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COMPARISON OF CALCULATED VS MEASURED GAMMA-RAY HEATING
IN THE BULK SHIELDING FACILITY

SUMMARY

A comparison has been made between corresponding calculated and experimental gamma-ray heating results for the Bulk Shielding Reactor. The calculated gamma-ray heat generation rates were obtained assuming straight exponential absorption of gamma rays, with narrow beam absorption coefficients, and energy absorption buildup factors based on isotropic sources in a homogeneous medium. The calculated results agreed with the experimental measurements to within -15% to +5% for three different target metals. For the heavy Z (atomic number) targets, i.e., iron and lead, the principal difference between the experimental and calculated curves was accounted for by the rapid absorption of the low energy gamma spectrum built up in the light Z material. It is concluded that the methods and data outlined should yield results generally acceptable for reactor design purposes.

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INTRODUCTION

In any detailed reactor design it is necessary to have a reasonable picture of the reactor temperature distribution in order to determine the thermal stresses and cooling requirements in various parts of the reactor. The temperature distribution is a function of the heat distribution which, for regions external to the core, is primarily dependent on the absorption of gamma rays.

This work contains a comparison between corresponding calculated and experimental gamma-ray heating results for a specific reactor. Such a comparison is of considerable interest, since agreement between the corresponding results tends to confirm the methods and data used in the analytic approach. The Bulk Shielding Reactor was chosen since the series of experiments performed by F. T. Binford, E. S. Bettis and J. T. Howe¹ to determine the rate of gamma heating in various target materials near the BSR provided the experimental data. Experimental heat-generation rates were measured in aluminum, iron and lead samples at several distances along the reactor centerline as illustrated by Fig. 1. The experimental method used employed measurements of transient temperature of the samples during heating in the gamma field and cooling after removal from the gamma field.

The basic gamma-ray data used was obtained in large part from ORNL-2113.² As the criterion for judging the validity of the methods and data used is the comparison of the calculated and experimental results, the calculated sources used are described in considerable detail.

(a) SAMPLE CAPSULE

(b) EXPERIMENTAL ARRANGEMENT

Fig. 1. BSR Gamma Heating Experimental Arrangement.

CALCULATED SOURCES

The calculated heat generation rates indicated that the energy deposition in the target metals is due to the following principal radiation components:

- 1) core gammas,
- 2) reflector gammas (water capture gammas),
- 3) target gammas and betas.

As an ORACLE code for the calculation of gamma heating in reactors of rectangular geometry^{3,4} had been previously developed, this code was used to determine the heat generation rate in the target samples due to gammas emanating from the core. The heat generation in the target due to gammas from the i^{th} energy group for one volume element of the core is

$$H_i(v) \left[\frac{\text{watts}}{\text{gram-Mw}} \right] = \frac{K N_i(v) \bar{E}_i}{4\pi [\bar{r}_c(v) + \bar{r}_r(v)]^2} \left[e^{-x} \left\{ A (e^{\alpha x} - 1) + 1 \right\} \right] \left(\frac{\mu_E}{\rho} \right),$$

- K = a constant which normalizes the thermal flux to 1 Mw of reactor power and converts Mev/sec to watts,
- $N_i(v)$ = number of gammas/sec in the i^{th} energy group for the particular volume element, v ,
- $\bar{E}_i$ = average energy of the i^{th} energy group, Mev/gamma,
- $x = \sum \mu_1 r_1 = \mu_c \bar{r}_c(v) + \mu_r \bar{r}_r(v)$, subscripts c and r refer to core and reflector respectively; μ 's indicated are total absorption coefficients, cm^{-1} ; r 's represent distances in respect medium, cm,
- A, α = buildup factor parameters,
- μ_E = energy absorption coefficient of target, cm^{-1} ,
- ρ = density of target metal, g/cm^3 .

The bracketed term just represents the product of the exponential attenuation factor and an approximate form of the energy absorption buildup factor for a point isotropic source in a homogeneous medium. As the code used contained a polynomial form of the buildup factor, it was necessary to transform the bracketed term in the basic equation as follows:

$$e^{-x} \left\{ A (e^{\alpha x} - 1) + 1 \right\} = A e^{-(1-\alpha)x} + (1 - A) e^{-x},$$

where

$$\left\{ A (e^{\alpha x} - 1) + 1 \right\} = B_a = \text{energy absorption buildup factor.}$$

Since the heat generation equation used contained a summation of two terms, the ORACLE computing time was doubled. About an hour of computing time was required to compute the heat generation at one point for the 1485 volume elements and 7 energy groups used. The volume element sources were represented by point sources at the centers of the cubes.

The exponential function used for B_a was obtained directly from ORNL-2113 and is a simplification of the double-exponential form suggested by Taylor.⁵ The indicated expression can be made to fit the appropriate B_a data to within $\pm 5\%$ for distances less than 7 mean free paths (maximum x for BSR experiment ≈ 10). Appropriate B_a data were obtained by using an equivalent atomic number $\bar{Z}$, and interpolating the available buildup factor data⁶ for point isotropic sources in homogeneous mixtures. As the effective Z of the core is 9.9 and the effective Z of the reflector is 7.5, the homogeneous mixture approximation is valid and an equivalent $\bar{Z} = 9$ was used.

As the Bulk Shielding Reactor is a thermal reactor, the significant gamma radiation results from thermal neutron fission or capture. Thus, the spectrum of prompt gamma rays plus U^{235} capture gamma rays is $8.8 e^{-1.01E}$ photons/Mev-fission.² For 5500 kw hr of reactor operation per year and 8 hr of operation per day,⁷ about 10% saturation of the fission product decay gamma energy would be present at the startup of a day's activity, resulting in an average of 85% saturation and a maximum of 90% over the 8 hr period.⁸ Using 85% saturation, the decay gamma spectrum is $8.92 e^{-1.33E}$ photons/Mev-fission. The gamma energies per thermal neutron capture in aluminum for the various intervals from 3 to 10 Mev were obtained by summing up the individual contributions for each interval from a paper by Bartholomew, Kinsey and Walker.⁹ An additional energy of 1.80 Mev was added to the third group (1.5-3.0 Mev) to account for the decay gamma energy resulting from Al^{28} ($T_{1/2} = 2.3$ min). Thermal neutron capture by water gives rise to a single gamma ray per capture, 2.23 Mev, resulting from capture by hydrogen.

A possible gamma-ray source resulting from the inelastic scattering of fast neutrons by aluminum was also determined by considering the fast fluxes⁷ obtained for loading 33 to have an energy spectrum similar to the fast fluxes

calculated for a spherical mockup of the Bulk Shielding Reactor.¹⁰ As the gamma-ray source due to the inelastic scattering of fast neutrons by aluminum was found to be less than 0.1% of the total core gamma source it was neglected.

Table 1 lists the individual core gamma source strengths for various energy intervals, while Table 2 contains some of the pertinent reactor parameters.

TABLE 1. PHOTONS PER FISSION OR CAPTURE IN VARIOUS ENERGY INTERVALS FOR BSR MATERIALS

$$\text{Photons/fission at } \bar{E} = \frac{E_{ab}}{\bar{E}}$$

$$E_{ab} = \int_a^b E N(E) dE$$

a Mev	b Mev	$\bar{E}$ Mev	Prompt Plus U ²³⁵ Capture Gammas Photons/fission	Decay Gammas Photons/fission	Aluminum Capture Plus Decay Gammas Photons/capture	Water Capture Gammas Photons/capture
0	0.75	0.5	3.032	2.654	0	0
0.75	1.5	1.0	2.337	1.664	0.425	0
1.5	3.0	2.0	1.546	0.795	0.213 + 0.900*	1.115
3.0	5.0	4.0	0.3373	0.1040	0.727	0
5.0	7.0	6.0	0.0460	0.00752	0.202	0
7.0	9.0	8.0	0.00618	0.00054	0.344	0
9.0	11.0	10.0	0.000828	0.000038	0	0

*Decay gamma contribution.

TABLE 2. REACTOR PARAMETERS FOR GAMMA HEATING MEASUREMENTS IN BSR

Load No. 33*

Critical mass of uranium = 3636 grams*

Temperature in core = 106°F + 22°C = 63°C*

Actual power = 0.859 nominal power*,†

$$\frac{\phi}{\text{actual watt}} = 0.731^{*,\dagger} \frac{\phi}{\text{nominal watt}} \quad (\text{tabulated in Ref. 3})$$

Volume ratio of Al to H₂O = 0.69*

Total volume of core = 99,100 cc

Material	Volume Fraction	Nuclei per cc times 10 ⁻²⁴	σ barns	Σ cm ⁻¹
Uranium	0.00196	0.94×10^{-4}	$\sigma_f = 512$	$\Sigma_f = 0.0481$
Aluminum	0.41	0.0247	$\sigma_a = 0.204$	$\Sigma_a = 0.00504$
Water	0.59	$N_H = 0.0394$	$\sigma_a = 0.293$	$\Sigma_a = 0.0115$

$$\sigma_f^{**} \text{ uranium} = f(E_o) \sigma_f(E_o) \frac{V_o}{V} = (0.98) (550b) (0.95) = 512 \text{ barns}$$

* All the indicated references obtained from E. B. Johnson or K. M. Henry of Bulk Shielding Facility.

† Appendix 2.

** Appendix 3.

The heating in the target samples due to capture gammas emanating from the water reflector was obtained by using disk sources 2 in. thick and 40 cm in radius. The heat generation in a sample due to a disk source is

$$H(x) = \frac{\mu c}{\rho} \frac{S}{2} \left\{ A \left(E_1 \left[(1 - \alpha) \mu y \right] - E_1 \left[(1 - \alpha) \mu \sqrt{a^2 + y^2} \right] \right) + (1 - A) \left(E_1 \left[\mu y \right] - E_1 \left[\mu \sqrt{a^2 + y^2} \right] \right) \right\},$$

where

S = source strength per unit area, watts/cm²,

$E_1(x)$ = E_1 function = $\int_1^{\infty} e^{-x\lambda} \frac{d\lambda}{\lambda}$ where λ is the mean free path,

y = perpendicular distance from center of disk to field point, cm,

a = radius of disk, cm,

with the other terms being defined previously. An average flux in the disk was obtained from the average flux along the disk center line, determined experimentally⁷ as a function of distance from the reactor north face, multiplied by 0.8 to account for the decrease in flux in the disk radially.

In computing the heating in the target sample due to self absorption of gammas and betas resulting from thermal neutron capture in the targets, local perturbation in flux due to the presence of the target sample was not considered. The only significant beta source in the target samples is the 2.87 Mev beta resulting from the decay of Al^{28} . This beta source was assumed to be entirely absorbed in the aluminum sample. The fraction of gamma rays absorbed in a target sample, F , was obtained from an expression by Storm, et al.,¹¹ based on the straight ahead scattering approximation for an infinite cylinder containing a uniform source distribution. Since the expression neglects multiple scattering effects, the energy absorbed in each cylinder was taken as the mean of the values calculated using the energy and the total-absorption cross sections. The variation of F with energy was taken into consideration.

RESULTS AND DISCUSSION

The individual contributions to the calculated heat generation rates along with the experimental rates are tabulated in Table 3. As the original experimental heat generation rates were based on the nominal power, it was necessary to multiply these rates by a factor ($1/0.859$, see Table 2) to obtain the heat generation rates corresponding to the actual reactor power.

Figure 2 shows a comparison of the experimental and calculated results. The rounding of the calculated curves close to the reactor surface results from the peaking of the thermal flux in the reflector region. The magnitudes of the experimental and calculated values agree quite well where the Z of the target metal is close to the Z of the surrounding mixture, $\bar{Z} = 9$, but the agreement becomes worse as the differences in the atomic number increases. For the distances considered, the calculated curve for the aluminum ($Z = 13$) fits the experimental curve to within $\pm 5\%$; the calculated curve for the iron ($Z = 26$) is about 14% low, and that for the lead ($Z = 82$) is about 12% low. The equivalent Z method should yield good results for materials having similar Z 's, and this is confirmed by the aluminum sample. However, for a heavy Z material following a light Z material, the large, low energy spectrum built up in the light Z material due to Compton scattering is highly absorbed in the first mean-free-path of the heavy material. Thus a buildup factor based on a homogeneous mixture will yield a low result in the heavy material, increasing in severity as the depth of penetration in the light material increases. This light-heavy sequence phenomenon has been noted elsewhere,⁶ and demonstrated by Monte Carlo calculations of energy absorption resulting from gamma radiation incident on a water-lead slab geometry.¹² Appendix 1 contains an analysis made of the available Monte Carlo slab geometry data to obtain a qualitative estimate of the ratio of calculated to actual energy absorption for a geometry approximating that of the experiment. The results obtained, although inconclusive, indicate that the difference between the experimental and calculated curves for lead and iron can be explained by this light-heavy sequence phenomenon.

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TABLE 3. INDIVIDUAL HEAT CONTRIBUTIONS IN TARGET MATERIALS FOR BSR
ALUMINUM

Distance from Core Face (in.)	Heat generation, watts/gram-Mw of power					
	Core Gammas	Water Capture Gammas	Target Capture Gammas	Target Decay Betas (Al ²⁸)	Calculated Total	Experimental Total
0	0.1770	0.0130	0.0027	0.0230	0.2158	
0.5	0.1530*	0.0150	0.0034	0.0293	0.2007	0.219
2.0						0.132
4.0	0.0545	0.0125	0.0011	0.0096	0.0777	0.0745
9.0	0.0178	0.0046	0.0001	0.0007	0.0232	

IRON

Distance from Core Face (in.)	Heat generation, watts/gram-Mw of power				
	Core Gammas	Water Capture Gammas	Target Capture Gammas	Calculated Total	Experimental Total
0	0.1804	0.0130	0.0503	0.2437	
0.5	0.1560*	0.0150	0.0640	0.2350	0.271
2.0					0.173
4.0	0.0557	0.0125	0.0210	0.0892	0.105
9.0	0.0183	0.0046	0.0015	0.0244	

LEAD

Distance from Core Face (in.)	Heat generation, watts/gram-Mw of power				
	Core Gammas	Water Capture Gammas	Target Capture Gammas	Calculated Total	Experimental Total
0	0.3254	0.0164	0.0016	0.3434	
0.5	0.2800*	0.0190	0.0020	0.3010	0.332
3.0					0.175
4.0	0.0975	0.0158	0.0007	0.1140	
6.0					0.090
9.0	0.0308	0.0058	0.00005	0.0367	0.043

*The 0.5 in. core gamma contributions were obtained by assuming a smooth function between the 0, 4 in. and 9 in. ORACLE values.

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Fig. 2. Gamma Heating in Target Metals for BSR

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CONCLUSIONS

In view of the good agreement between the experimental and calculated heat generation values for samples near the Bulk Shielding Reactor, it seems reasonable to conclude that the appropriate gamma-ray data used in conjunction with the basic analytic approach outlined should give representative results for the gamma-ray heat deposition in various parts of most reactors. Although the model used may be somewhat inadequate for reactors typified by multiple layers of widely varying Z, as indicated by the light-heavy sequence phenomenon, the equivalent Z method should yield results acceptable for design purposes for any reactor. Further refinements in calculations, i.e., reduction of core volume elements, finer division of energy groups, etc., do not appear to be justified.

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APPENDIX 1ESTIMATE OF THE RATIO OF CALCULATED TO ACTUAL GAMMA ENERGY ABSORPTION
IN A THIN LEAD SLAB FOLLOWING VARIOUS THICKNESSES OF WATER

Monte Carlo calculations of energy absorption resulting from 1-Mev gamma rays incident on a water-lead slab geometry at 0 deg, 60 deg, 70 deg, 32 min and 75 deg, 31 min for a maximum thickness of the composite slab of 2 mean-free-paths at the initial energy, were performed by S. Auslender.¹² An approximate representation of the energy absorption resulting from a semi-isotropic, infinite plane source of 1-Mev gamma rays was obtained by weighting the available incident angles with respect to their corresponding solid angles. Energy absorptions were obtained for lead slabs 0.5 mfp thick (0.25 in. at 1 Mev) and for water slabs 0.5 mfp thick, following 0.5, 1.0, and 1.5 mfp of water (1 mfp water = 5.6 in. at 1 Mev). The energy absorption was then calculated for the corresponding slabs using the appropriate² buildup factor for water and

$$H = S \mu_e \left\{ A E_1 \left[(1 - \alpha) \sum_i \mu_i t_i \right] + (1 - A) E_1 \left[\sum_i \mu_i t_i \right] \right\},$$

where

H = heating at the field point, w/cm³,

S = semi-isotropic, infinite plane source strength, w/cm²,

with the other terms being defined previously and

$$F(t) = \frac{H_x t}{S} = \text{fraction of total energy absorbed in slab, } t \text{ cm thick.}$$

The corresponding energy absorption values for the 0.5 mfp of water agreed quite well, while those for the 0.5 mfp of lead did not, as expected. The ratio of the calculated energy absorption, E_{aC} (0.5 mfp Pb), to the actual energy absorption, E_{aA} (0.5 mfp Pb), was obtained as

$$\frac{E_{aC} (0.5 \text{ mfp Pb})}{E_{aA} (0.5 \text{ mfp Pb})} = \frac{P(t) \text{ Pb calculated}}{P(t) \text{ Pb Monte Carlo}}$$

The ratios obtained are shown as a function of water mfp and are represented by a straight line since the energy buildup factors for a plane source in water are linear in nature.⁶ A comparison was made between these ratios and the actual calculated to experimental energy absorption ratio for the lead sample in the BSR, by assuming the core gamma source strength to be concentrated at a point 3 in. closer to the experimental points than the core center. The value of 3 in. was determined by weighting the core contributions by their respective mfp to a target location 4 in. from the reactor surface. The comparison was further limited by the differences in the target geometries. However, although the agreement indicated is fortuitous, the rapid absorption of the low energy spectrum built up in a low Z material by a high Z material apparently does account for the differences in the calculated and experimental curves for the light-heavy sequence.

Fig. 3 Comparison of Results for 0.5 mfp Lead Slab and BSR Lead Target Sample

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APPENDIX 2

The coefficients relating the actual power to the nominal power are determined at the BSF in the following way.⁷

The nominal power is the reading on an instrument which is attached to an ionization chamber located outside of the reactor core.

The actual power is obtained by numerically integrating the product of $\sum_f \Phi$ over the core where the flux, Φ , is determined from over 600 gold foil measurements taken at various points in the core.

Although the instrument which gives the nominal power reading can be adjusted to give the actual power for a particular configuration, any perturbation of the ionization chamber position or core configuration will disrupt the calibration causing the nominal power reading to be different from the actual power.

Then in the manner described above, the ratio

$$\frac{\text{actual power}}{\text{nominal power}} = 0.859$$

was determined⁷ for the experiments performed by Binford, et al.,¹ and the ratio

$$\frac{\text{nominal power}}{\text{actual power}} = 0.731$$

was determined⁷ for the flux measurements made on loading 33.

APPENDIX 3

The factor $f_x(E_0)$ for any process, x , is defined as¹³

$$f_x(E_0) = \frac{\int \sigma_x(E) n v dv}{\int \sigma_x(E_0) \frac{v_0}{v} n v dv},$$

where

n = Maxwellian distribution of neutron density about energy E_0 ,

v_0 = velocity corresponding to energy E_0 .

In our case, E_0 corresponds to a temperature of 63°C. We need a fission cross section, σ_f , such that

$$\sigma_f \times \bar{\Phi} = \int \sigma_f(E) n v dv,$$

$\bar{\Phi}$ = neutron flux obtained from the Bulk Shielding Facility* and is defined at the average velocity of a room temperature Maxwellian distribution, i.e., $\bar{\Phi} = \bar{v} \int n dv = \bar{v} n_T$, where $\bar{v} = 1.128 \times 2200$ m/sec.

Now

$$\begin{aligned} \sigma_f \bar{v} n_T &= \int \sigma_f(E) n v dv = f(E_0) \int \sigma_f(E_0) \frac{v_0}{v} n v dv \\ &= f(E_0) \sigma_f(E_0) v_0 n_T. \end{aligned}$$

$$\therefore \sigma_f = f(E_0) \sigma_f(E_0) \frac{v_0}{\bar{v}},$$

where $f(E_0)$ is the f -factor for the U^{235} fission cross section at E_0 corresponding to 63°C.¹⁵

*All foil measurements in the BSF are calibrated at the X-10 standard graphite pile to determine the flux.¹ The flux at this pile is defined at $\bar{v} = 1.128 \times 2200$ m/sec.¹⁴

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