE 31

MTR GRAPHITE PEBBLE BED STORED ENERGY RELEASE RATE AS A FUNCTION OF TEMPERATURE

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of the temperature effect on the properties is estimated to result in an error in heat transfer coefficient of less than 20% in the range of interest.

- (2) The heat transfer coefficient and coolant velocity are related by a first power dependency. This assumption is conservative for the analysis since the literature^[6] reports a velocity dependency to about the 0.6 power for packed beds.

The analysis consists of a point by point energy balance (in time) following the accidents. The gamma heat generation rate used in the analysis is 0.12 watts/gram at normal reactor power. This value is conservative since the location of measurement is closer to the core than the innermost pebbles.

Figures 32 and 33 show the pebble bed temperature behavior as a function of time at steady state temperatures of 200 and 240°F assuming no power reduction after losing one coolant fan. The time required for corrective action is 18 and 5 minutes respectively to prevent an uncontrolled energy release.

B. Step Increase in Power Accident

Increasing reactor power causes an increase in gamma heat absorbed in the pebble bed. Core and experimental changes in the MTR are also possible causes of gamma heat variations. These effects are small compared to reactor power changes. A step increase in reactor power provides the most severe temperature excursion. The MTR safety circuitry employs a reverse at 10% above normal power backed up by a setback. A scram occurs when the reactor power reaches 1.5 times normal operating level. Therefore, a step increase of 1.5 normal power was chosen as the limiting accident.

The stored energy release curve, gamma heat, and assumptions used in the decrease in coolant flow accident are also used in this analysis. The gamma heat was also assumed to be linearly proportional to reactor power in the analysis.

Figures 34 and 35 show the pebble bed temperature behavior following a step increase in reactor power of 1.5 times normal without a power reduction. The time required for corrective action is 31 and 8 minutes respectively for the 200 and 240°F steady state conditions. Normal power reductions accompanying the above accidents would terminate the temperature rise in much less than one minute.

C. Maximum Hypothetical Accident

A maximum hypothetical accident leading to an adiabatic release of stored energy in the MTR pebble bed reflector was evaluated in 1959^[2] using stored energy information obtained from VG-10 samples. The temperature rise for several graphite reflector zones were plotted

as a function of reactor operating time. In addition, the results were extrapolated to 1964 and 1969. The data obtained from work in this report and calculated using the same assumptions are shown in Figure 36, together with the original curves as reference. The data show that the adiabatic temperature rise in the pebble bed is only about one half the predicted value. Extrapolation of present data to 1969 yields a value of maximum temperature rise less than the original prediction for 1964.

Calculated MTR structure temperatures based on the above accident are less than allowable values^[2] for MTR operation to at least 1969.

Some damage to ionization chambers is possible following this accident if coolant air flow to the chamber housings is not sufficient.

FIGURE 32

MTR GRAPHITE PEBBLE BED TRANSIENT LOSS OF ONE COOLING FAN NO POWER REDUCTION

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FIGURE 33

MTR GRAPHITE PEBBLE BED TRANSIENT LOSS OF ONE COOLING FAN NO POWER REDUCTION

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FIGURE 34

MTR GRAPHITE PEBBLE BED TRANSIENT STEP INCREASE
TO 1.5 TIMES NORMAL POWER NO SCRAM

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FIGURE 35

MTR GRAPHITE PEBBLE BED TRANSIENT STEP INCREASE
TO 1.5 TIMES NORMAL POWER NO SCRAM

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FIGURE 36

MTR PEBBLE BED TEMPERATURE RISE BASED ON
ADIABATIC STORED ENERGY RELEASE

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IX. REFERENCES

- [1] E. Fast, Graphite Damage as an Index to the Integrated Damaging Neutron Flux, IDO-16182, September 1954.
- [2] E. Fast, E. H. Smith, and J. D. Ford, A Proposal for the Controlled Release of Stored Energy in the MTR Reflector Graphite, IDO-16656, December 1959.
- [3] R. E. Nightingale, Editor, Nuclear Graphite, New York: Academic Press, (1962).
- [4] Maximum Permissible Concentration of Radio Nuclides in Air and in Water for Occupational Exposure, Handbook No. 69, National Bureau of Standards, U. S. Department of Commerce, June 1959.
- [5] L. D. Weber and C. H. Hogg, MTR Gamma Heat Generation Measurements, IDO-16652, May 1961.
- [6] W. H. MacAdams, Heat Transmission, (3rd Edition), New York: McGraw-Hill Book Co., Inc., (1954).

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