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Argonne National Laboratory

A STEADY-STATE DIFFERENTIAL CALORIMETER
USED TO MEASURE GAMMA HEATING
IN A REACTOR ENVIRONMENT

by

Dale A. Herbst and James H. Talboy

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Reactor Operations Division

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A STEADY-STATE DIFFERENTIAL CALORIMETER USED TO MEASURE GAMMA HEATING IN A REACTOR ENVIRONMENT

by

Dale A. Herbst and James H. Talboy

1.0 INTRODUCTION

Information on the amount of heat generated in materials being irradiated in a reactor is of importance in the design of in-pile experiments. Therefore, work was conducted to devise a method for measuring the gamma heat deposited in different samples in Argonne's reactors. Results of an extensive literature search showed that a steady-state differential calorimeter was the most practical instrument available. Originally used in France, the instrument displayed good accuracy and reproducibility of results.¹ With the French design as a basis for development, improvements and modifications were made until a dependable and accurate in-

strument was obtained. Results of tests and measurements have demonstrated the ability of the instrument to reproduce results with an accuracy of 2%. Two different calorimeter systems of the same type have also reproduced each other's results to an accuracy of better than 5%.

Present instruments have been constructed with measuring ranges of from 3 to 500 mW/g of sample using copper samples of approximately 4 g.

2.0 CALORIMETER DESCRIPTION AND OPERATION

A cutaway drawing of the calorimeter is shown in Fig. 1. The instrument, as shown, is 3.1 cm in diam and 15.8 cm long. Essentially, the instrument consists of two aluminum sample cells with internal heaters mounted on aluminum pedestals. One cell is empty; the other holds a sample material. The pedestals

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Fig. 1. Cutaway Drawing of Two-cell Calorimeter

are arranged symmetrically on a controlled-temperature heat sink, which is also made of aluminum and contains an internal heater. All the heaters, which are made of ceramic-coated No. 30 B & S gauge Nichrome wire, are wound on cores made from an insulating material called lava A.² The cell heaters are 3 cm long and 0.6 cm in diam and hold 35 turns of wire. The heat-sink heater is 1.6 cm long and 1.2 cm in diam and holds 19 turns of wire. Experience with glass insulation showed that the combined effects of the radiation and heat destroyed the insulation after a few hours. This prompted the use of the ceramic insulation.

Type No. 28 B & S gauge thermocouples are attached to each pedestal and to the heat sink. The pedestal thermocouples are connected in electrical opposition to indicate the temperature difference between the pedestals. The heat-sink thermocouple is used to indicate temperature.

The two pedestal units are insulated from each other by a lava A divider and placed in a lava A container. The container is designed so that only the bottom of the heat sink is left uninsulated. This allows a path for the internally generated heat to escape to the environment. Two terminal rings on top of the container allow cable leads to be connected from the associated instrumentation.

The electronic equipment used in conjunction with the calorimeter is shown in Fig. 2. Sorensen model QR-150-A power supplies are used to operate the two-cell heaters. A diagram of the heater circuit used in the calorimeter system is shown in Fig. 3. The precision resistors have a calibration accuracy of $\pm 0.002\%$. The power coefficient is $0.06\%/W$ and has a negligible effect on the accuracy of current measurements in the operating range of the instrument. The precision resistors are used with John Fluke model 801BR differential voltmeters, which are accurate to within $\pm 0.05\%$, to determine the electrical power delivered to the heaters with an accuracy of $\pm 0.07\%$. The heater voltage probes are attached directly across the heaters since the resistance of the leads is sensitive to temperature. Since the differential voltmeters are null-balance instruments and draw no current, the resistance of the probe leads does not affect the voltage measurement. A Sorensen model QRB-40-.75 power supply and a West model JPY proportioning temperature controller are used to keep the temperature of the heat sink set at a known value to within $\pm 0.2^\circ C$. The reason for this will be discussed in Section 4.4.

The pedestal thermocouples are connected in opposition across a Leeds and Northrup catalog No. 9834-1 null detector. The null meter has a sensitivity of $0.2 \mu V$ or $0.005^\circ C$ per minor division. Accordingly, in practice, equal pedestal temperatures can be measured with an uncertainty of $\pm 0.01^\circ C$.

All connections from the calorimeter to the instrumentation are made via a 100-ft-long cable composed of 19 No. 24 B & S gauge copper conductors insulated with polyvinyl. Specific quantities of electrical power

are supplied to each cell to obtain a zero temperature difference between pedestals in the absence of radiation. After this balance is obtained, the calorimeter is placed in a radiation field. The presence of the radiation causes heat to be deposited in the sample. This additional heat source in the sample cell disturbs the calorimeter balance. To compensate for it, the electrical power delivered to the sample-containing cell is reduced to re-establish balance. The gamma heating value is then obtained by using the measured electrical power delivered to each cell, in an equation derived from the analysis of a theoretical model of the calorimeter. Additional parameters are obtained from a laboratory calibration of the instrument.

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Fig. 2. Electronic Apparatus Used with Two-cell Calorimeter

Fig. 3
Two-cell Calorimeter
Heater Circuit

3.0 THEORY

The equation used to calculate heating rates is derived from the analysis of a theoretical model of the calorimeter. Figure 4 shows a sample contained within a cell. The cell is attached to a pedestal and heat sink. An insulated container surrounds all parts except the end of the heat sink. Thus, the only path for heat exchange between the instrument and the environment is through the heat sink. When the sample is heated by radiation, the following heat-balance equation applies:

$$\text{heat input} = \text{heat gain} + \text{heat loss},$$

or

$$M_p dt = M_c d\theta + \frac{\theta - \theta_e}{R'} dt, \quad (3.0.1)$$

where

M = mass of sample, g;

p = heat deposited per gram of sample,
cal/sec-g;

t = time, sec;

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Fig. 4. Preliminary Theoretical
Model of Calorimeter

c = specific heat of sample material, cal/°C-g;

θ = sample temperature, °C;

θ_e = heat-sink temperature, °C;

and

R' = bulk thermal resistance, °C-sec/cal.

Rearrangement of Equation (3.0.1) gives

$$dt = \frac{R' Mc}{R' M_p - (\theta - \theta_e)} d\theta.$$

Integrating yields

$$t = -R' Mc \ln [R' M_p - (\theta - \theta_e)] + K_1.$$

When t is zero, θ is θ_e , so

$$K_1 = -R' Mc \ln (R' M_p),$$

and

$$P = \frac{\theta_e - \theta}{R' M [\exp(-t/R' Mc) - 1]}. \quad (3.0.2)$$

When steady-state conditions are reached, t becomes infinite, so Equation (3.0.2) may be simplified, yielding

$$P = \frac{\theta_1 - \theta_e}{R' M}. \quad (3.0.3)$$

Equation (3.0.3) is the expression for the heat deposited per gram of sample material contained in the cell.

If the air space between the cell and the container is small, the convective heat loss may be considered negligible when compared with the heat lost by conduction down the pedestal.³ Therefore, the assumption is made that the only heat loss is by conduction through the pedestal to the base of the container. Proof of this statement is given in Section 4.2. The situation is shown in Fig. 5. From Fig. 5 and Equation (3.0.3) it is seen that

$$\theta_A - \theta_S = R(aP), \quad (3.0.4)$$

where

R = thermal resistance to heat loss, $^{\circ}\text{C}/\text{W}$;

a = the fraction of sample heat deposited in the pedestal at A;

P = total sample heat, W ;

θ_A = pedestal temperature at point A, $^{\circ}\text{C}$;

and

θ_S = temperature of base of container, $^{\circ}\text{C}$.

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Fig. 5. Intermediate Model of Calorimeter

The two temperatures, θ_A and θ_S , in Equation (3.0.4) can easily be obtained with thermocouples.

An electromotive force, e , proportional to the temperatures at the points A and S, is generated by the thermocouples.

Therefore,

$$e_A = \xi \theta_A$$

and

$$e_S = \xi \theta_S,$$

where ξ is a characteristic of the thermocouple.

Then

$$\Delta e_{AS} = \xi(\theta_A - \theta_S).$$

From Equation (3.0.4) it is found that

$$\Delta e_{AS} = KP, \quad (3.0.5)$$

where

$$K = \xi(aR).$$

If two cells, designated by A and B, are mounted on pedestals and attached to the same base, a situation as shown in Fig. 6 is obtained. The following equations are then applicable:

$$\Delta e_{AS} = K_A P_A = \xi(\theta_A - \theta_S),$$

and

$$\Delta e_{BS} = K_B P_B = \xi(\theta_B - \theta_S).$$

These give

$$\Delta e_{AB} = \Delta e_{AS} - \Delta e_{BS} = K_A P_A - K_B P_B, \quad (3.0.6)$$

which is an expression relating K_A and K_B , independent of the base temperature θ_S .

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Fig. 6. Final Theoretical Model of Calorimeter

The quantity K_B/K_A is the calibration factor. A plot of K_B/K_A versus heater power obtained in the absence of radiation is the calibration curve. After this balance is obtained, the calorimeter is placed in a radiation field. This causes heating in the cells. If cell A also contains a sample of absorbing material, heat is deposited in it by the radiation. This additional heat source disturbs the temperature distribution along the pedestal. As a result, the balance condition is upset.

The following expression is written for cell A:

$$e_A = K_A(P_A^0) = K_A(P_A' + q + w_A),$$

where

$$K_A = \xi(R_A a), \text{ constant;}$$

q = heat deposited in sample by gamma radiation, W ;

w_A = heat deposited in cell material by gamma radiation, W;

P'_A = heat deposited in cell from heater, W;

and

P_A^0 = total heat supplied to cell, W.

The following similar expression is written for cell B:

$$e_B = K_B(P_B^0) = K_B(P_B + w_B).$$

If P'_A is varied to give a null indication from the differential thermocouple, the following expression is applicable:

$$e_{AB} = e_A - e_B = 0. \quad (3.0.8)$$

Combining Equations (3.0.7) and (3.0.8) and assuming that

1) the sample cells are identical so that

$$w_A = w_B = w,$$

2) P_B is unchanged;

and

3) K_B/K_A is constant,

we obtain the following expression:

$$q = P_A - P'_A + (K_B/K_A - 1)w.$$

Defining

$$q' = \frac{q}{M},$$

where

q' = gamma-radiation heat deposited in sample, W/g, we obtain

$$q' = \frac{P_A - P'_A}{M} + \left(\frac{K_B}{K_A} - 1 \right) \frac{w}{M}, \quad (3.0.9)$$

where

P_A = heat supplied to sample cell in absence of radiation by the heater, W;

P'_A = heat supplied to sample cell in presence of radiation by the heater, W;

w = gamma radiation heating of cell material, W;

and

K_B/K_A = calibration factor obtained by calibration in absence of radiation.

Equation (3.0.9) is the basic working equation used with the calorimeter to calculate heating rates.

4.0 INVESTIGATIONS

In obtaining Equation (3.0.9), we made the following assumptions:

- 1) The two sample cells and pedestals were identical and were symmetrically placed on the base.
- 2) The thermocouples were placed at identical positions on pedestals A and B.
- 3) The heat deposited in each sample container by gamma radiation was equal; i.e.,

$$w_A = w_B = w.$$

- 4) The thermal resistance of the pedestals remained constant over an extended range of power inputs.
- 5) Radial heat losses from the sample cell were negligible.

During construction of the calorimeter, great care was taken to insure that the two sample cells and pedestals were the same. The pedestals were attached to the base in a symmetrical manner and thermocouples were placed at similar positions on the pedestals. This arrangement allowed the pedestal units to be within 1/2 in. of each other and should result in each sample cell being in approximately the same gamma-radiation field. Therefore, the assumption of equal sample-cell heating seems reasonable.

4.1 Demonstration of Constant Thermal Resistance

A test was performed to determine if the thermal resistance of the pedestal remained constant over an extended range of heat inputs to the cells. Known amounts of heat were supplied to the sample cell, and

Fig. 7. Demonstration That Thermal Resistance Does Not Depend on Power

cavity was considered a rod in an insulated container. This is shown in Fig. 8. Assuming no radial convective heat loss, the following heat-balance equation applies:

$$\text{heat gain} = \text{heat loss}$$

or

$$-KA \frac{dT}{dx} + q^0 A dx = -KA \left(\frac{dT}{dx} + \frac{d^2T}{dx^2} \right) dx, \quad (4.2.1)$$

where

K = thermal conductivity of the rod material, cal/sec-cm-°C;

A = cross-sectional area presented to axial heat flow, cm²;

q^0 = heat deposited per unit volume of sample material, cal/sec-cm³;

equilibrium conditions were allowed to be established. Thermocouple emf versus heat input is plotted in Fig. 7. Equation (3.0.3) relates the steady-state temperature to power input.

Since

$$\Delta e_{AE} = \xi(\theta_A - \theta_E),$$

the thermocouple emf is given by the following expression:

$$T/C \text{ emf} = \xi(\theta_A - \theta_E) = \xi R_A P \text{ mV.} \quad (4.1.1)$$

If R_A is constant, a graph of Equation (4.1.1) should yield a straight line. The curve of Fig. 7 is linear; therefore R_A is constant.

4.2 Calculation of Convective Heat Loss

Earlier (p. 9) it was stated that the major path of heat loss for the sample cavity was by conduction down the pedestal. To prove this statement, the sample

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Fig. 8. Model Used in Derivation of Heat-transfer Coefficient

x = distance from insulated end of sample rod, cm;

T = temperature of rod at x , °C.

If we let $\theta = (T - T_e)$, where T_e is the temperature of the environment, Equation (4.2.1) gives

$$\frac{d^2\theta}{dx^2} = \frac{-q^0}{K}. \quad (4.2.2)$$

Solving Equation (4.2.2) by using the conditions that $d\theta/dx$ is equal to zero when x equals zero, and $\theta = 0$ when x equals L , gives

$$\theta = \frac{-q^0}{2K} (x^2 - L^2).$$

Defining θ^0 as $(T_{x=0} - T_e)$ results in the following expression for the heat deposited per cm³ of sample material:

$$q^0 = \frac{2}{L^2} (K\theta^0), \quad (4.2.3)$$

where

L = length of rod, cm;

and

$T_{x=0}$ = temperature of rod at $x = 0$.

Now, if we use Fig. 8 and assume radial convective heat losses, the following heat-balance equation may be written:

heat gain = heat loss,

or

$$-KA \frac{dT}{dx} + q^0 A dx = -KA \left(\frac{dT}{dx} + \frac{d^2T}{dx^2} \right) dx + hC(T - T_e) dx,$$

or

$$\frac{d^2T}{dx^2} = \frac{hC}{KA} (T - T_e) - \frac{q^0}{K}, \quad (4.2.4)$$

where

x = distance from insulated end of cell, cm;

T = temperature of cell at x , °C;

K = thermal conductivity of cell material, cal/sec-cm-°C;

A = cross-sectional area cell presents to axial heat flow, cm²;

h = heat-transfer coefficient, cal/sec-cm²-°C;

C = circumference of sample cell, cm;

T_e = temperature of environment, °C;

and

q^0 = heat generated in sample material, cal/sec-cm³.

For this case, the small air space between the sample rod and the insulated container is considered a solid.³ Therefore, the heat transfer from the rod to the container is a conductive heat loss. Equation (4.2.4) is replaceable by the following expression:

$$\frac{d^2\theta}{dx^2} - m^2\theta = \frac{-q^0}{K}, \quad (4.2.5)$$

where

h was replaced by $\frac{K'}{r_1 \ln(r_2/r_1)}$;

K' = thermal conductivity of air, cal/sec-cm-°C;

r_1 = radius of sample rod, cm;

r_2 = radius of container, cm;

$\theta = T - T_e$, °C;

and

$$m^2 = \frac{2K'}{Kr_1^2 \ln(r_2/r_1)}.$$

The transformation of Equation (4.2.4) to Equation (4.2.5) is given in the appendix. The solution of Equation (4.2.5) yields

$$q^0 = \frac{2N+1}{2N} \theta^0 K m^2, \quad (4.2.6)$$

where

$$N = \sinh^2 \left(\frac{mL}{2} \right)$$

under the conditions that $d\theta/dx$ is zero when x is zero, and θ is zero when x is L .

Equations (4.2.3) and (4.2.6) give expressions for the amount of heat deposited per cm^3 of sample for the two different situations. With the appropriate constants, Equation (4.2.3) yields

$$q^0 = 0.551 K\theta^0$$

for no radial heat loss, and Equation (4.2.6) yields

$$q^0 = 0.555 K\theta^0$$

assuming radial heat loss. Comparison of these results supports the assumption of negligible radial convective heat loss.

4.3 Effect of Temperature Gradients in Heat Sink

A major concern was whether a temperature gradient across the heat sink of the instrument would greatly disturb the calorimeter characteristics. From the theory of the calorimeter in Section 3,

$$\theta_A = \frac{K_A P_A}{\xi} + \theta_{AS}$$

and

$$\theta_B = \frac{K_B P_B}{\xi} + \theta_{BS}$$

Therefore

$$\theta_A - \theta_B = \frac{K_A P_A}{\xi} + \theta_{AS} - \frac{K_B P_B}{\xi} - \theta_{BS} \quad (4.3.1)$$

When a uniform heat-sink temperature distribution exists,

$$K_A = \frac{K_B P_B}{P_A}$$

Now, suppose the temperature distribution of the heat sink is not uniform. θ_A and θ_B are controllable by using the cell heaters, so the following conditions may be set:

$$\theta'_B = \theta_B,$$

$$\theta'_{BS} = \theta_{BS},$$

$$K'_B = K_B,$$

and

$$P'_B = P_B.$$

The primes denote the case in which the heat-sink temperature is not uniform. From Equation (4.3.1), with the condition of calorimeter balance, it is seen that

$$K'_A = \frac{K_B P_B}{P'_A} + (\theta_{BS} - \theta'_{AS}) \xi P'_A. \quad (4.3.2)$$

Therefore, as compared to Equation (3.0.7) for the case of uniform heat-sink temperature, a temperature gradient across the base will invalidate the calorimeter calibration factors obtained without a gradient.

This problem was also investigated by means of an experiment that created temperature gradients across the instrument heat sink. A heater was attached to one side of the heat sink, and a temperature gradient was generated. Heat was also applied to different points on the calorimeter container. Results of these tests indicated the need for encasing the instrument in a good, thermally insulating container. Accordingly, the calorimeter was encased in the "lava A" envelope.

4.4 Effect of Heat-sink Temperature on Calibration

Tests were also performed to determine the effect of the heat-sink temperature on the calibration factor, K_B/K_A , which is given by Equation (3.0.7). Figure 9 shows the results of one such test and indicates the strong dependence of the calibration factor on the heat-sink temperature. The temperature distribution in the calorimeter was monitored. Results shown in Fig. 10 indicate that a small increase in base temperature causes a large increase in cell temperature. Since radiant-heat loss is proportional to the fourth power of temperature, it appears that a large increase in radiant-heat loss will follow from an increase in base temperature. The dependence of K_B/K_A on heat-sink temperature can be quantitatively predicted by considering the different rates of radiant-heat transfer from the aluminum sample cell and the copper sample to the "lava A" envelope. (The temperature of the envelope depends on the heat-sink temperature, which must be taken into account in the analysis.) These tests and evaluations prompted the modification of the instrument into a controlled-temperature device. This change enables the calorimeter to be calibrated and operated at the same temperature and therefore reduces the possibility of using an incorrect calibration factor. Thus, the instrument has evolved from the French design to a significantly different and more dependable calorimeter.

Fig. 9

Effect of Base Temperature
on Calorimeter Calibration
Factor

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Fig. 10
Temperature Distribution
in Calorimeter

5.0 CALIBRATION

The instrument was calibrated over a wide range of power inputs. Temperature balance was obtained at heater powers ranging from 100 mW to 2 W. The calibration factor, K_B/K_A , was then calculated and plotted as a function of the empty-cell heater power. Figure 11 shows the calibration curves for two instruments. The difference in the curves indicates the need

to calibrate each instrument completely. However, it is significant that the calibration curves are reproducible for all conditions of heating and forced-air cooling, provided the instrument is vertical and the heat-sink temperature is maintained at a specified level. Calibration was performed under the condition of forced-air cooling because the reactor thimbles are cooled in a similar manner. The heat-sink temperatures corresponding to the calibration curves of Fig. 11 are shown in Fig. 12.

144-892

Fig. 11. Two-cell Calorimeter Calibration Curves

Fig. 12. Two-cell Calorimeter Calibration-temperature Curves

6.0 RESULTS

Two differential calorimeters have been used in the CP-5 and Juggernaut reactors. In December 1965, two copper-containing instruments were used to measure the gamma heating in two of the vertical irradiation facilities of the CP-5 reactor. The results of these measurements are listed in Table I. Different power levels yielded heating results per megawatt that agree to better than 5%. This error is larger than the 2% error quoted for calorimeter results but is acceptable in light of the error in calculating reactor power.

TABLE I. Results of Gamma-heating Measurements in CP-5 Reactor

Reactor Power, MW	Facility	Calorimeter No.	Heating Rate of Copper, mW/g-MW	Position
1.26	VT-27	1	42.7 ± 0.8	On centerline
1.98	VT-27	1	41.8 ± 0.8	On centerline
1.26	VT-31	2	31.0 ± 0.6	On centerline
1.98	VT-31	2	32.9 ± 0.6	On centerline

Gamma-radiation heating measurements were also made for copper samples in two of the vertical irradiation facilities of the Juggernaut reactor. The two facilities mapped were 4V2 and 8V1-S. Figures 13 and 14 show the results of the heating measurements. Comparison of the results indicates a strong similarity in heating-rate profiles. Examination of the horizontal cross section of the Juggernaut reactor, shown in Fig. 15, indicates the two facilities are symmetrical with respect to the vertical core centerline. Therefore, the similarity of heating rates appears logical.

The data shown in Figs. 13 and 14 are a composite of results from two different calorimeters. Specifically, these are the instruments for which calibration curves were given in Fig. 11. The agreement of results yielded by the two different calorimeters emphasizes the excellent reproducibility of the design. This strengthens the belief that an absolute measurement of gamma heating has been made.

The two-cell calorimeter was analyzed to determine the error in the heating rates. Using standard expressions for calculating errors,⁴ we obtained a value of $P \pm 0.07\%$ for the electrical power measurements. This enabled K_B/K_A to be determined to $\pm 0.1\%$. Application of error analysis to Equation (3.0.9) yielded the following expression for the heating rates obtained with the two-cell calorimeter:

$$q' = \frac{\left[\left(\frac{K_B}{K_A} \right) P_B - P'_A \right]}{M} \pm \frac{\left[\left[\left(\frac{K_B}{K_A} \right) P_B (1.2 \times 10^{-3}) \right]^2 + (7 \times 10^{-4} P'_A)^2 \right]^{1/2}}{M} \quad (6.0.1)$$

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Fig. 13. Results of Heating Measurements in 4V2 of Juggernaut Reactor

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Fig. 14. Results of Heating Measurements in 8V1-S of Juggernaut Reactor

Fig. 15. Juggernaut Reactor Horizontal Cross Section

Note that the second term of Equation (3.0.9) was dropped in obtaining Equation (6.0.1). This was possible because its exclusion had a negligible effect on the resulting error in calculating q' .

A rough calculation was performed to determine expected heating rates in Juggernaut's 4V2 and 8V1-S facilities. First, the heating from core gammas was analyzed. The core was considered as a cylindrical source with layers of attenuating materials around it.⁵ The following expression was used to determine gamma transmission:⁶

$$\phi = \left[\frac{B\phi_S R_0^2}{V2a} \right] \int_0^\theta \exp \left[- \sum_i^N \mu_T^i t^i \sec \theta \right] d\theta, \quad (6.0.2)$$

where

ϕ = gamma heat flux at point of interest, W/cm^2 ;

ϕ_S = gamma heat of source, W ;

R_0 = source cylinder radius, cm ;

V = source volume, cm^3 ;

a = distance of point of interest from source, cm ;

μ_T^i = total gamma-absorption cross section for i th material, cm^{-1} ;

t^i = thickness of i th material, cm ;

θ = angle between line drawn from end of cylinder to point of interest and line perpendicular to source cylinder through point of interest, rad ;

and

B = buildup factor.

The situation that exists in the Juggernaut reactor is shown in Fig. 16. From the data in Table II,⁷ a value of $\phi = 0.93 \text{ mW/cm}^2$ was obtained. The sample in the calorimeter has a surface area of 6.45 cm^2 . Therefore, a value of 1.50 mW/g of copper was obtained as the expected heating rate from core gammas.

Fig. 16. Materials Affecting Gamma Attenuation in Juggernaut Reactor

TABLE II. Constants Used for Gamma Attenuation Calculations

$B = 5$	$F(\theta, b) = 1.1 \times 10^{-4} = \int_0^\theta e^{-b \sec \theta} d\theta$
$S = 14 \text{ kW}$	$\mu_T(\text{Pb}) = 0.5182 \text{ cm}^{-1}$
$R_O = 29.5 \text{ cm}$	$\mu_T(\text{carbon}) = 0.999 \text{ cm}^{-1}$
$L = 57.2 \text{ cm}$	$t(\text{Pb}) = 5.0 \text{ cm}$
$V = 5.97 \times 10^4 \text{ cm}$	$T(\text{carbon}) = 55.0 \text{ cm}$
$a = 60 \text{ cm}$	$\theta = 40^\circ$

Another source of sample heating is secondary gamma and beta radiation. These are the gammas and betas released from the neutron reactions in copper. It was assumed that all the secondary radiation energy was absorbed by the sample. For the general case,

$$\text{Rate of change} = \text{Rate of production} - \text{Rate of decay}$$

or

$$\frac{dN^r}{dt} = \phi \sigma N - \lambda^r N^r, \quad (6.0.3)$$

where

N = number of parent nuclei present;

N^r = number of gamma- or beta-releasing daughter nuclei present;

λ^r = decay constant of daughter nuclei, sec^{-1} ;

σ = thermal-neutron cross section of parent nuclei, cm^2 ;

ϕ = thermal-neutron flux incident on material, $\text{n/cm}^2\text{-sec}$;

and

t = time in flux, sec.

Integration of Equation (6.0.3), by using the initial conditions that the number of daughter nuclei present when the sample is placed in the reactor is zero, yields an expression for the number of daughter nuclei present at any time. Then the rate of decay of the daughter nuclei after an extended period of irradiation is simply

$$\text{Rate of decay of } N^r = \xi \text{ dis/sec}, \quad (6.0.4)$$

where

$$\xi = \phi \sigma N.$$

If the daughter nuclei have a large thermal-neutron cross section, a second daughter nucleus will be formed. The equation for the general case is

$$\text{Rate of change} = \text{Rate of production} - \text{Rate of decay}$$

or

$$\frac{dN^o}{dt} = \sigma^r \phi N^r - \lambda^o N^o, \quad (6.0.5)$$

where

σ^r = thermal-neutron cross section of gamma- or beta-emitting first daughter, cm^2 ;

λ^o = decay constant of second gamma- or beta-emitting daughter, sec^{-1} ;

and

N^0 = number of gamma- or beta-emitting second-daughter nuclei.

Integration of Equation (6.0.5), by using the conditions that at time zero the number of second-daughter nuclei is zero, results in an expression for the number of second-daughter nuclei present at any time. Therefore the rate of decay of the second-daughter nuclei after an extended period of irradiation is

$$\text{Rate of decay of } N^0 = \alpha \text{ dis/sec,} \quad (6.0.6)$$

where

$$\alpha = \frac{\sigma^r \phi^2 \sigma N}{\lambda^r}$$

The energy released from all secondary gamma and beta sources is the sum of the individual gamma and beta energies released. Symbolically,

$$E^T = \sum_{r=0}^n G^r E_r^r + \sum_{o=0}^R G^o E_o^o + \sum_{r=0}^n G^r E_\beta^r + \sum_{o=0}^R G^o E_\beta^o,$$

where

n = number of gamma- or beta-releasing first-daughter isotopes;

R = number of gamma- or beta-releasing second-daughter isotopes;

$$E^T = \gamma E^T + \beta E^T;$$

= total energy released from gamma and beta radiation, MeV;

and

G^r or G^o = percentage of disintegration releasing E^r or E^o energy.

Natural copper is composed of two isotopes. Activation yields two gamma- and beta-emitting first-daughter isotopes and one gamma- and beta-emitting second-daughter isotope. Table III lists the pertinent information for the isotopes of interest.⁸ For natural copper,

$$\gamma E^T = 6.7 \times 10^{-3} \xi_{63} + 1.12 \times 10^{-2} \xi_{65} + 5.2 \times 10^{-4} \alpha_{66}, \quad (6.0.7)$$

and

$$\beta E^T = 1.545 \times 10^{-1} \xi_{63} + 6.32 \times 10^{-1} \xi_{65} + 1.157 \times 10^{-1} \alpha_{66}. \quad (6.0.8)$$

TABLE III. Pertinent Information on Five Isotopes of Copper

Isotope	Atomic Weight	Abundance, %	Thermal-neutron Cross Section, barns	Half-life	E ^γ , MeV		E ^β , MeV		G ^γ , %	G ^β , %
					Gamma	Beta	Gamma	Beta		
⁶³ Cu	62.9298	69.09	4.5	-	-	-	-	-	-	-
⁶⁴ Cu	-	0.00	-	12.9 hr	1.34	0.165	-	-	0.5	-
⁶⁵ Cu	64.9278	30.91	2.3	-	-	0.143	-	-	60.0	-
⁶⁶ Cu	-	0.00	130.0	5.1 min	1.87	-	-	-	0.6	-
⁶⁷ Cu	-	0.00	-	61.0 hr	-	0.658	-	-	91.0	-
					-	0.375	-	-	9.0	-
					-	-	0.272	-	-	0.2
					-	-	-	0.099	-	45.0
					-	-	-	0.121	-	35.0
					-	-	-	0.144	-	20.0

The subscripts in Equations (6.0.7) and (6.0.8) refer to a particular isotope of copper. For example, 63 refers to Cu⁶³. Equations (6.0.7) and (6.0.8) and the information in Table III result in the following expression for the maximum heating (in W/g) from secondary radiation in copper:

$$\gamma E^{T'} = 4.38 \times 10^{-14} \phi + 3.166 \times 10^{-35} \phi^2, \quad (6.0.9)$$

and

$$\beta E^{T'} = 1.406 \times 10^{-12} \phi + 7.042 \times 10^{-33} \phi^2. \quad (6.0.10)$$

The results of neutron-flux mapping of irradiation facilities 4V2 and 8V1-S for the Juggernaut reactor are shown in Figs. 17 and 18. Using a

Fig. 17. Neutron-flux Map of 4V2 of Juggernaut Reactor

thermal-neutron flux of 2.0×10^{11} n/cm²-sec yields a heating rate for secondary radiation of 0.3 mW/g. Therefore, an expected maximum heating rate of 1.8 mW/g of copper is obtained. The calculated heating is approximately 40% of the measured heating. Thus, the measured values appear reasonable. The additional heating measured could be due to extraneous gamma sources in the facility (for example, the aluminum facility liner).

7.0 CONCLUSION

The two-cell calorimeter appears to be a dependable and accurate

Fig. 18. Neutron-flux Map of 8V1-S
of Juggernaut Reactor

instrument. It has shown the ability to reproduce results on a day-to-day basis. Once an instrument has been calibrated, its life expectancy is long because it is virtually unharmed by the reactor environment.

Tests have shown that it is possible to calibrate an instrument that will operate in a horizontal position. Thus, the calorimeter can be used to measure gamma heating in reactor beam holes as well as vertical facilities. Instruments that contain stainless-steel and aluminum samples have been constructed. As time permits, these will be calibrated and operated like the two copper-containing models. Therefore, it appears that the possibilities for use of the two-cell calorimeter are great.

APPENDIX

Derivation of Heat-transfer Coefficient

For the two-cell calorimeter, the air space between the sample and the container is small enough to be considered a solid.³ Therefore, the heat transfer is essentially a conductive heat loss. A model of the situation is shown in Fig. 8 where the imperfect insulator is air. The heat loss between the sample and the container is governed by the conduction equation.

$$q = -K'A \frac{dT}{dr}, \quad (A.1)$$

where

r = distance in radial direction, cm;

A = cross-sectional area presented to radial heat flow, cm^2 ;

T = temperature of rod, $^{\circ}\text{C}$;

and

K' = thermal conductivity of air, $\text{cal/sec-cm-}^{\circ}\text{C}$.

Equation (A.1) may be rewritten as

$$q \frac{dr}{A} = -K'dT. \quad (A.2)$$

Integration between the limits

$$r_1 \leq r \leq r_2$$

and

$$T_E \leq T \leq T$$

gives

$$q = \frac{(2\pi r_1 L) K'(T - T_E)}{r_1 \ln (r_2/r_1)}, \quad (A.3)$$

where

r_1 = radius of sample rod, cm;

r_2 = radius of container, cm;

T_E = temperature of environment, $^{\circ}\text{C}$;

T = temperature of rod, °C;

$A = 2\pi rL$ = cross-sectional area to radial heat flow, cm²;

and

L = length of sample rod, cm.

The expression that governs convective heat loss is

$$q = hA(T - T_E), \quad (\text{A.4})$$

where

h = heat-transfer coefficient, cal/sec-cm²-°C.

Comparison of Equations (A.3) and (A.4) shows that

$$h = \frac{K'}{r_1 \ln(r_2/r_1)}. \quad (\text{A.5})$$

Substituting Equation (A.5) in Equation (4.2.4) gives

$$\frac{d^2\theta}{dx_2^2} = m^2\theta = \frac{-q^0}{K}, \quad (4.2.5)$$

where

$$\theta = T - T_E,$$

and

$$m^2 = \frac{2K'}{Kr_1^2 \ln(r_2/r_1)}.$$

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A few words should be said concerning the construction of the lava A calorimeter parts. Raw lava A is a soft, gray machinable material, which becomes a rock-hard pink material after firing. The lava A parts are slowly heated to 1800°F and slowly cooled. This process creates two major problems. The first is that the material is nonmachinable after firing; secondly, the firing causes the parts to grow 2%. Therefore, a person possessing a very high degree of skill is required to construct the lava A parts of the calorimeter. Fortunately, such a person, Melvin Thompson, was available. Therefore, special thanks is due him because without his skills, construction of the instrument would have been impossible.

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