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CHEMISTRY DIVISION

CALORIMETRIC MEASUREMENT OF RADIATION ENERGY DISSIPATED BY VARIOUS
MATERIALS PLACED IN THE OAK RIDGE PILE

D.M. RICHARDSON

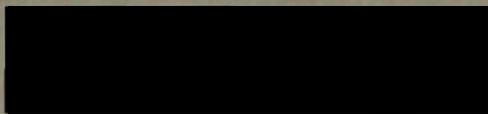
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Chemistry Division

CALORIMETRIC MEASUREMENT OF RADIATION ENERGY DISSIPATED BY VARIOUS
MATERIALS PLACED IN THE OAK RIDGE PILE

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D. M. Richardson

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ABSTRACT

The total amount of energy absorbed by carbon, water, heavy water, aluminum and bismuth in Hole #12 of the Oak Ridge pile was determined calorimetrically. The calorimeter consisted essentially of two concentric aluminum cylinders with an air gap between, good thermal insulation being provided at each end; the steady-state temperature difference across the gap provided a measure of the rate of heat production of the material inside. Calibration was obtained by electrical heating of the inner cylinder. By use of an assumed fast neutron spectrum, the observed heats were broken down into the parts arising from neutron scattering and gamma-ray absorption. The results are probably accurate to about 3%, and energy absorbed by practically any material from pile radiation at the point of measurement can be estimated from the results. The fast neutron flux obtained from the calorimetric results checked well with a determination of the amount of n_{pp} reaction on sulfur. Use of the present results for obtaining energy absorbed at any other point in the pile graphite is discussed.

I. INTRODUCTION

Of basic importance in the study of the effect of radiations on matter is the quantity of radiation energy which is absorbed by the material under study. With most sources of radiation this quantity is quite readily estimated. For materials exposed to radiation from a nuclear reactor, however, even a rough estimation of the quantity of energy absorbed is difficult, and an accurate estimation practically impossible. Materials placed in the pile absorb energy by slowing down fast neutrons, by absorption of γ -rays produced during fission and from the decay of fission products, and by self-absorption of rays from the radioactivities induced in the materials themselves. The flux and spectrum are not accurately calculable in a thermal pile for either the fast neutrons or the γ -rays. A large number of experiments on the effect of pile radiation on water and other materials has been performed by members of the Chemistry Division at Oak Ridge National Laboratory. Proper interpretation of these experiments obviously requires a knowledge of the energy absorbed by the material during its sojourn in the pile and, if possible, the distribution of this energy between that produced by fast neutrons and that caused by absorption of γ -rays. It was therefore decided to measure this energy absorption by a calorimeter.

Such a calorimetric measurement in the pile is subject to certain unusual difficulties. All parts of any sort of calorimeter placed in the pile will absorb radiation and generate heat, so that some special provision must be made for distinguishing between heat generated by the sample material and that being produced in the rest of the apparatus. This problem does not arise in ordinary calorimetry, and an unusual design, therefore, needed to be devised.

In Hole 12 of the pile, a constant-temperature jacket of flowing water around the hole provides a favorable thermal environment for calorimetric work. Early rough experiments in which test tubes containing water, mercury and other materials were lowered into this hole showed that pile radiation was sufficient to raise the temperatures of the materials many degrees above the surroundings, thus indicating the feasibility of a calorimetric measurement. A measurement of the heat produced in water by pile radiation was later attempted by Mr. John Ghormley⁽¹⁾. He used an evacuated double-walled silica vessel shaped like a Dewar flask, with water in the inner container. A thermocouple was placed in the water, and another thermocouple was taped to the outside of the vessel. The assembly was cooled to a temperature somewhat lower than the ambient temperature in Hole 12 and then lowered into the hole. The outer wall quickly warmed to a temperature slightly above the ambient temperature; the temperature of the water rose more slowly but reached and then exceeded the temperature of the outer wall. At the instant when the two temperatures were equal, it was assumed that no heat was being transferred to the water from the outside, and consequently the rate of temperature rise of the water indicated the rate at which the water was receiving heat from radiation. Difficulties with this method lay in maintaining a uniform temperature within the water specimen, the uncertainty that the outer thermocouple gave accurately the effective temperature of the outer vessel wall, and the uncertain correction for the amount of heat contributed by the wall of the inner vessel and by the connection between the inner and outer vessels.

In considering how the measurement could be refined, it was thought better to abandon any kinetic method such as that of Ghormley, and rely

instead upon a steady-state method, in which the total heat flow across a boundary surrounding the material was determined by the steady-state temperature difference across this boundary. This method also provided the possibility of direct comparison of the heat generated by the sample with heat introduced electrically. Measurements have now been carried out which are believed to represent the true heat production in samples irradiated in Hole 12, with an accuracy of a few per cent.

II. EXPERIMENTAL

1. Method. The calorimeter consisted essentially of two coaxial aluminum cylinders with a thermocouple embedded in each. Within the inner cylinder was placed either a can containing the sample, or an identical can containing only air. The heat generated within the inner assembly was conducted mainly across the air gap between the two cylinders, good thermal insulation being provided at the ends of the cylinders. A coil of fine wire was also embedded in the wall of the inner cylinder, through which electrical heat could be imparted to the system at an accurately known rate. The relationship of the temperature difference between the inner and outer walls and the total heat produced within the inner assembly was thus determined empirically. The difference in heat production with the sample present and with the empty can present was the quantity to be determined.

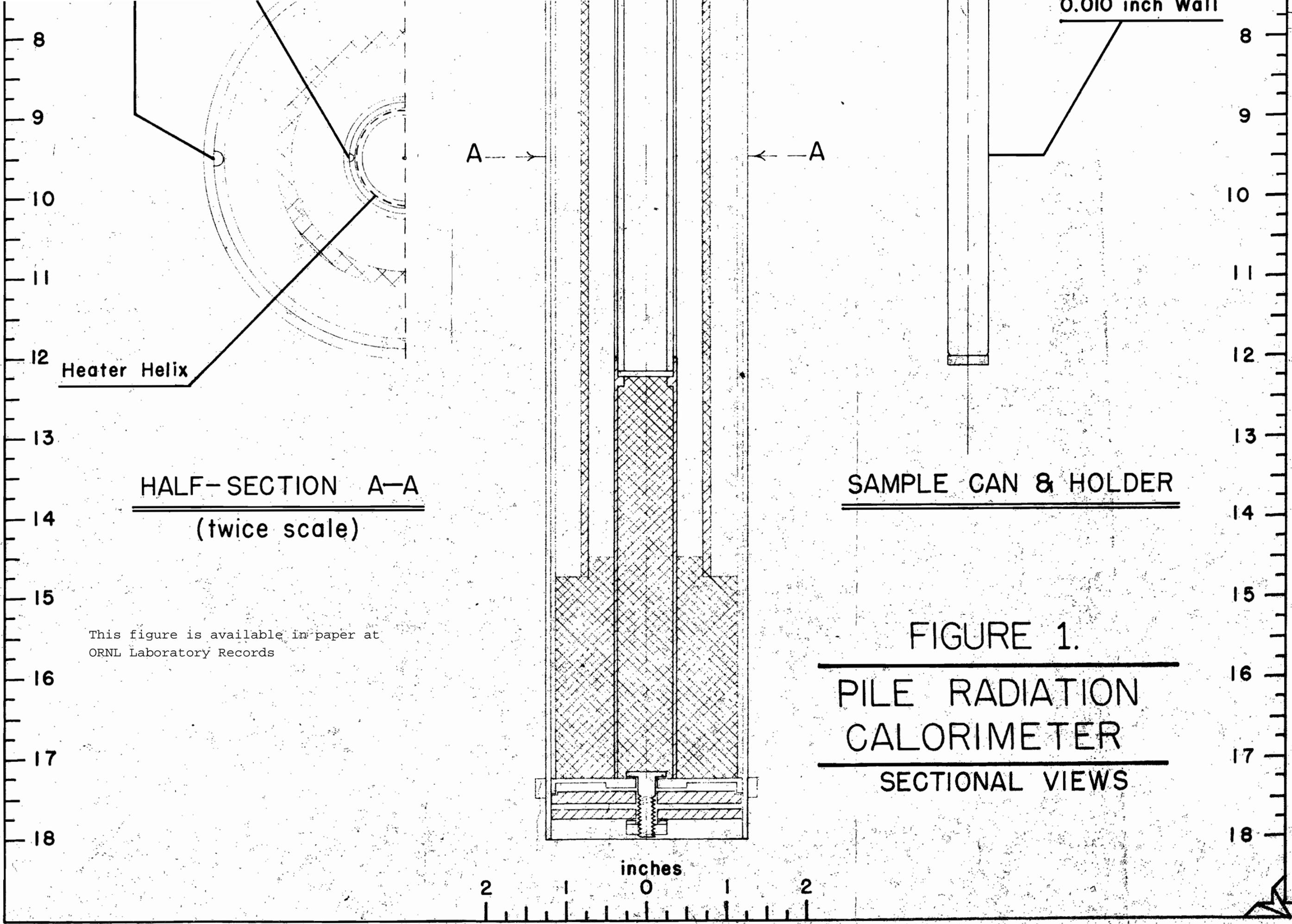
The assembly was restricted to dimensions conformable to the size of the hole, which is about 3" in diameter. The equation for heat conduction between concentric cylinders is⁽²⁾

$$Q/L\Delta T = \frac{2.73 K}{\log_{10} r_2/r_1}$$

where $Q/L\Delta T$ is the heat flow per unit length in cal/sec/degree temperature difference, χ is the specific conductivity of the material in the gap and r_2 and r_1 are the outer and inner radii of the gap. Thus, the rate of heat flow depends upon the ratio of the outer and inner radii, and not upon the actual width of the air gap. It was necessary to make the resistance of the gap to heat flow as large as possible in order to obtain an accurately measurable temperature difference. This required a large ratio between outer and inner radii. At the same time the diameter of the inner assembly should not be too small, because the mass of the sample should form a considerable part of the total mass of the inner assembly. Increasing the width of the air gap favors convection, which, if prominent, will cause a non-linear relationship between temperature difference and rate of heat transfer. It has been stated⁽³⁾ that with an air gap of 12 mm, such convection effects are already appreciable. In the present calorimeter a considerably wider air gap was used, but convection was minimized by placing a thin sleeve of Styrofoam (polystyrene foam) in the middle of the air gap between the aluminum cylinders. A linear relationship between the heat flow and temperature difference was found, and readily measurable temperature differences were obtained.

To minimize end effects a high ratio of length to diameter of sample can is obviously desirable. Since the neutron flux and therefore the rate of heat generation in any sample varies along the hole, it is desirable that the can should be made no longer than necessary. A length-diameter ratio of 10 was arbitrarily chosen.

2. Construction of calorimeter. Figure 1 shows a section through the length of the calorimeter. Diameters of the various sections of the



This figure is available in paper at
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inner and outer cans are shown in Table 1. The innermost section of the inner cylinder carried the heater wire. A square thread, 40 to the inch, was cut over a length of 5" on this cylinder to receive the heater wire, and slots were provided at the ends to bring out the lead wires. The 2S aluminum flowed considerably during the cutting of this thread, causing a bulging of the outer parts; the outside of the piece was machined down and the threads chased, leaving a shallow groove in which the heater wire readily fitted. The heater consisted of 979.2 cm. of enameled and double-silk-covered #38 copper wire. The leads from the ends of the can to the spiral part consisted of 3.3% of the total length of wire. The length of the spiral was exactly equal to the inside length of the sample can so that the distribution of heat produced by the heater and by the sample should be similar. The heater wire leads were brought out at the top and bottom of the assembly through ceramic plugs swaged into the aluminum, and upon emerging from the calorimeter were connected to large diameter lead wires which led to the outside of the pile.

In estimating the electrical heat input to the assembly, when comparison is made between electrical heat input and temperature difference, it was assumed that 3.3% of the heat was being generated in the leads and therefore should not be counted. Since the leads were surrounded with insulating material, they were presumably warmer than the spiral part of the wire so that their specific resistance was probably somewhat higher; and if this temperature difference was as much as 50°C. the probable correction figure should be 4% rather than 3.3%. This introduces a possible error of a few tenths of a per cent in the determination. Another possibility is that, because of electrical heating of the lead wires, the end losses of heat may

be slightly less important when the heater is on than when the heater is off and the sample is supplying the heat. The error from this cause is probably negligible.

Table 1

Diameters of Calorimeter Parts

	I.D., in.	O.D., in.
Sample can	.500	.520
Inner wall (1)	.53125	.620
Inner wall (2)	.620	.680
Inner wall (3)	.680	.750
Outer wall (1)	2.250	2.375
Outer wall (2)	2.375	2.500

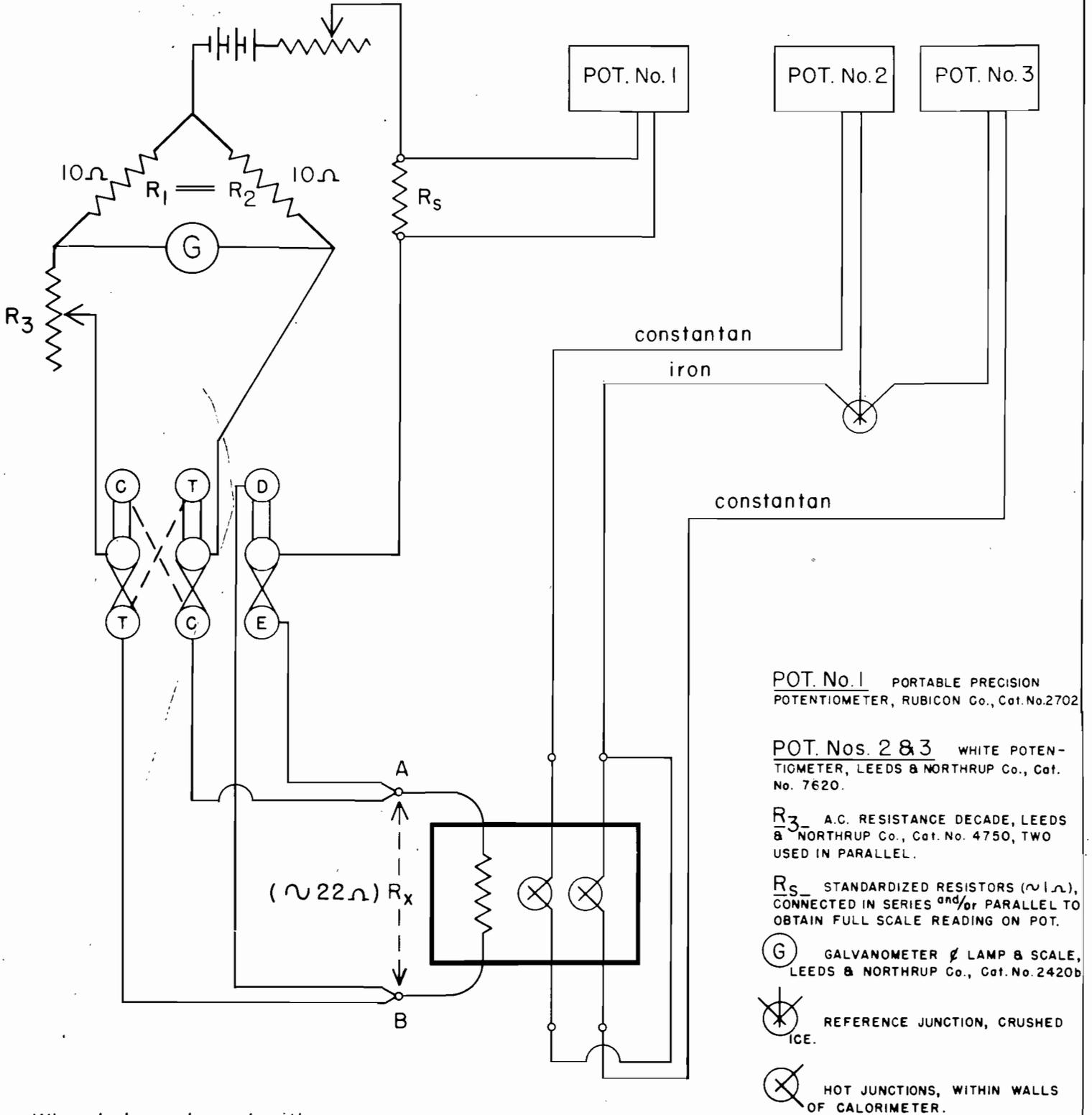
The inner can was held in place by sleeves of polystyrene, machined to a thickness of $1/32''$, and insulation at the ends was provided by pieces of Styrofoam. This material has a density of 0.027 g/cc and a specific heat conductivity of $1.0 \times 10^{-4} \text{ cgs. units}^{(4)}$, and is readily machined. The Styrofoam was found to be surprisingly free of radioactivity after being exposed in the pile. After being in the pile over a month the material became yellow and very brittle but remained sufficiently cohesive to maintain its function. From the conductivities of Styrofoam, polystyrene and lead wire materials, it is calculated that the heat lost by conduction out the ends was less than 1% of the total heat produced in the inner assembly. To avoid heat loss by any chimney effect around the sample can, an aluminum plate was placed across the bottom of the inner assembly and the top of the sample can was provided with a shoulder which rested on the upper end of the inner cylinder. The center space below the inner can was blocked with

Styrofoam to prevent convection losses, while the polystyrene guide on the sample can served the same function at the upper end.

Using the formula for cylindrical heat flow given above, and taking the conductivity of air as 0.3×10^{-4} oga units, one calculates from the actual dimensions of the assembly that a heat input of 0.00125 cal/sec. should give a temperature difference across the gap of $5.2^{\circ}\text{C}.$, whereas the observed temperature difference was only $1.56^{\circ}\text{C}.$ The discrepancy probably arises from the effective heat conductivity of air being increased by convection, although this convection was not strong enough to produce any non-linearity in the relationship between heat input and temperature difference. Also, end losses through the air gap would cause ΔT to be smaller than expected from the formula, which applies rigorously only to infinite cylinders.

3. Electrical. The heat input was determined by simultaneous measurement of current and resistance. In the resistance measurement, the resistance of the 35-foot lead wires connecting the actual heater to the measuring instrument was eliminated by use of the method of potential terminal compensation, as used in Mueller type bridges⁽⁵⁾. The circuit used is illustrated in Figure 2. Measurement of the current, which was drawn from a storage battery, was accomplished by determination of the potential drop across a known resistance of 0.9974 ohms, evaluated by comparison with a Leeds and Northrup standard ohm, warranted by the makers to be accurate to 0.1%. It is estimated that the current measurement may be in error by 0.2%, leading to an error of 0.4% in determinations of the absolute heat input.

The thermocouple circuit is also shown in Figure 2. The iron-constantan thermocouple junctions in the calorimeter were made of #30 wire;



POT. No. 1 PORTABLE PRECISION POTENTIOMETER, RUBICON Co., Cat. No. 2702

POT. Nos. 2 & 3 WHITE POTENTIOMETER, LEEDS & NORTHRUP Co., Cat. No. 7620.

R_3 A.C. RESISTANCE DECADE, LEEDS & NORTHRUP Co., Cat. No. 4750, TWO USED IN PARALLEL.

R_s STANDARDIZED RESISTORS ($\sim 1\ \Omega$), CONNECTED IN SERIES and/or PARALLEL TO OBTAIN FULL SCALE READING ON POT.

G GALVANOMETER ϕ LAMP & SCALE, LEEDS & NORTHRUP Co., Cat. No. 2420b

\otimes REFERENCE JUNCTION, CRUSHED ICE.

\otimes HOT JUNCTIONS, WITHIN WALLS OF CALORIMETER.

When balanced, and with constant current:

$$\left(\otimes\right), R_3 + TB = R_x + CA$$

$$\left(= \right), R_3' + CA = R_x + TB$$

$$\text{Or, } R_x = \frac{R_3 + R_3'}{2}$$

HEATER & THERMOCOUPLE CIRCUITS FOR PILE CALORIMETER

FIGURE 2.

after emerging from the calorimeter the leads were joined to #20 wire of the same material. A single Leeds and Northrup galvanometer (Type HS having a sensitivity of 0.5 microvolts/mm. and a period of 1.5 seconds) was used for measurements with both White potentiometers.

In the first runs made with the calorimeter, a mistake in wiring was made by connecting the thermocouple leads to the measuring instruments through a double throw switch; this led to spurious thermocouple readings due to changes in room temperature, and all the results of these experiments had to be rejected. After the thermocouple wiring was changed, "background" heating (produced in the assembly by pile radiation when an empty sample can was present) showed no significant fluctuations with time.

4. Sample cans. The aluminum sample cans were welded at both ends. The sample material was placed in the can through a $5/32$ " hole at its top. The cans were made as uniform in dimensions as possible and their weights were uniform to within $\pm 0.3\%$. The polystyrene piece shown in Figure 1 served as a closure and as a guide in lowering the can into the calorimeter. The can was connected to the polystyrene piece by a steel pin shown in Figure 1 as a dot at the upper end of the can. The cans were lowered into the calorimeter by an aluminum wire which was looped around an aluminum pin at the upper end of the polystyrene guide. When the can was in place, there was a clearance of $1/16$ " between the upper part of the polystyrene piece and the inner wall of the calorimeter.

Water and heavy water react with aluminum at a considerable rate, yielding hydrogen, until the aluminum has been seasoned by long contact with water and a good protective film has formed on the metal. This reaction is highly exothermic, and it was necessary to be sure that it was not occurring

at an appreciable rate during the measurement period. The cans, after filling with water or D_2O , were accordingly placed in an oil bath at $80-90^\circ C.$, and the gas resulting from the aluminum corrosion was collected from time to time and measured. After seasoning at this temperature for eleven days the rate of hydrogen production had decreased to about 0.1 cc. per hour, corresponding to a heat production of 0.26 cal/hr. (based on a heat of reaction of 66,400 cal/mole⁽⁶⁾). The rate of corrosion in the pile was presumably much less than this because the temperature was only about $20^\circ C.$ Also, it is known that the corrosion of aluminum is not appreciably accelerated by radiation. Even if the corrosion rate had been as rapid in the pile as it was at 80° outside the pile, after eleven days of passivification, the rate of heat production would still have been less than 0.5% of that produced by radiation in a water sample. The error due to evaporation of water was negligible, since the polystyrene closure fitted very snugly, and after the assembly had come to a constant temperature in the pile no tendency to breathe was to be expected.

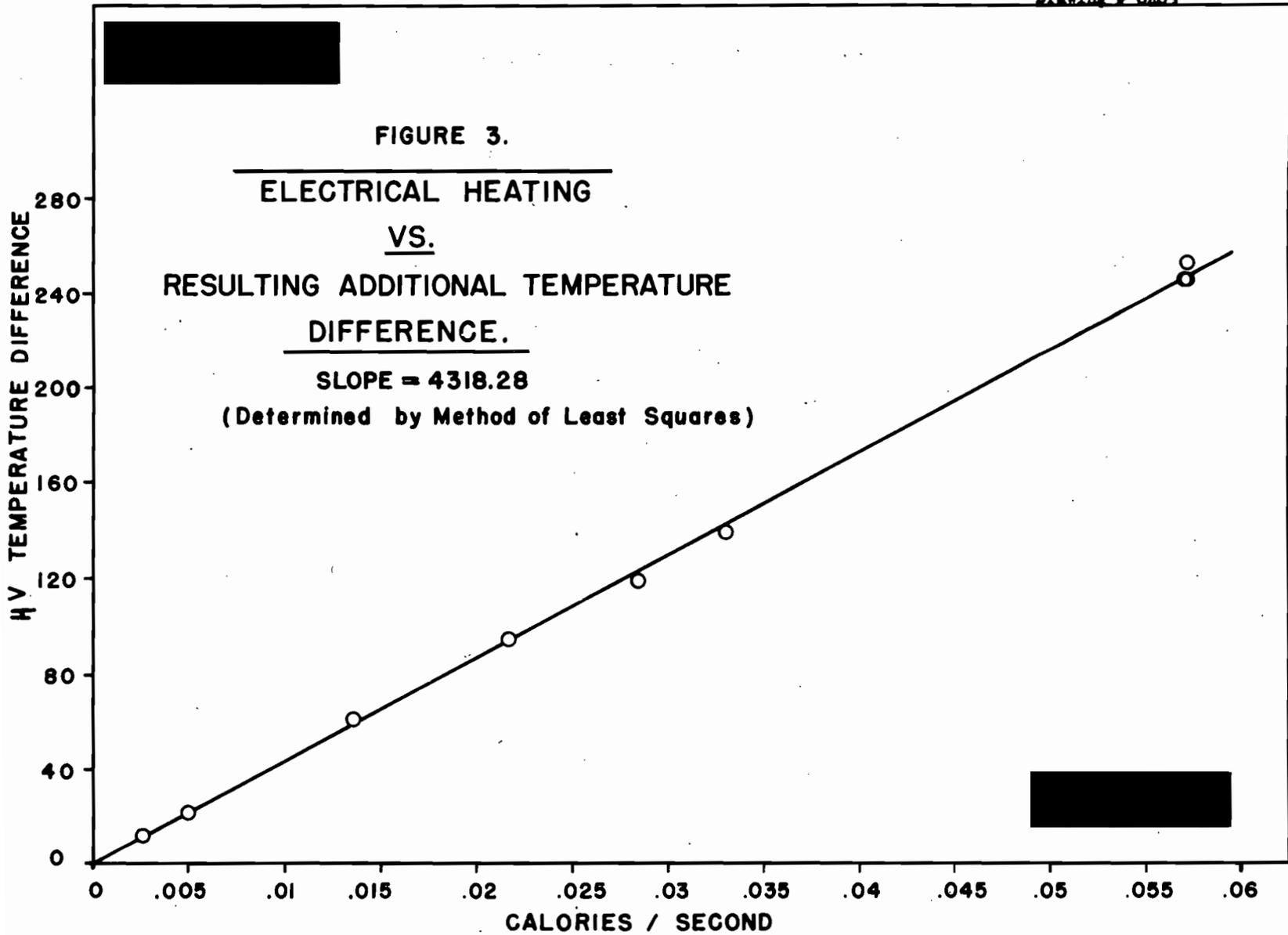
The sample materials used were redistilled H_2O , D_2O taken from stainless steel drum No. MOWP-32 of 99.85 mole per cent isotopic purity; graphite of pile quality, powdered by machining; C. P. granulated bismuth, 99.8% pure; and 2S aluminum. For the aluminum sample a solid body of aluminum was used of the same shape and size as the sample cans, and the weight of the aluminum "sample" was taken as the difference between the total weight of this body and the weight of the empty sample can used for background determinations.

5. Results. Runs were made at night. During any run the pile power was held constant to within $\pm 0.1\%$. An empty can was first placed

in the calorimeter and left until the temperature difference between the thermocouples was constant, usually requiring about 3 hours. Electrical heat was then sometimes introduced and the current maintained constant to $\pm 0.1\%$ until the temperature difference had again become constant at a higher level. The empty can was then pulled out and replaced by a can containing a sample. Several times, after the temperature difference had again become constant, electrical heat was added.

The "background" values of temperature difference, obtained with an empty can and no electrical heat added, are shown in Table 2-A. When normalized to 3500 kw. the values fluctuate randomly around a mean value of 151.93 microvolts until the last night, when a definite drop in background was observed. This drop was ascribed to a change in effective conductivity of the air gap, caused by radiation deterioration of some of the materials present, probably the Styrofoam. For the earlier nights, the probable error in the background (taken as 0.6745 times the root mean square deviation) was 0.64 microvolts. All readings were subject to an error of about 1 microvolt, caused by galvanometer reading errors and the uncertainty in determining just when the temperature difference should be taken as constant (since the temperature of the cooling water in Hole 12 drifted slowly, and the resulting drift in temperature of the outer calorimeter wall was followed with some lag by the inner wall).

The determinations of steady-state temperature difference as a function of electrical heat added are shown in Table 2-B and Figure 3. At the beginning of the series of runs it was found that turning on the heating current had no immediate effect on the EMF appearing in the thermocouples, indicating that the thermocouple and heating circuits were effectively



insulated from each other. Near the end of the series, however, this point was again checked and it was found that turning on the heating current produced an instantaneous deflection in the thermocouple-circuit galvanometer. The deflection being greater when the galvanometer was connected to the outer thermocouples than when connected to the inner thermocouple. It was concluded that an electrical leak had developed between the thermocouple circuit and the heater circuit. Measurement of resistance between the thermocouple and heater leads by an ohmmeter showed a resistance of 100,000 ohms. The deflection was proportional to the current supplied to the heater. The observed phenomena are consistent with the presence of two electrical leaks, one occurring between one of the heater leads and the lead to the outer thermocouple, the other from the other heater lead to the inner thermocouple, both leaks presumably being of the order of 200,000 ohms. The result of these leaks will be that an error is produced in the thermocouple reading which is proportional to the heating current. In the last three electrical heating determinations, after the effect was noticed, it was corrected for; some of the previous runs may have been subject to some error from this cause.

The plot, Figure 3, shows that the relationship between temperature difference and electrical heat input is linear; the best value of the factor connecting temperature rise (in microvolts) and heat input was obtained by least squares. The value obtained on the last night, with the D₂O sample present, was also corrected by assuming that the temperature rise produced by the electric current should drop by the same factor as the background heat, due to change in gap conductivity; the value shown in the table as "due to heating current" was corrected by this factor, and fell

in line with the other determinations. (The "corrected background" at any given time during the last night was obtained by linear interpolation between the background values observed at the beginning and end of the night.) From the scattering of the points in Figure 3, the probable error in the slope seems to be about 1.5%; the correction for leakage from the heating to the thermocouple circuit in some of the points should increase the probable error a little, say to 1.7%.

Data on the material samples, and values of the heat produced per gram in the various materials by pile radiation, are shown in Table 2-C.

Table 2-A

"Background" Temperature Differences with Empty Can

Wt. of Empty Can 7.5048g.

Date	Time	Power	Temp. diff., μV	Corrected to 3500 kw. μV	Deviation from Ave. (151.93)
7-8-48	14:30	3650	159	152.47	+0.54
7-9-48	1:00	3750	164	153.07	+1.14
	7:30	3750	163	152.13	+0.20
7-10-48	21:00	3900	171	153.46	+1.53
7-11-48	8:00	3900	168.8	151.49	-0.44
7-12-48	14:00	3750	162	151.20	-0.73
7-13-48	4:00	3750	161	150.27	-1.66
	20:00	3900	169.5	152.12	+0.19
7-14-48	4:30	3750	162	151.20	-0.73
	20:30	3750	158	(147.47)	-4.46
7-15-48	9:00	3750	154	(143.73)	-8.20

Table 2-B

Temperature Rises Produced by Electrical Heating

Date	Time	Power	Material	Temp. diff., μ V	μ V due to heating current	I, amp.	R, ohms	$\frac{I^2 R}{4.186} \times 0.967$
7-8-48	18:00	3650	Empty can	253	94.6	.06317	22.103	0.02169
7-8-48	21:30	3750	Empty can	415	252.2	.10523	22.354	0.05718
7-10-48	23:30	3900	Empty can	182	12.2	.02255	21.856	0.00257
7-11-48	06:00	3900	Graphite	213	22.2	.03107	21.902	0.00488
7-12-48	19:00	3750	Empty can	302	139.2	.08021	22.169	0.03295
7-13-48	02:00	3750	Aluminum	400	119.0	.07419	22.307	0.02836
7-14-48	01:30	3750	Bismuth	644	245.0	.10433	22.719	0.05713
7-14-48	06:30	3750	Empty can	408	245.2	.10523	22.299	0.05104
7-15-48	03:00	3750	D ₂ O	271	60.8 ^(a)	.05163	22.081	0.01360

(a) Corrected for change in heat conductivity of gap as shown by background change.

Table 2-C

Heat Produced by Radiation Absorbed in Materials

Date	Time	Power kw.	Material	Wt. of Sample in Grams	μ V Reading	μ V above Backgr. corr. to 3500 kw.	Cal./sec. produced by Sample at 3500 kw.	Cal./sec. per gram of material
7-9-48	05:30	3750	H ₂ O	16.0253	253	84.20	0.01950	0.001217
7-11-48	03:30	3900	C	10.1002	192	20.38	0.00472	0.000467
7-12-48	22:00	3750	Al	43.6912	281	110.34	0.02555	0.000585
7-13-48	22:30	3750	Bi	89.1033	399	220.47	0.05106	0.000573
7-15-48	00:30	3750	D ₂ O	16.6532	214	55.63	0.01288	0.000774 ^(a)
7-15-48	05:30	3750	H ₂ O	15.7651	240	83.43	0.01932	0.001226 ^(a)

(a) Corrected for change in heat conductivity of gap as shown by background change.

6. Probable errors. Various sources of error are discussed above, and a summary of probable errors is shown in Table 3. The errors in the electrical heating determinations appear as a direct percentage of the result for each sample, but reading errors and pile power fluctuations appear as an error in the value of the observed temperature difference, which will give a percentage error inversely proportional to the rate of heat production in any sample. The percentage error was estimated for each material separately, and the results appear in Table 3; the combined error is taken as the square root of the sum of the squares of the separate probable errors. The probable error appears to be 4.5% for carbon and about 2% for the other materials.

7. Auxiliary Experiment - monitoring fast neutrons by the n,p reaction on sulfur. This experiment was performed a year ago (August, 1947) when differences in the decomposition of aqueous sulfuric acid were found at different positions in Hole 12. The fast neutron flux, as given by the absolute rate of the n,p reaction on sulfur, was determined at three positions in Hole 12, designated as positions -1, -2 and -3, located respectively 6, 16, and 24 inches below the center plane of the pile. In the present study the calorimeter was located in position -1, and we have for comparison the fast neutron flux deduced from the measured values of the heats, with that obtained in this position by the n,p reaction on sulfur.

Samples of C.P. H_2SO_4 were sealed in 4 mm. I.D. fused silica tubes, 4" in length, and kept in the pile for about 24 hours while the pile was maintained at constant power of 3600 kw. After removal from the pile, the tubes were opened, and carefully measured amounts of sulfuric acid and water were mixed to give known dilutions. Aliquots of the resulting solutions were taken, neutralized with excess NH_4OH , and gently evaporated to dryness on a cover-glass by means of a heat lamp. The cover-glasses were then mounted and covered with a piece of cellophane in the usual manner, and placed on the second shelf of a standard beta counting setup.

TABLE 3. Probable Errors

1. Estimated errors in electrical heat input (%)					
Absolute electrical heat input					0.4
Heating of lead wires					0.4
Slope of heating curve					<u>1.7</u>
Combined error					1.8%
2. Estimated errors in observed temperature difference (μV)					
Pile power fluctuation					0.2
Background error					0.64
Reading error					<u>0.5</u>
Combined error					0.84 μV
3. Percentage errors for each material					
Material	H ₂ O	D ₂ O	C	Al	Ri
Heat input error, %	1.8	1.8	1.8	1.8	1.8
Temp. diff. error, %	<u>1.0</u>	<u>1.5</u>	<u>4.1</u>	<u>0.76</u>	<u>0.38</u>
Combined error, %	2.1	2.3	4.5	2.0	1.9

An absorber of 55.5 mg. of aluminum was placed between the samples and the counting tube to remove all the soft betas arising from the S^{35} . The Feather curve of the radiation being counted was determined and found to agree exactly with that given by a standard specimen of P^{32} .

The counting rates of five aliquots of unshielded sulfuric acid and four aliquots of cadmium shielded acid were averaged respectively to give the values presented in Table 4. The half-life was determined for each separate specimen by the method of least squares over a total counting period of a month, and averaged 14.6 days with a mean deviation of 0.25 days, to be compared with a literature value of 14.3 days for P^{32} . The absolute geometry of the setup was determined by comparison with a standard sample of P^{32} supplied by Dr. Lloyd Zumwalt and stated to have an absolute activity known to $\pm 5\%$. The radiochemical purity of the material was shown by the complete absence of γ -rays and the agreement of the Al absorption curve and half-life with that of P^{32} . Chemical separation of phosphorus from the irradiated samples was therefore unnecessary. The results of the determinations for position -1 are shown in Table 4, together with the calculated values of the number of n,p reactions produced per sec. per cc. of H_2SO_4 .

Table 4. <u>Monitoring fast flux by n,p reaction on sulfur exposed 0.9971 day at "Position -1" in Hole 12 of the Oak Ridge Pile.</u>		
	No Cd.	Surrounded by 24 mil Cd
No. of aliquots	5	4
Ave. counting rate $\text{min.}^{-1} \text{mg. S}^{-1}$, corrected to time of removal from pile	9234	8644
Total disintegrations $\text{sec.}^{-1} \text{mg S}^{-1}$ at time of removal from pile, corrected for absorption and geometry	2973	2783
No. of n,p events occurring sec.^{-1} (cc. of acid) $^{-1}$	3.551×10^7	3.324×10^7
Ratio of Cd shielded/no shield = 93.6%		

III. DISCUSSION

1. Division of the measured heat into fast neutron and γ -ray components. The relative contributions of the fast neutrons to the total radiation absorption varies with different materials. The neutron contribution for any element is proportional to σ_s , the scattering cross section per atom, and k , the average fraction of the kinetic energy of the neutron lost per collision with an atom of that element. The relative values of γ -ray energy absorbed by different materials will vary for small samples proportionally to μ_T , which is the "true" absorption coefficient of the material for γ -rays of the effective wave length present in the pile. The true absorption coefficient, defined as the fraction of the energy in a beam of γ -rays which is dissipated per gram by a small sample of material, includes the energy of all photoelectrons and Compton electrons, and the kinetic energy of positron-electron pairs, but does not include the energy of the quanta scattered in the Compton effect or the annihilation radiation quanta. Since the γ -ray absorption coefficient and the neutron scattering cross section vary quite independently for different elements, it is possible in principle by comparing the heat production of different materials in the pile to divide this heat into portions arising from neutrons and from γ -rays. This is particularly obvious in the cases of ordinary and heavy water, which have exactly the same absorption per mole for γ -rays, but are quite different in neutron scattering properties.

Since σ_s for any element varies with neutron energy, the neutron heat imparted to any material will depend upon the spectrum of the neutrons present as well as the total fast flux. In general, the number of collisions made by neutrons of energy between E and $E + d(\ln E)$ is given by $(nv)_u \sigma_s N du$, where $u = \ln E$, $(nv)_u$ is the flux of neutrons having energy between E and $E + d(\ln E)$ and N is the number of atoms present. The average amount of energy transferred on each collision is

KE. K is given by $2A/(A+1)^2$, where A is the atomic weight of the scattering atom (7). The rate of energy transferred by neutrons in this logarithmic energy interval is then $KE(nv)_{\text{u}} \sigma_{\text{g}} N du = K (nv)_{\text{u}} \sigma_{\text{g}} N dE$, and the rate of energy lost to the material by all fast neutrons is obtained by integrating this expression over all energies. Calculated per mole of material, the resulting integral is

$$I = N_A K \int (nv)_{\text{u}} \sigma_{\text{g}} dE$$

where N_A is Avogadro's number.

The total heat produced by pile radiation in a mole of material is then

$$QM_m = XI + \gamma (M_m/M_{\text{H}_2\text{O}}) (\mu_{\text{T},m}/\mu_{\text{T},\text{H}_2\text{O}}) \quad \text{Equation 1}$$

where Q is the heat absorption in cal./g.-sec.; X is the ratio of the total fast flux in the Oak Ridge pile at 3500 kw to the flux taken as normal in setting up the function $(nv)_{\text{u}}$, times the number of calories per ev; γ is the amount of heat absorbed by 1 g. of water from γ -rays in the pile and the M 's and μ_{T} 's are the molecular weights and true absorption coefficients of the material m and of H_2O . Knowing values of Q for any two substances, as well as the appropriate values of σ_{g} and μ_{T} and the energy spectrum of pile neutrons, one can readily solve for the two unknown coefficients X and γ , and thereby obtain the way in which the observed heat is to be divided into heat originating from fast neutrons and heat originating from γ -rays. Having a value for a third substance supplies a check on the values of the first two. We have carried out this calculation for the three materials H_2O , D_2O and graphite and fitted best values of the constants X and γ to the four resulting equations (two experimental values for H_2O were obtained) by the method of least squares. Some uncertainties were involved in treatment of the data for aluminum and bismuth which are discussed below. The coefficient X can also be obtained from the data on the n,p reaction on sulfur (paragraph 5).

2. Calculations for the relative neutron heats. Values of σ_{g} as a function of energy were obtained from the data collected by Goldsmith, Ibser and Feld (8).

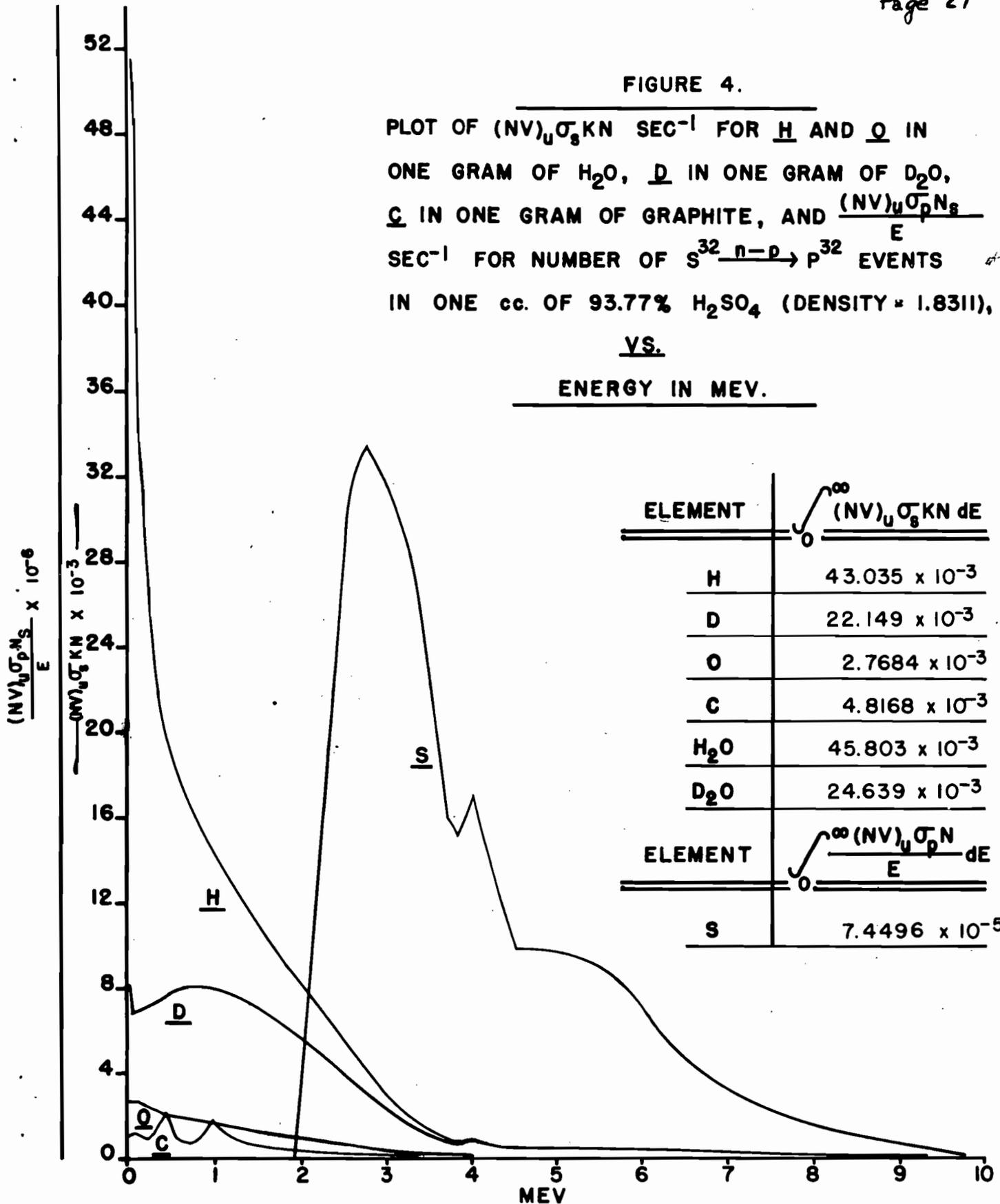
A neutron spectrum for the pile had to be assumed and was taken from report CP-2439, Figure 6, curve for " $\alpha = \frac{1}{2}, \beta = 0$ ". This report presents a calculation of the neutron spectrum for various points in the lattice of the Hanford graphite pile and it is thought that the spectrum should be very similar for corresponding points in the Oak Ridge pile. The coordinates $\alpha = \frac{1}{2}, \beta = 0$ mean that the point is taken as the midpoint of a line joining a metal channel with the closest neighboring channel. Curves are also given for other points in the graphite farther from metal, but the differences are small. Close to the metal the spectrum is quite different as a result of the presence of neutrons which have not yet made one collision in the graphite. One could not be sure if an appreciable component of such neutrons was present in the position in Hole 12 used in the present experiments; it was decided to ignore this possibility, and the results indicate that the spectrum chosen was an adequate approximation to that actually present. The calculation is not very sensitive to the detailed form of the spectrum.

Values of σ_g at various energies for H, D, O, and C, were multiplied by corresponding values of $(nv)_{\text{H}}$ obtained from CP-2439 and the product $(nv)_{\text{H}} \sigma_g$ plotted as a function of energy. The area under the curve, then gave the value of I. The curves and values of I are shown in Figure 4.

3. Calculations for the relative γ -ray heats. Calculation of the true mass absorption coefficients of the elements are summarized by Safford⁽⁹⁾. The true mass absorption coefficient is given by the equation $\mu_T = \gamma + \sigma_{PT} + \sigma_g$; where γ is the mass photoelectric absorption coefficient; σ_{PT} is the true pair formation coefficient, that is, the total absorption coefficient for pair production multiplied by the ratio of the kinetic energy of the electron and positron to the total energy of the absorbed quanta; and σ_g is that part of the Compton absorption coefficient which relates to the scattered electrons. Values of γ are given by Victoreen⁽¹⁰⁾ in the form $\gamma = C \lambda^3 - D \lambda^4$, where C and D are

FIGURE 4.

PLOT OF $(NV)_U \sigma_s KN \text{ SEC}^{-1}$ FOR H AND O IN ONE GRAM OF H_2O , D IN ONE GRAM OF D_2O , C IN ONE GRAM OF GRAPHITE, AND $\frac{(NV)_U \sigma_p N_s}{E} \text{ SEC}^{-1}$ FOR NUMBER OF $S^{32} \xrightarrow{n-p} P^{32}$ EVENTS IN ONE cc. OF 93.77% H_2SO_4 (DENSITY = 1.8311),
VS.
ENERGY IN MEV.



ELEMENT	$\int_0^{\infty} (NV)_U \sigma_s KN dE$
H	43.035×10^{-3}
D	22.149×10^{-3}
O	2.7684×10^{-3}
C	4.8168×10^{-3}
H_2O	45.803×10^{-3}
D_2O	24.639×10^{-3}

ELEMENT	$\int_0^{\infty} \frac{(NV)_U \sigma_p N}{E} dE$
S	7.4496×10^{-5}

constants given for each element and λ is the wave length of the γ -rays in angstroms. $\sigma_{PT} = (5.797 \times 10^{-28}) N_A (Z+1) (Z/A) (\phi_{pair}/\bar{\phi}) (E - 1.02)/E$ where N_A is the number of atoms in a mole, Z and A are the atomic number and weight of the element, E is the energy of the radiation in Mev. and $\phi_{pair}/\bar{\phi}$ is a function given by Heitler⁽¹¹⁾. Values of $(A/Z)\sigma_a$ are given by Safford⁽⁹⁾ as a function of λ . Calculations of μ_T for H, D, C, O, Al and Bi were carried out for radiation energies of mc^2 , $2mc^2$, and $4mc^2$ and the results are shown in Table 5. It is seen that the ratios of μ_T for the lighter elements are nearly independent of wave length, but the value for Bi is abnormally high at the lowest energy because of the prominence of the photoelectric effect. The spectrum of the γ -radiation present in the pile is not well known, but this makes little difference for the light elements.

4. Heat generation in water, heavy water and graphite. The heat produced, Q , in water, heavy water, graphite, aluminum and bismuth, was experimentally measured and is given in Table 2-C. This heat is composed of two portions, derived from neutron scattering and gamma absorption, as discussed in paragraph 1 and expressed mathematically in equation 1. X and γ in this equation are the empirical constants which we wish to determine. When these constants are evaluated, it is possible to calculate for most materials the heat energy which will arise from neutron scattering and the heat energy which will arise from gamma absorption. Although values for only two substances are necessary, we have used four experimental values (two H_2O determinations, D_2O and C) and obtained the constants X and γ by least squares solution of the four resulting equations. The values for Al and Bi were not used in the determination of X and γ due to uncertainties which are discussed in paragraphs 6 and 7.

TABLE 5
Calculation of True Mass Absorption Coefficients for γ -rays

Material	Absorption Coefficients	mc^2	$2mc^2$	$4mc^2$
H	σ_{PT}	0.00000	0.00000	0.00011
	τ	0.00000	0.00000	0.00000
	σ_a	<u>0.05873</u>	<u>0.05526</u>	<u>0.04623</u>
	μ_T	0.05873	0.05526	0.04634
C	σ_{PT}	0.00000	0.00000	0.00020
	τ	0.00002	0.00000	0.00000
	σ_a	<u>0.02957</u>	<u>0.02782</u>	<u>0.02328</u>
	μ_T	0.02959	0.02782	0.02348
O	σ_{PT}	0.00000	0.00000	0.00025
	τ	0.00004	0.00001	0.00000
	σ_a	<u>0.02960</u>	<u>0.02785</u>	<u>0.02330</u>
	μ_T	0.02964	0.02786	0.02355
Al	σ_{PT}	0.00000	0.00000	0.00038
	τ	0.00021	0.00003	0.00000
	σ_a	<u>0.02853</u>	<u>0.02684</u>	<u>0.02246</u>
	μ_T	0.02874	0.02687	0.02284
Bi	σ_{PT}	0.00000	0.00000	0.00186
	τ	0.06193	0.00807	0.00102
	σ_a	<u>0.02351</u>	<u>0.02212</u>	<u>0.01851</u>
	μ_T	0.08544	0.03019	0.02139
H ₂ O	$\mu_T(H)/9$	0.00652	0.00614	0.00515
	$\mu_T(O)8/9$	<u>0.02635</u>	<u>0.02476</u>	<u>0.02093</u>
	μ_T	0.03287	0.03090	0.02608
H ₂ O/C	$\mu_T(H_2O)/\mu_T(C)$	1.1108	1.1107	1.1107
Al/C	$\mu_T(Al)/\mu_T(C)$	<u>0.97127</u>	<u>0.96585</u>	<u>0.97274</u>
Bi/C	$\mu_T(Bi)/\mu_T(C)$	2.8875	1.0852	0.91099

The equations per mole of material are as follows:

Equation 1	$Q \times M_m = X \times I + \gamma (M_m/M_{H_2O}) (\mu_{T,m}/\mu_{T,H_2O})$
H ₂ O	$(0.001217)(18.016) = X(8.2519 \times 10^5) + \gamma (1)$
H ₂ O	$(0.001226)(18.016) = X(8.2519 \times 10^5) + \gamma (1)$
D ₂ O	$(0.000774)(20.028) = X(4.9348 \times 10^5) + \gamma (1)$
C	$(0.000467)(12.01139) = X(5.7857 \times 10^4) + \gamma (0.600)$

where the values of Q are taken from the last column of Table 2-C; the values of I are taken from Figure 4, and the values of μ_T are taken from Table 5. The resulting values were $X = 1.7491 \times 10^{-8}$ and $\gamma = 7.4156 \times 10^{-3}$.

The corresponding calculated values for neutron heat, γ -heat and total heat per gram of material are given in Table 6, together with the observed values and the number of μV change in the observed temperature difference reading which would be required to bring the observed values into agreement with the calculated. The heavy water deviated more from the calculated values than the other two, possibly because of the uncertainty in the determination of the background heat on the night on which the sample

was run. Agreement between calculated and observed heats is within experimental error and gives some indication that the assumed neutron spectrum was a fair approximation to the real spectrum. We accept the calculated values for the total heat as being the best available for the particular materials in this location in the pile and believe that they are accurate to $\pm 3\%$.

5. Comparison with the monitoring by the n,p reaction on sulfur. The rate of transmutation of S^{32} to P^{32} by the n,p reaction is given, in $\text{sec.}^{-1}(\text{cc. H}_2\text{SO}_4)^{-1}$, by $X(\text{no. of ev./cal.}) \int_0^{\infty} (nv)_u \sigma_p N_S d\ln E$ where σ_p is the cross section for the n,p reaction and is given in the tabulation of Goldsmith et al, and N_S is the number of S atoms per cc. of H_2SO_4 . This integral was evaluated graphically as shown in Figure 4 and the resulting value of X was 1.824×10^{-8} , for the unshielded and 1.708×10^{-8} for the Cd shielded acid, in good agreement with the calorimetric value of 1.749×10^{-8} . Only neutrons of energies greater than about 2 Mev. contribute appreciably to the sulfur activation, and the close agreement indicates that the assumed spectrum was essentially correct at the higher energies.

6. Heat generation in aluminum. Heat is produced in aluminum not only by the absorption of pile radiation but also by activation of the aluminum by the n, γ reaction with the pile thermal neutrons to produce Al^{28} , which decays with a half-life of 2.4 min. and is consequently in radiative equilibrium during the measurement. Each decay of Al^{28} produces a γ -ray of 1.8 Mev.⁽¹²⁾, and a β -ray having a maximum energy of 2.75 Mev.⁽¹²⁾ and an average energy of 0.4385 times the maximum⁽¹³⁾. The β -rays will contribute appreciably to the total heat produced in the Al specimen and the γ -rays may also contribute somewhat. To calculate these contributions, we must assume a value of the thermal flux at the point where the exposure was made. According to Overman⁽¹⁴⁾ the maximum thermal flux in the Oak Ridge pile is 1.01×10^{12} . The ratio of the thermal flux at the point of our exposures in Hole 12 to the maximum flux is 0.764, as determined by

E. Shapiro at this point directly⁽¹⁵⁾, and also determined by the Pile Operations Department at a point in Hole 60 located symmetrically with reference to the pile center from our exposure point in Hole 12. The activation cross section for aluminum is 0.21 barns⁽¹⁶⁾.

From these data it is readily calculated that the saturated activation of aluminum at this point in the pile amounts to 95.085 millicuries/g. This corresponds to an output of 0.000162 cal./g.-sec. in the form of β -rays, and 0.000242 cal./g.-sec. in the form of γ -rays. All the heat produced as β -radiation will appear in the determination, since any β -rays which escape the sample will be absorbed in the walls of the inner part of the assembly. Only a fraction of the γ -rays will be absorbed in the inner part of the calorimeter, however. A rather rough estimate of this fraction was made by assuming that all the activity was concentrated in the form of a line source down the center of the specimen. From the formula for the absorption of radiation from a line source⁽¹⁷⁾, the geometry of the system, and the true absorption coefficient of aluminum for rays of 1.8 Mev. energy, we estimate that about 5.3% of the γ -ray energy will be absorbed in the inner assembly, or 0.000013 cal./g.-sec. The heat produced by pile γ -rays per gram of aluminum was simply equal to that produced in graphite multiplied by the ratio of their true absorption coefficients, and amounted to 0.000358 cal./g.-sec. The neutron heat was a relatively small contribution; it was estimated by taking 2.5 barns as the average scattering cross section for fast neutrons and multiplying the neutron heat for carbon by the ratio 2.5/2 (since the average cross section for carbon appears to be about 2) and by the ratio of the values of K for aluminum and carbon and also by the ratio of the atomic weights of carbon and aluminum; the result was 0.000023 cal./g.-sec.

Still another source of heat is furnished by the capture of gamma rays which are emitted when the Al^{28} is formed. The total energy which must be emitted on capture is about 8 Mev; it is not known with what probability this energy appears

as one quantum, or as two or more in cascade. Assuming all the energy is emitted in one quantum, and calculating as before the fraction of the energy which is absorbed in the calorimeter, we find that the capture gammas contribute 0.000042 cal./g.-sec. As shown in Table 6, the total calculated heat becomes 0.000598 cal./g.-sec., to be compared with the experimental value of 0.000585. The difference of 2.2% is only slightly greater than the estimated probable error of the experiment.

The discussion of aluminum activation serves to remind us that the γ -heat found for the various materials includes the heat from the γ -rays produced by the activation of the aluminum walls of the calorimeter. The β -rays coming from the walls are always absorbed to the same degree within the inner assembly whether a sample is present or not, since all β -rays that traverse the inner can in the absence of a sample will be completely absorbed by the opposite wall.

7. Heat generation in bismuth. Because of the small value of K , the heat generated in bismuth by neutron scattering is negligible compared to the other substances used. The scattering in bismuth is mostly inelastic, but the kinetic energy contributed to the bismuth atoms will be no greater for inelastic than for elastic scattering, since the extra energy lost by the neutron produces activation of the bismuth nucleus and will appear in the form of γ -rays which mostly escape. The heat produced in bismuth arises almost entirely from γ -rays, and may be estimated by multiplying the γ -ray component of the graphite heat by the ratio of the true absorption coefficients of bismuth and graphite. This ratio is 1.085 for 1 Mev. γ -rays and 2.88 for 0.5 Mev. γ -rays. The ratio between the measured heat per gram of bismuth, 0.000573 cal./g.-sec., and the calculated heat produced by γ -rays in carbon, 0.000370 cal./g.-sec., is 1.55. Thus, it seems that the effective wave length of the γ -rays in the pile is considerably greater than that corresponding to 1 Mev. It may be that the γ -rays emitted in

Energy Absorbed by Various Materials in Oak Ridge Pile,
in Calories per Gram per Second, at 3500 K.W.

Material	γ energy calc.	n-scattering energy calc.	Total energy calc.	Total energy observed	ΔW change to make observed equal. calc.
H	0.000738	0.006727	0.007465		
D	0.000369	0.001928	0.002296		
O	0.000371	0.000055	0.000426		
H ₂ O	0.000412	0.000801	0.001213	0.001217 0.001226	-0.28 -0.89
D ₂ O	0.000370	0.000431	0.000801	0.000774	+1.94
C	0.000370	0.000084	0.000454	0.000467	-0.57
Al	Pile Radiation	0.000358	0.000023		
	Al ²⁷ + $\alpha \longrightarrow$ Al ²⁸ + 8 Mev	0.000042			
	Al ²⁸ \longrightarrow Si ²⁸ + β^-	0.000162			
	Al ²⁸ \longrightarrow Si ²⁸ + γ	0.000013			
	Sub-total	0.000575	0.000023	0.000598	0.000585

bismuth as a result of inelastic neutron collisions are rather soft and contribute appreciably to the heat produced in the bismuth. In any event, no exact calculation can be made for bismuth without a better knowledge of the spectrum of the pile γ -rays.

8. Application to other points in the pile. Since, between different points in the pile lattice, not extremely close to active metal, fast flux and thermal flux are approximately proportional, it should be possible to estimate the heat produced in any material placed in another part of the Oak Ridge pile by multiplying the value obtained in Hole 12 by the ratio of the thermal flux at the two points. Equations for the spatial distribution of thermal flux in the pile are given in report CP-G-2602. A further correction must be made, however, to take into account the absorption of radiation by the cooling jacket in Hole 12 and the walls of the calorimeter, and also the production of γ -rays in the aluminum in both these assemblies, which would ordinarily be absent in exposures made in other holes. Hole 12 is lined with an annular aluminum jacket containing cooling water. The thickness of water surrounding any sample placed in the hole is 0.25". The number of neutrons of energy E getting through 0.25" of water without collision is given by

$$(nv)_{0,E} \int_0^{\frac{\pi}{2}} \sin \theta e^{-N\sigma h \sec \theta} d\theta = (nv)_{0,E} dE F_1(N\sigma h)$$

where h is the thickness of water, N the number of atoms/cc. and F_1 the function tabulated in the Project Handbook⁽¹⁷⁾. For a rough calculation, we take an average value of $\sigma_H^- = 6$ and $\sigma_O^- = 3$ barns. We then find that, of the incoming fast neutrons, about 4/9 get through the water without collision, 1/9 collide with oxygen and 4/9 collide with hydrogen. The neutrons lose only 1/9 of their energy in collision with oxygen so that this loss is negligible, but they lose 1/2 of their energy by colliding with hydrogen, so that 4/9 times 1/2 or 2/9 of the total energy of the incoming neutrons is lost to the water. If the cross

section for the material were independent of energy, the heat produced by fast neutrons in a corresponding position outside the Hole 12 jacket would be $9/7$ of that produced within the jacket. In the case of hydrogen, however, a reduction in the energy of a neutron by a factor of 2 produces an increase of 50% in the collision cross section. Therefore, the neutrons that have collided with hydrogen in the Hole 12 jacket, although they have lost half their energy, will collide with hydrogen in a material within the jacket 50% more frequently than they would have if the jacket were not there. Neutrons that have collided with hydrogen in the jacket will impart to hydrogen inside the jacket $1/2$ times 1.5 equals $3/4$ the energy that they would have imparted in the absence of the jacket. Therefore, instead of losing $2/9$ of the neutron energy in the jacket, we will, in the case of hydrogenous materials, effectively lose only $4/9$ times $1/4$ equals $1/9$. In estimating, for equal thermal flux, the neutron energy imparted to materials in other parts of the pile, we therefore should multiply the value given here by a factor of $9/8$ in the case of H and $9/7$ in the case of other elements, (whose collision cross section is independent of energy.)

γ -rays from the pile are reduced by absorption by the aluminum in the hole jacket and in the calorimeter itself; the total thickness of Al is 0.5 inch. Taking the formula for an infinite line source with and without absorber⁽¹⁷⁾, we calculate a ratio of 0.85. The number of γ -rays produced by capture and decay of the Al was estimated, and the intensity of the resulting radiation at the center of the long cylindrical emitter calculated to be 17.4% of the total measured γ effect in our experiments. Consequently, the γ -heat produced at another point in the pile should be obtained for equal thermal flux by multiplying our figure by $.826/.85 = 0.97$.

REFERENCES

- (1) Report MonN-311, "Report of the Chemistry Division for March, April and May, 1947", p. 159.
- (2) J. Strong, "Procedures in experimental physics", Prentice-Hall (1943).
- (3) W. P. White, "The modern calorimeter", Chemical Catalog Co. (1938).
- (4) Dow Chemical Co., "Styrofoam - Technical data" (1947).
- (5) R. L. Weber, "Temperature measurement", Edwards Bros. (1941).
- (6) "Handbook of Chemistry and Physics", section on "Heat of Formation and Solution", Chemical Rubber Publishing Co.
- (7) Report, ORNL-115, p. 4.
- (8) "The science and engineering of nuclear power", Vol. I, Appendix C, Addison-Wesley Press (1947).
- (9) F. J. Safford, PPR Vol. 10B (to be published).
- (10) J. A. Victoreen, J. Appl. Phys. 14, 95 (1943).
- (11) W. Heitler, "The quantum theory of radiation", p. 200, The Clarendon Press, Oxford (1936).
- (12) Bleuler and Zunti, Helv. Phys. Acta 20, 195 (1947).
- (13) Marinelli, Brinckerhoff and Hine, Rev. Mod. Phys. 19, 25 (1947).
- (14) R. Overman, personal communication.
- (15) E. Shapiro, personal communication.
- (16) K. Way and G. Haines, Report CNL-33, "Thermal neutron cross sections for elements and isotopes."
- (17) Project Handbook, Chap. V, F.

