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SUBJECT: Gamma-Ray and Fast Neutron Heat Deposition
in the EGCR Core

TO: Listed Distribution

FROM: E. A. Nephew

Abstract

The heat deposition rate in the EGCR due to fast neutrons and gamma rays has been calculated as a function of position in the core. Based on a source spectrum of 20.74 Mev/fission, the total gamma heating in the non-fuel region of the core is calculated to be 3.567 Mw. The detailed distribution of the gamma heat deposition in the moderator columns, loop tubes, graphite fuel assembly sleeves and reflector has been determined for the case of a typical reactor power distribution at operating conditions. Heating due to the moderation of fast neutrons is assumed to be proportional to the fast flux distribution in the core. Based on a source spectrum of 5.01 Mev/fission, the total neutron heating in the non-fuel region of the core is calculated to be 2.16 Mw. Thus it is estimated that 6.8% of the total reactor power is deposited outside of the fuel elements.

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GAMMA-RAY AND FAST NEUTRON HEAT DEPOSITION IN THE EGCR CORE

Introduction

In the EGCR core most of the fission energy is liberated near the point of fission in the form of kinetic energy of the fission fragments and beta particles from fission fragment decay. A fraction ($\sim 6.8\%$) of the total reactor power, however, is transported outside the fuel elements and subsequently deposited in other parts of the reactor. The carrier mechanism for this transported energy may be either penetrating gamma radiation or fast neutrons. To determine the over-all core cooling requirements for the EGCR, information on the heat deposition rates in the moderator and other core components is required. For this purpose a study has been made to determine heat deposition rates due to both fast neutron and gamma-ray absorption as a function of radial and axial position in the EGCR core.

I. Gamma Heat Deposition

This study differs from a previous one¹ mainly due to a more detailed analysis of the fraction of the total gamma-ray energy which escapes a fuel element and to a revised gamma-ray source spectrum. The total gamma-ray source is taken as 20.74 Mev/fission with 9.26 Mev/fission escaping the fuel rods. The energy distributed gamma-ray source spectrum based on the reaction rates which prevail in the EGCR core at 5000 Mwd/T in an equilibrium cycle to 10 000 Mwd/T is shown in Table 1. Gamma rays arising from the beta decay of U^{239} and Np^{239} are not included in Table 1. It is estimated that their contribution to the EGCR gamma spectrum would be less than 0.25 Mev/fission for the stated conditions.

¹"GCR Quar. Prog. Rep. Mar. 31, 1960," ORNL-2929, pp. 3-5.

Table 1. Spectral Distribution of EGCR Gammas

Average Group Energy, Mev →	0.5	1.0	2.0	4.0	6.0	8.0	10.0	Total Mev/fission
Prompt fission and U^{235} , Pu^{239} , and Pu^{241} capture gammas, Mev/fission	2.429	2.864	2.712	1.021	0.197	0.020	0.008	9.25
Fission product gammas, Mev/fission	1.840	2.308	2.205	0.577	0.063	0.007	0.001	7.00
Stainless steel capture gammas, Mev/fission	0.008	0.032	0.069	0.197	0.394	0.936	0.107	1.74
U^{238} capture gammas, Mev/fission	0.809	0.668	0.913	0.105	0	0	0	2.50
U^{236} and Pu^{240} capture gammas, Mev/fission	0.080	0.067	0.090	0.010	0	0	0	0.25
Total, Mev/fission	5.166	5.939	5.989	1.910	0.654	0.963	0.116	20.74

Due to the complex nature of the interaction of gamma rays with matter, the varying operating conditions of the EGCR core and the complicated geometries involved, the following simplifying assumptions and initial conditions were selected as a basis for the calculations.

1. The radial and axial power distribution in the core is that resulting from the operating condition in which the core has a uniform radial loading, the four central loops contain a homogeneous graphite-uranium experiment, $C/U = 200$, the central control rod is fully inserted, and the remaining control rods are inserted as a bank to 62 in.

2. The seven-rod cluster fuel elements are represented by finite long line sources whose gamma source strengths, $S(Z)$ w/cm, are proportional to the reactor radial and axial power distribution, and to the fraction of gamma energy in the actual volume distributed source region which succeeds in escaping the cluster.

3. The gamma-ray heat deposition at a point in the reactor is the sum of the contributions of all the line sources to the heating at that point. The contribution of a single line source is calculated by direct exponential attenuation modified by an energy absorption build-up factor.

A. Fraction of Total Gamma Source Energy which Escapes the Seven-Rod Cluster

The EGCR fuel element consists of seven stainless steel clad UO_2 rods, six outer rods being arranged hexagonally about a central rod. The oxide rods have dimensions 0.707 in. o.d. by 0.323 in. i.d.; the steel tubes are 0.750 in. o.d. with a 0.020-in. wall; the six outer rods have their centers on a 2-in.-diam circle. For a given gamma energy group, the gamma energy which escapes the cluster is taken as

$$E = \int_A \int_{\Omega} S(\bar{r}) e^{-\mu_T P(\bar{r}, \Omega)} B_E [\mu_T P(\bar{r}, \Omega)] \frac{d\Omega}{4\pi} d\bar{r}, \quad (1)$$

where

$S(\bar{r})$ = gamma source strength as a function of position in the cluster,

$\bar{r}$ = point of gamma ray origin in the cluster,

$\bar{\Omega}$ = direction of gamma-ray trajectory,

$P(\bar{r}, \bar{\Omega})$ = the straight ahead distance in UO_2 and stainless steel traversed by a gamma photon originating at $\bar{r}$ and leaving the cluster in direction $\bar{\Omega}$,

μ_T = total linear attenuation coefficient of the UO_2 and stainless steel medium,

$B[\mu_T P(\bar{r}, \bar{\Omega})]$ = energy build-up factor of the medium.

The seven-rod cluster is taken as being infinitely long and the integral was evaluated over total solid angle and cluster cross sectional area. The function $P(\bar{r}, \bar{\Omega})$ was first determined for the seven-rod cluster by the use of a code written for the IBM-704 computer. The results of foil activation experiments conducted at Hanford with the EGCR lattice cell were fitted to obtain an analytic expression for $S(\bar{r})$. Evaluation of expression (1) was accomplished on the IBM-704 by means of the ESCAPE code. In this code the vectors $\bar{r}$ and $\bar{\Omega}$ are represented by the source position coordinates (r, θ) and trajectory coordinates ϕ, ψ . Here ϕ is taken with respect to r , and ψ is the angle of elevation with respect to the r, θ plane. The number of mesh point intervals used in r, θ, ϕ and ψ was (5, 10, 200, 10). The numerical integration procedure employed was that of fifth order Gaussian quadrature. The results of this phase of the study are listed in Table 2.

Table 2. Gamma Escape Fraction for the EGCR Seven-Rod Cluster

Average Group Energy (Mev)	Escape Fraction	Effective Gamma Source (Mev/fission)	Gamma Source ^a (w/cm)
0.5	0.2237	1.156	4.7196
1.0	0.4458	2.648	10.8096
2.0	0.5698	3.413	13.9334
4.0	0.5782	1.104	4.5090
6.0	0.5584	0.365	1.4911
8.0	0.5280	0.570	2.3260
Total		9.26	37.79

^a Average over reactor core.

B. Gamma-Ray Heating Rate Due to a Line Source

The gamma-ray heating rate at a point P in graphite due to a line source having a source strength (w/cm) of unity is found by integrating the point kernel

$$H(R) = \mu_E B_A(\mu_T R_g) \frac{e^{-\mu_T R_g}}{4\pi R^2}$$

over the reactor height, where

R = total distance (cm) from a point on the line source to the sink point P,

R_g = total distance (cm) in graphite from a point on the line source to the sink point P,

$\mu_T(E_g)$ = total linear attenuation coefficient in graphite (cm^{-1}) for a given energy group,

$B_A(\mu_T R_g)$ = energy absorption build-up factor in graphite,

$\mu_E(E_g)$ = energy absorption coefficient (cm^{-1}) for graphite.

Fig. 1. Gamma-Ray Line Source in Graphite-Void Medium

If $W(E_g, Z)$ is the gamma power, w/cm, emitted by the line source, then the heat deposition rate at P due to a line source is for each energy group

$$Q_P(E_g) = \int_0^H W(E_g, Z) \mu_E(E_g) B_A(\mu_T R_g) \frac{e^{-\mu_T R_g}}{4\pi R^2} dZ, \text{ w/cm}^3 \quad (2)$$

C. Gamma Heat Deposition in Graphite Region of the EGCR

The gamma source term $W(E_g, Z)$ in Eq. (2) was calculated for each energy group by normalizing the average gamma energy emission rate (w/cm) for the reactor according to the assumed reactor power distribution shown in Figs. 2 and 3. The heat deposition rate Q (w/cm³) was obtained by evaluating Eq. (2) by means of the IBM-704 GAMA-2 program, and summing over-all energy groups and all line sources located less than 40 cm from the sink point. Figure 4 shows the heat deposition rates in graphite so obtained for $P(Z) = 1$ at points in the reactor equidistant from four surrounding fuel channels. To avoid calculating the heat deposition rate at an extremely large number of points in the reactor, a detailed study of the gamma heating rate distribution in one symmetry cell of the 16 in. x 16 in. graphite columns was made. The results of this study are shown in Fig. 5. In this calculation a uniform reactor power distribution was assumed. A traverse of the variation in the gamma heat deposition rate through the graphite fuel assembly sleeve is shown in Fig. 6. Due to the local nature of gamma-ray heat deposition it is felt that a reasonably good estimate of the heating at an arbitrary point in the core can be made by renormalizing the data of Figs. 4 and 5 according to the actual reactor power distribution.

The results of integrating the computed heat deposition rates over quadrants of each moderator column in the EGCR core are shown in Fig. 7. The corresponding gamma heat deposited in the graphite fuel assembly sleeves is listed in Fig. 8.

D. Gamma Heat Deposition in the EGCR Experimental Loop Tubes

The use of the build-up factor concept to calculate a specific signal attenuation in a homogeneous medium is straightforward and very convenient. For a heterogeneous region with complex geometry, however, simple combinations of the build-up factors and attenuation coefficients of the various component materials cannot necessarily be expected to yield valid results. A rigorous solution in this case could be obtained only through recourse to costly Monte Carlo calculations or by direct experimental measurements. In the EGCR the incentive to provide such accurate heat deposition rates in the graphite-steel region near the loop tubes is not sufficiently great to justify these methods. In this study the following assumptions have been made in obtaining an estimate of the gamma heat deposition in the stainless steel loop tubes, due to sources outside the tubes.

1. The energy flux arriving at the outer surface of the stainless steel loop tube is nearly that which is calculated considering the line sources to be in an infinite homogeneous graphite medium. That is, the presence of the steel tubes cause no appreciable energy flux perturbation; the energy absorption build-up factor of graphite alone is used. For the filament sources located behind the loop tube, straight exponential attenuation through steel is assumed.

2. The gamma heat deposition rate at the outer surface of the steel tube differs from that in the adjacent graphite by the constant factor $\bar{\mu}_E(\text{steel})/\bar{\mu}_E(\text{graphite})$.

3. The heating rate within the tube wall decreases exponentially with distance from the outer surface according to the relation $e^{-\mu_T r}$, where μ_T is the source-spectrum-weighted-average stainless steel total linear attenuation coefficient.

4. The midwall heating rate computed in the above manner is the average heating rate for the total volume of stainless steel in the tube.

In view of the rather small steel-to-carbon volume ratio in the reactor, the first assumption does not appear too unreasonable. The second assumption, however, is not generally valid for two arbitrarily selected materials. If for example the materials were lead and water this assumption would be extremely poor. Fortunately in the case of graphite and steel, the variation with energy exhibited by the energy absorption coefficients of these two materials has nearly the same shape. This is shown in the Appendix where it is seen that the ratio $\mu_E(E)(\text{steel})$ to $\mu_E(E)(\text{graphite})$ is nearly constant over the more important energy ranges. The last two assumptions are not critical because of the thinness of the tube walls. They contribute a reduction factor of about 0.9 to the total heat deposited in the experimental tubes if the outer wall rate were assumed to apply throughout the stainless steel volume.

The outer wall heating rate for the small loop tube was found to be 0.272 w/cm^3 , giving a mid-wall rate of 0.24 w/cm^3 . No variation with angular position was taken into account. The total gamma heat deposited in the $11,758 \text{ cm}^3$ steel volume of the small loop tube is 2.82 kw. Since the large loop tube is located near the core periphery the heat deposition rate depends greatly upon angular position around the tube. Figures 9 and 10 show the variation of heating rates in the vicinity of the large loop tube. Integrating over the volume of steel and the volume of the graphite plug, a total gamma heat of 2.35 kw is obtained for the steel loop tube and 1.48 kw for the graphite plug. Figures 11 and 12 show the additional heating rates in the core due to a 1-Mw seven-rod cluster experiment operating in the loop tubes.

E. Gamma Energy Balance in the EGCR Core

The average gamma power emitted from an EGCR fuel channel is 37.79 w/cm . The cumulative gamma heat deposited in graphite as a function of distance from a single line source is shown in Fig. 13. Here it is seen that the curve approaches the value of 37.79 asymptotically, thus confirming the approximate consistency of the values of μ_E and B_A used in this study. In

the EGCR core consideration must be taken of the fact that not all of the gamma power emitted from a fuel channel is deposited in graphite, but that a portion of it is deposited in neighboring fuel elements. From Fig. 13 it is seen that about 61% of the total gamma power has already been deposited in graphite before the nearest neighboring fuel element has been reached. Consequently, it can be expected that the fraction of total power deposited in other fuel channels will not be great. An estimate of this quantity was obtained by considering that the surface heat deposition rate in an element due to all other elements applies throughout the cluster volume with no flux depression. The value of 8.5 w/cm obtained in this manner is clearly too high. A second estimate was made by considering the gamma heat from a line source deposited in neighboring fuel elements. In this case allowance was made for the partial transparency of the fuel elements to gamma radiation and for the geometry effects of the fuel element array. The value of 3.0 w/cm obtained in this manner was used in the calculations since it represents a more conservative estimate from the standpoint of graphite cooling requirements.

A summary of the over-all gamma energy balance for one quadrant of the EGCR core is listed in Table 3.

Table 3. Gamma Energy Balance in Quadrant of EGCR Core

Component	Power Deposited (kw)
Graphite sleeves	251.2
Fuel elements (escaped energy which re-enters other fuel elements)	76.9
Reflector columns	38.3
Steel of small loop tube	2.82
Steel of large loop tube	2.35
Graphite plug of large loop tube	1.48
Graphite moderator columns	<u>595.7</u>
Total ^a	968.57

^aTotal emitted power = (58 elements)(37.79 w/cm)(442 cm) = 968.75 kw.

II. Fast Neutron Heat Deposition

The heat deposition rate due to the moderation of fast neutrons is assumed to be directly proportional to the fast flux distribution in the EGCR core. This distribution has been calculated by means of the two-dimensional PDQ program for the case of a uniform core loading in which the central control rod is fully inserted, and the remaining control rods are inserted to 62 in. as a bank. The four central loops are considered to contain a homogeneous graphite-uranium experiment, C/U = 200, operating at a power of 1.07 Mw. Based on an average fission spectrum energy of 1.98 Mev and an average $\bar{\nu}$ of 2.53, the total energy deposited in the core by fast neutrons is 5.01 Mev/fission or 2.16 Mw. From the PDQ fast flux calculations it is found that

$$\frac{\int_{\text{core}} \phi_1 \, dx \, dy}{\int_{\text{core} + \text{reflector}} \phi_1 \, dx \, dy} = 0.9104,$$

giving a core heat deposition of 1.97 Mw and a reflector heat deposition of 0.19 Mw. Figures 14, 15, and 16 show the manner in which this heat is distributed in a reactor core quadrant.

APPENDIX

Gamma-Ray Constants Used in the Calculations

Material	Quantity	Energy (Mev)					
		0.5	1.0	2.0	4.0	6.0	8.0
Graphite	$\mu_T(\text{cm}^{-1})$	0.1436	0.1040	0.0733	0.0502	0.0404	0.0351
Graphite	$\mu_E(\text{cm}^{-1})$	0.0490	0.0462	0.0391	0.0314	0.0274	0.0252
Graphite	A^*	2.77	4.64	7.24	58.7	-47.0	-10.1
Graphite	α^*	0.44	0.23	0.11	0.01	-0.01	-0.04
Stainless steel	$\mu_T(\text{cm}^{-1})$	0.6566	0.4718	0.3362	0.2617	0.2411	0.2339
Stainless steel	$\mu_E(\text{cm}^{-1})$	0.2331	0.2070	0.1832	0.1776	0.1832	0.1895
Ratio	$\frac{\mu_E(\text{steel})}{\mu_E(\text{graphite})}$	4.757	4.481	4.685	5.656	6.686	7.520
	$\frac{\mu_T(\text{steel})}{\mu_T(\text{graphite})}$	4.572	4.537	4.587	5.213	5.968	6.664

$$* B_A = A(e^{\alpha \mu_T r} - 1) + 1$$

μ_T = total linear attenuation coefficient

μ_E = energy absorption coefficient

B_A = energy absorption build-up factor

EGCR Data

Average power, Mw (thermal)	84.3
Number of fuel channels	232
Height of fuel channel, cm	442
Small loop tube, inside diameter, in.	5.00
outside diameter, in.	5.50
Large loop tube, inside diameter, in.	8.5
outside diameter, in.	9.5
Graphite moderator columns	16 in. x 16 in.

		x (in.)							
		0		16		32		48	
y (in.)	0	0.946	1.203	1.359	1.356	1.274	1.146	0.993	0.830
	16	1.203		1.332	1.331	1.239	1.106	0.955	0.809
	32	1.359	1.332	1.342	1.278	1.165	1.026	0.878	0.779
	48	1.356	1.331	1.278	1.183	1.052	0.902	0.757	0.675
	64	1.274	1.239	1.165	1.052	0.904	0.748	0.611	0.548
80	0	1.146	1.106	1.026	0.902	0.748			
	16	0.993	0.995	0.878	0.757	0.611			
	32	0.830	0.809	0.779	0.675	0.548			
	48	0.728	0.738						
	64								
	80								

Fig. 2. Radial Power Distribution Normalized to Unity
in Southeast Quadrant of the EGCR Core

Control Rod Configuration: Central rod fully inserted,
all remaining rods inserted 62 in.

FIGURE 3

FIG 4. SYMMETRY PORTION OF SOUTH-EAST REACTOR QUADRANT

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FIG. 5. THE GAMMA HEAT DEPOSITION RATES GIVEN ABOVE ARE BASED ON A UNIFORM RADIAL AND AXIAL POWER DISTRIBUTION

FIGURE 6

		x (in.)							
		0		16		32		48	
y (in.)	0	10.948	11.614	13.360	14.302	13.677	12.347	10.752	8.949
	16	11.614	6.770	12.894	14.025	13.304	11.932	10.320	8.240
	32	13.360	12.894	13.379	13.529	12.533	11.088	9.459	6.906
	48	14.302	14.025	13.529	12.648	11.288	9.693	8.062	5.493
	64	13.677	13.304	12.533	11.288	9.370	7.220	5.552	3.671
y (in.)	80	12.347	11.932	11.088	9.693	7.220	4.067	2.226	1.424
	0	10.752	10.320	9.459	8.062	5.552	2.226	2.484	
	16	8.949	8.240	6.906	5.493	3.671	1.424		
	32	5.984	5.111	7.013		2.484			
	48	2.113	1.851						

Fig. 7. Gamma Heat Deposition (kw) in Graphite Columns

(The gamma heat deposition for each quadrant of the 16 in. x 16 in. graphite columns is based on the radial power distribution of Fig. 2 and an average axial power distribution of unity.)

		x (in.)							
		0		16		32		48	
y (in.)	0	4.096	5.209	5.884	5.871	5.516	4.906	4.299	3.549
	16	5.209		5.767	5.763	5.365	4.798	4.135	3.503
	32	5.884	5.767	5.811	5.533	5.044	4.442	3.802	3.373
	48	5.871	5.763	5.533	5.122	4.555	3.905	3.278	2.923
	64	5.516	5.365	5.044	4.555	3.914	3.239	2.646	2.373
	80	4.906	4.798	4.442	3.905	3.239			
		4.299	4.135	3.802	3.278	2.646			
		3.549	3.503	3.373	2.923	2.373			
		3.152	3.195						

Fig. 8. Gamma Heat Deposition (kw) in Graphite Fuel Element Sleeves

(The gamma heat deposition is based on the radial power distribution shown in Fig. 2 and an average axial power distribution of unity.)

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GAMMA HEAT DEPOSITION RATES IN VICINITY OF LARGE LOOP
TUBE (watts/cm³)

FIG. 9. DISPOSITION RATES BASED ON RADIAL POWER DISTRIBUTION OF
FIGURE 2 AND AN AVERAGE AXIAL POWER DISTRIBUTION OF UNITY

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FIG. 10. CALCULATION BASED ON RADIAL POWER DISTRIBUTION OF FIGURE 2 AND AN AVERAGE AXIAL POWER DISTRIBUTION OF UNITY

FIG. II. 1MW EGCR CLUSTER EXPERIMENT IN SMALL LOOP TUBE,
HEAT DEPOSITION RATE IN GRAPHITE AS A FUNCTION OF
DISTANCE FROM THE LOOP TUBE

FIG. 12. 1MW EGCR CLUSTER EXPERIMENT IN LARGE LOOP TUBE,
HEAT DISPOSITION RATE IN GRAPHITE AS A FUNCTION OF
DISTANCE FROM THE LOOP TUBE

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FIGURE 13

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FIG. 14. FAST NEUTRON HEAT DEPOSITION RATE (WATTS / cm^3)
IN A SYMMETRY CELL OF A GRAPHITE COLUMN QUADRANT

		x (in.)											
		0		16		32		48		64		80	
y (in.)	0	1.987	2.526	2.854	2.848	2.675	2.407	2.085	1.743	1.529			
		2.526		2.797	2.795	2.602	2.323	2.006	1.699	1.550			
	16	2.854	2.797	2.818	2.684	2.447	2.155	1.844	1.636				
		2.848	2.795	2.684	2.484	2.209	1.894	1.590	1.418				
	32	2.675	2.602	2.447	2.209	1.898	1.571	1.283	1.151				
	2.407	2.323	2.155	1.894	1.571								
48		2.085	2.006	1.844	1.590	1.283							
		1.743	1.699	1.636	1.418	1.151							
64		1.529	1.550										
80													

Fig. 15. Fast Neutron Heat Deposition (kw) in Graphite Fuel Assembly Sleeves

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- FIG. 16 - HEAT DEPOSITION (KW) IN (16 X 16) INCH SQUARE
GRAPHITE COLUMNS DUE TO FAST NEUTRONS

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