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ANALYSIS OF THE STORED ENERGY
DISTRIBUTION IN D REACTOR

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ANALYSIS OF THE STORED ENERGY
DISTRIBUTION IN D-REACTOR

W. C. Morgan

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Nonmetallic Materials Development Operation
Hanford Laboratories Operation

May 19, 1961

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ANALYSIS OF THE STORED ENERGY DISTRIBUTION IN D-REACTOR

W. C. Morgan

INTRODUCTION

Previous investigations have to some extent characterized the buildup of stored energy as a function of exposure for controlled temperature irradiations.^(1,2,3) The work of Ballinger⁽⁴⁾ contributed to the knowledge of stored energy accumulation in the reactor moderator, but a complete evaluation of the stored energy situation in the HAPO reactors has not been attempted.

The purpose of this document is to characterize, as completely as possible, the stored energy distribution in D Reactor as of March, 1958, the date of the last stored energy survey⁽⁵⁾, and to estimate the temperature rises which can be expected to occur during a stored energy release. D Reactor was chosen for this study only because it represents one of the oldest operating Hanford reactors and not because of any circumstances peculiar to this reactor.

SUMMARY

A loss of coolant to D Reactor can cause two distinct spontaneous stored energy releases in the graphite moderator. Each stored energy release will start at the bore of the process tube-block. A thermal wave with a sharp front will propagate radially out from the bore as additional stored energy is released by the moderator. Local temperatures in the wave front are expected to exceed 900° C during the first spontaneous release and 1800° C during the second spontaneous release.

No attempt has been made to extrapolate the 1958 stored energy content of

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D Reactor to the present time. However, 40 percent of the total reactor exposure has occurred after March, 1958, and there may have been considerable increases in the stored energy content since that time. The graphite temperatures have not changed enough during the same period of time to accomplish much annealing.

DISCUSSION

Distribution of Stored Energy in a Reactor

Results of various controlled temperature irradiations of graphite in the HAP0 reactors^(1,3) have shown that the rate of stored energy accumulation is reduced as the total stored energy content increases and as the irradiation temperature is raised. Since various regions of a reactor are at different temperatures and exposure levels, the stored energy is not uniformly distributed.

The estimation of stored energy accumulation in a reactor starting from a knowledge of only the reactor temperatures and exposures is much too complicated to be attempted. During normal operation the temperature distributions are not constant, and the dependence of stored energy accumulation rate on neutron energy is not known with any degree of certainty. The distribution of stored energy in a reactor can be established from systematic sampling of the graphite throughout the moderator. However, no extensive sampling of the HAP0 reactors has been performed, so the stored energy in an entire reactor must be estimated by analogy with conditions in regions of the reactors where measurements have been made. Two methods have been used to obtain moderator samples for stored energy measurements:

1. Mining - scraping a thin layer of graphite powder from a moderator block.
2. Coring - cutting a small cylindrical plug of graphite from the process tube-block wall.

Heat of combustion measurements have been made on these samples to obtain the stored energy content. Furthermore, the interlayer spacing or c spacing in

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graphite crystals is related to the stored energy content⁽⁵⁾ and can be used to estimate the stored energy of any graphite sample.

Release of Stored Energy

The manner in which stored energy is released as the graphite is heated is as important as the total amount of energy released. Annealing studies of the irradiated samples indicate that the stored energy content is released in several distinct annealing peaks^(6,7):

Stored Energy Release Peak I	- 100-350° C
II	- 350-500° C
III	- 600-900° C
IV	- 1000-1600° C
V	- 1700-2000° C

A sample containing only 514 cal/gm stored energy, mined from 2273-D on February 8, 1950, near the reactor center line, was used to determine the amount of stored energy released in each 100° temperature increment from 0° C to 2000° C⁽⁶⁾. The results of this experiment are presented in Figure 1. The stored energy released in Peaks I, II and IV exceeds the specific heat of the sample and would result in spontaneous temperature increases.

Figure 2 is a plot of the total stored energy accumulation as a function of exposure at 30° C and the approximate amount of stored energy remaining after thermal anneals to various temperatures*. The extrapolation of these curves from a limited amount of data below 5000 MWD/AT to exposures of 15,000 MWD/AT is admittedly not a desirable practice. Although checks will be made at a later date, the extrapolated data are the best available at the present time.

TOTAL STORED ENERGY CONTENT OF D-REACTOR

Core samples were obtained on March 27, 1958, from the top of process tube

* Data collected by the author from notebooks and reports of several Hanford researchers.

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channel 2477-D at positions 9', 9'4", 10', 12' and 22' from the front Van Stone flange. Total stored energy was determined for the top and bottom halves of the 9'4" and 22' core samples.

Distribution of stored energy in the cores was obtained from c spacing measurements. Figure 3 is a plot of total stored energy as a function of c spacing* for core samples taken from all the HAP0 reactors⁽⁵⁾. c spacings were obtained at 1/16 inch intervals along the D Reactor core samples. Figure 4 is a plot of c spacing versus distance along the core for the samples taken at 9'4" and 22'. Figure 5 was derived from the data in Figures 3 and 4 and is a plot of total stored energy versus distance for the same samples. The stored energy curve for the 22' core has been adjusted slightly so the integrated stored energy in each half of the core is equal to the total stored energy determined by NBS. The same steps were performed for the 9', 10' and 12' samples except that NBS total stored energy data were not available. The total stored energy for the 9' and 10' samples were obtained directly from Figure 4 and the sample c spacings. Total stored energy for the 12' core was adjusted to a maximum of 650 cal/gm at the bore end of the sample. Figures 6, 7 and 8 are plots of stored energy versus distance for these samples.

Previous estimates of the total stored energy content of the filler graphite were based on the assumption that graphite near process channels which had operated for a significant length of time without a fuel charge contained slightly more stored energy than the surrounding filler graphite⁽⁵⁾. Such an estimate gives much lower amounts of stored energy than are obtained by extrapolation of the data in Figures 5 through 8 into the filler blocks. The extrapolation procedure

* The designation "c spacing" is used here to apply to twice the interlayer spacing as obtained from x-ray data which was not corrected for broadening of the diffraction peak. The peak broadening corrections were not applied to x-ray data obtained at Hanford prior to mid-1958.

should be accurate since there is no significant temperature discontinuity at the tube block-filler block interface. Furthermore, the former estimates may be low because recent data obtained from C Reactor⁽⁸⁾ indicate that uncooled tube blocks may contain less stored energy than filler blocks. The stored energy content of filler end of a core, obtained from uncooled process channel 1960-C at 19' from the front Van Stone flange in March of 1958, averages 29 cal/gm. This is to be compared with a stored energy content of 48 cal/gm obtained from a graphite bar irradiated in G test hole at C Reactor from start-up to July, 1959. The lower amount of stored energy in the hot tube blocks may be the result of a stored energy release, occurring during the first operation of the process channel at high temperature after tube removal. Radiation annealing could further reduce the stored energy content of the hot tube blocks.

D Reactor has a significant history of operation at lower temperatures than the original temperatures at C Reactor. At the lower temperatures the stored energy content of all the annealing peaks accumulates at a much more rapid rate than at the higher operating temperatures. Furthermore, at low temperatures as the stored energy content approaches saturation, a larger fraction of this stored energy is concentrated in the high temperature release peaks than when the total amount of stored energy is small⁽³⁾. Thus, the filler block stored energy contents extrapolated from the measurements made in the tube blocks do not seem unreasonable even though the stored energy content is much larger than that found for the bar taken from G test hole of C Reactor.

Previous calculations⁽⁹⁾ of the temperature distribution outward from the process tube have indicated that the isotherms may be approximated by a series of concentric circles centered around a point about one-third of the process tube diameter vertically up from the bottom of the process tube channel. Total stored energy distributions are related to the temperature distribution.

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For convenience in averaging the stored energy content of a reactor lattice, ten 0.5 cm thick stored energy zones, as shown in Figure 9 were considered. Figure 10 is a plot of the total stored energy distribution along the process tube for each stored energy zone of Figure 9; smooth curves were fitted to the data points obtained from the solid lines in Figures 5 through 8. The total stored energy in the front fringe graphite was extrapolated to zero at the edge of the moderator; this procedure may result in a low estimate of the stored energy in the front fringe. In particular, stack height traverses⁽¹⁰⁾ show graphite expansion which may be indicative of as much as 300 cal/gm of stored energy at the edge of the stack.

During all of the calculations the stored energy distribution in the reactor was assumed to be symmetrical with respect to the centerline planes. Therefore, the 22' core data were used as $\bar{C}$ minus 1'3" instead of $\bar{C}$ plus 1'3".

Figure 11 is a cutaway drawing of an idealized old reactor moderator. The central active region process tube-blocks in this ideal model, all have the same radial stored energy distribution. Across the fringe active region, from the E metal charge to the outside process tubes, the temperature decreases, but the neutron flux is still high and consequently the stored energy content increases. Across the inactive fringe region the stored energy content decreases due to the decrease in high energy neutron flux with distance from the outside process tubes. Figure 12 is a diagram of the front face, for the cutout reactor section of Figure 11, showing the reactor regions.

It is possible to estimate the stored energy content and distribution in the process tube blocks of the active fringe region by assuming that the side-to-side stored energy change with distance out from the E metal ring is proportional to the stored energy change with front-to-rear distance along a central zone process

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tube. No stored energy data were obtained for the fringe regions of D Reactor.

Having made the above approximations, the total stored energy accumulated at any position in the reactor can be estimated and, by averaging the amount stored in each stored energy zone of each lattice unit, the average total stored energy content of the reactor can be obtained.

The average stored energy content of the reactor will not aid in the prediction of release rates nor temperature excursions to be expected in the event of a stored energy release. Therefore, it is of no concern here and will not be derived.

STORED ENERGY RELEASE

Loss of coolant from a reactor will result in redistribution of heat in the graphite accompanied by additional temperature rise due to fission product decay. During such an incident some of the graphite containing large amounts of stored energy may be subjected to much higher temperatures than those experienced during equilibrium operation.

In order to estimate the additional temperature rises which can result from the spontaneous release of stored energy, the amount of stored energy releasable as a function of temperature is needed. There are no recent data available for the reactors, but the approximation is made that the stored energy has been saturated under cold ($\sim 30^\circ \text{C}$) irradiation conditions, and then partially annealed to the present total stored energy content.

If the above assumption is valid for D Reactor, the stored energy distribution in the graphite adjacent to the process tubes was approximately as follows (see Figure 2) before the hypothetical thermal anneal:

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<u>Stored Energy Release Peak</u>	<u>Temperature Range of Peak</u>	<u>Stored Energy Content</u>
I	100-350 °C	130 cal/gm
II	350-500	80
III	600-900	70
IV	1000-1600	315
V	above 1700	55
Total stored energy content:		650 cal/gm

Thus, a sample containing 520 cal/gm would not show a release of stored energy until a temperature of more than 350° C was reached.

This assumption should be a good approximation for the cooler zones of an old reactor where significant exposures were obtained at low operating temperature. The stored energy content of the newer reactors, which have not been operated at low temperature, almost certainly cannot be obtained by this method because the stored energy content of the filler is probably still increasing.

Even in the old reactors such as D, the stored energy content of the central filler graphite may have been reduced by radiation annealing as well as thermal annealing. Radiation annealing can reduce the stored energy content of the high temperature release peaks without removing all of the stored energy from lower temperature peaks. The assumption that the stored energy content was reduced by a thermal anneal, which would first remove all stored energy from the lowest temperature release peaks, may result in underestimating the stored energy content of release Peaks I, II and III for the filler graphite. At the same time the energy content of Peaks IV and V will be overestimated. However, no data are available on which to base an estimate of the amount of radiation annealing which might have taken place. Radiation annealing will be ignored in the following development, but if radiation annealing is significant the average temperature rise due to the first spontaneous stored energy release will be underestimated and the average temperature rise due to the second spontaneous stored energy release

will be overestimated. The maximum temperatures, reached in either release, will not be affected because they are reached at positions where neither thermal nor radiation annealing loss occurred.

As an example of a calculation of the temperature increases during a stored energy release, consider the 12' core where the stored energy is distributed as in Table I.

TABLE I
STORED ENERGY DISTRIBUTION

<u>Stored Energy Zone</u>	<u>Total Stored Energy</u>	<u>Stored Energy in Release Peak (in cal/gram)</u>				
		<u>I</u>	<u>II</u>	<u>III</u>	<u>IV</u>	<u>V</u>
1	650 cal/gm	130	80	70	315	55
2	650	130	80	70	315	55
3	645	125	80	70	315	55
4	595	75	80	70	315	55
5	480	0	40	70	315	55
6	360	0	0	10	295	55
7	265	0	0	0	210	55
8	200	0	0	0	145	55
9	155	0	0	0	100	55
10	145	0	0	0	90	55

Since the number of grams of graphite in any zone is proportional to the cross-sectional area, Table II may be used to average the amount of stored energy in several zones.

TABLE II
CROSS-SECTIONAL AREA OF STORED ENERGY ZONES

<u>Stored Energy Zone</u>	<u>Radius</u>	<u>Cross-Sectional Area</u>
Process Tube	2.22 cm	---
1	1.95	1.71 cm ²
2	2.45	3.64
3	2.95	6.50
4	3.45	10.1
5	3.95	11.6
6	4.45	13.2
7	4.95	14.8
8	5.45	16.3
9	5.95	18.8
10	21.3 cm ²	342.6

Total Lattice Area: 438.2 cm²

If, because of some unusual circumstance, like a loss of coolant accident, a uniform temperature through the lattice of about 150° C is established, a spontaneous stored energy release will begin at the inside of the process tube-blocks at Zone 1. Considering the heat capacity of Zone 1, the spontaneous release of 130 cal/gm stored energy from Peak I produces a temperature higher than that necessary to begin the spontaneous release of 80 cal/gm stored energy in Peak II, which in turn produces a higher temperature than needed to initiate the spontaneous release of 70 cal/gm stored energy in Peak III. If the thermal wave front progresses at a rate of 2.5 cm per minute*, then at the end of 12 seconds Zone 1 should be at a uniform temperature of about 910° C.

At the end of each 12-second interval the wave propagates through a zone and the average stored energy ($\overline{\Delta SE}$) released in the zones, through which the wave front has progressed, can be calculated:

$$\overline{\Delta SE} = \frac{\sum_{i=1}^j \Delta SE_i A_i}{\sum_{i=1}^j A_i}$$

where:

- j is the last zone traversed by the wave front
- ΔSE_i is the stored energy released in the ith zone
- A_i is the cross-sectional area of the ith zone

The temperature should be almost uniform across the zones traversed by the wave front and the average temperature can be found from the integrated specific heat curve for graphite⁽¹¹⁾ shown in Figure 13.

* Calculated wave front velocities of 1.2⁽¹²⁾ to 3⁽¹³⁾ cm per minute have been reported; the value of 2.5 cm per minute used above was determined experimentally by H. A. Fowler⁽¹⁴⁾ for HAPO irradiated graphite.

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TABLE III

FIRST STORED ENERGY RELEASE SEQUENCE

<u>Time, t</u>	<u>Zones</u>	<u>ΔSE of Last Zone</u> <u>cal/gm</u>	<u>ΔSE</u> <u>cal/gm</u>	<u>Average Temperature at</u> <u>time, t, in annealed zones</u>
12 sec.	1	280	280	910° C
24 sec.	1 & 2	280	280	910° C
36 sec.	1 to 3	275	278	905° C
48 sec.	1 to 4	220	251	845° C
1 min.	1 to 5	70	174	660° C
1 min. 48 sec.	1 to 9	0	62	365° C
~3 min. 30 sec.	1 to 10	0	13	205° C

A second spontaneous release would begin if a graphite temperature of about 1150° C were established by some means, and the release sequence can be followed in the same manner as the first release.

TABLE IV

SECOND STORED ENERGY RELEASE SEQUENCE

<u>Time, t</u>	<u>Zones</u>	<u>ΔSE of Last Zone</u> <u>cal/gm</u>	<u>ΔSE</u> <u>cal/gm</u>	<u>Average Temperature at</u> <u>time, t, in annealed zones</u>
12 sec.	1	315	315	~1800° C
1 min.	1 to 5	315	315	1800° C
1 min. 12 sec.	1 to 6	295	310	1795
1 min. 24 sec.	1 to 7	210	285	1745
1 min. 36 sec.	1 to 8	145	256	1685
1 min. 48 sec.	1 to 9	100	227	1625
2 min. 24 sec.		70	164	1500
~3 min. 30 sec.	1 to 10	30	79	1320

The actual temperatures experienced during each release will be dependent on the distribution of the stored energy in the release peaks. For example, if the amount of stored energy in release peaks I, II or III has been underestimated by more than 70 cal/gm, part of release peak IV could be annealed during the first stored energy release. This could cause the maximum temperature during the first stored energy release to approach 1600° C, but it would also reduce the maximum

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temperature observed during the second stored energy release. Therefore, the amount stored in each release peak must be determined if the temperatures are to be predicted accurately during the release.

RECOMMENDATIONS AND CONCLUSIONS

The release of stored energy in D Reactor, which could result from an incident such as loss of coolant, can be expected to result in a spontaneous temperature rise. A critical evaluation of the effects of the stored energy release on the control criteria for the reactor should be made.

The results presented, although indicative of the magnitude of the stored energy content, are not expected to be exact. Furthermore, changes made in reactor operations since March, 1958, probably have altered the stored energy distribution slightly. The maximum temperature of the filler graphite has been increased from 600 to 650° C, but there is very little thermally annealable stored energy in this temperature range. The increased fuel column length may cause small amounts stored energy annealing at about 4' in from the front and rear edges of the graphite, but the increase in length will also shift the flux and cause a rapid buildup of stored energy at about 2 feet in from the edge of the graphite. The most significant factor which will affect the stored energy content is the increase in neutron exposure from about 2.1×10^6 MWD total reactor power in March of 1958, to approximately 3.5×10^6 MWD at the present time. It is expected that this increase in exposure has increased the stored energy content at every point in the reactor above that derived from the 1958 data.

In order to better characterize the stored energy content of D Reactor a sampling program should be initiated as soon as possible. The results obtained from this sampling program will be useful in determining the need for a sampling program at other reactors.

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FIGURE 1

Stored Energy Content of Mined Sample 2273-D, 2/8/50

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FIGURE 2

Stored Energy Accumulation as a Function of Exposure at 30°C
and Stored Energy Remaining after Thermal Anneals to Selected Temperatures

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FIGURE 3

Stored Energy vs ϵ Spacing - Cores From Graphite Tube Blocks

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FIGURE 4

c Spacing vs Distance Along Core Sample 2477-D, 3/27/58
Samples Taken at 9'4" and 22" from Front Van Stone Flange

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FIGURE 5

Total Stored Energy Distribution of Sample 2477-D, 3/27/58
Samples Taken at 9' 4" and 22' from Front Van Stone Flange

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FIGURE 6

Total Stored Energy Distribution of Sample 2477-D, 3/27/58
Sample Taken at 9" from Front Van Stone Flange

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FIGURE 7

Total Stored Energy Distribution of Sample 2477-D, 3/27/58
Sample Taken at 10' from Front Van Stone Flange

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FIGURE 8

Total Stored Energy Distribution of Sample 2477-D, 3/27/58
Sample Taken at 12' from Front Van Stone Flange

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FIGURE 9

Radial Stored Energy Zones of a Reactor Lattice

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FIGURE 10

Total Stored Energy Distribution vs Distance along Process Tube 2477-D, 3/27/58

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FIGURE 11

Cutaway View of an Idealized Old Reactor Moderator

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FIGURE 12
View of Old Reactor Moderator Face

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FIGURE 13

Integrated Specific Heat of Graphite vs Temperature

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