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A FIRST ESTIMATE OF THE GAMMA HEATING IN THE CORE VESSEL OF A MOLTEN FLUORIDE CONVERTER

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A B S T R A C T

A core vessel 6 feet in diameter having a Ni wall 1/3-inch thick is heated by gamma rays from the core, blanket, and the wall itself. The distribution of the gamma sources from fission, beta decay, radiative capture, and inelastic scattering of neutrons was computed by means of a multi-group nuclear calculation. The gamma heating in the vessel wall was then estimated using the straight-ahead-scattering, integral-spectrum method. It was estimated that, at a power level of 600 Mw (187 watts/cc average), core gammas would generate heat at the rate of 13.41 watts/cc; blanket gammas, 0.97; and gammas resulting from neutron captures in the vessel wall, 1.63; total, 16.0 watts/cc. Equations and sample calculations are given.

Introduction

The feasibility of homogeneous, molten salt reactors for central station power is being studied at Oak Ridge National Laboratory[1]. In order to locate and clarify the crucial design and development problems, the preliminary, conceptual design of a quasi-optimum system, referred to as the Reference Design Reactor, was carried through.

The RDR is a two region converter-breeder containing molten salt solutions in both regions. The integrity of the core vessel separating the core and blanket must, of course, be assured. Requirements in regard to maximum temperature, surface temperature, and thermal stress in the wall of the core vessel must be met. The first step in the calculation of these temperatures and stress is the estimation of the rate of heat release in the core vessel wall due to the dissipation of the energy of the radiations penetrating it. This paper illustrates the general approach to the problem, and gives the results for a typical set of conditions.

Description of System

The reactor [redacted] consists of a pear-shaped, core region 6 feet in diameter, surrounded by a blanket region 24 inches thick. The two regions are separated by the wall of a core vessel 1/3-inch thick, composed of an alloy of nickel which, for present purposes, is assumed to have the same nuclear properties as pure nickel. The core and blanket fluids have compositions and properties as shown in Table I.

Table I

Molecular Component	Core Fluid (mole %)	Blanket Fluid (mole %)
$U^{235}F_4$	0.63	
$U^{238}F_4$	0.05	
Li^7F	68.5	75
BeF_2	29.8	
$Th^{232}F_4$	1.0	25
Density at 1150°F, g/cc	2.18	4.25

The core fluid enters at 1100°F, is heated to 1200°F by the release of fission energy, and is discharged to the external system where the heat (600 megawatts) is removed and utilized in a steam-turbine cycle. Complete details are given in Reference 1.

Estimation of the Gamma Sources

Heat will be generated in the core vessel mainly by the dissipation of the energy of gamma rays coming from various sources. Because the mass of a nickel nucleus is high relative to that of a neutron, fast neutrons will be

able to transfer only negligible amounts of energy to the nickel directly by elastic and inelastic scattering. The range of fission fragments is so short that very few will penetrate the fuel and reach the core vessel. The range of beta particles (from the decay of fission fragments, etc.) is an order of magnitude greater than that of fission fragments, but the energy available is an order of magnitude less. Thus, only the heating effected by gamma rays need be considered.

The most important groups of gammas are: (1) "prompt" gammas accompanying fission; (2) "delayed" gammas from the radioactive decay of fission fragments; (3) "capture" gammas resulting from radiative capture of neutrons in core fluid, blanket fluid, and core-vessel wall; and (4) gammas resulting from the inelastic scattering of fast neutrons in the core, blanket, and core-vessel wall. Other gamma radiation, such as bremsstrahlung, annihilation radiation, etc., will be neglected.

Prompt Gamma Source - About 7.5 mev of prompt gamma energy is released per fission[2]. The relative fission-rate density distribution was estimated by means of a 31-group diffusion calculation[1] and is given in Table II.

Table II

Relative Fission-Rate Density Distribution

Radial Position, inches r	Relative Density (fissions per unit volume and per unit time) $S_c(r)$
0	1.000
5	0.979
10	0.911
15	0.805
20	0.670
25	0.518
30	0.359
32	0.298
34	0.240
35	0.211
36	0.184

This distribution must be proportioned, of course, with respect to the total power, viz:

$$Q_t\ (\text{Mw}) = \int_0^{36} N_c S_c(r) \left(\frac{\text{fissions}}{\text{inches}^3 \text{sec}}\right) 4\pi r^2 dr (\text{inches}^3) \times \frac{1}{3.1 \times 10^{16}} \left(\frac{\text{Mw sec}}{\text{fission}}\right) \quad (1)$$

where Q_t is the total reactor heat in megawatts and N_c is a proportionality factor. Setting $Q_t = 600$ Mw, and using the data from Table II, $N_c = 2.12 \times 10^{14}$. It follows that the prompt gamma source for the reactor under study has the following form:

$$S_\gamma(\text{prompt}) = 1.59 \times 10^{15}\ S_c(r)\ (\text{mev of gamma energy/inches}^3\ \text{sec}) \quad (2)$$

The spectral distribution for fission gammas presented by Francis and Gamble[2] appears to be adequately described by the relation:

$$P_\gamma(E_\gamma) = (N^o/E_\gamma^o)\ \exp(-E_\gamma/E_\gamma^o);\ 0.1 < E_\gamma < 8 \quad (3)$$

where P_γ is the probability, per mev of energy range, that a photon will be emitted with energy E_γ(mev); $N^o = 1.0$ and $E_\gamma^o = 1.0$ (mev).

<u>Delayed Gamma Source in Core</u> - Bertini et al[3] estimated that about 5.9 mev of "delayed" gamma energy is released per fission by the radioactive decay of fission products. The rate of release is a maximum at the instant of fission, and decreases thereafter. Rosenthal[4] predicts that the release rate would decrease about 10 percent in four seconds. The transit time for the fuel in the external heat exchange circuit for the reactor considered here is about 4.5 seconds. It appears that the "delayed" gamma source distribution will be approximately uniform over the core and external circuit, and takes the form:

$$S_\gamma(\text{delayed}) = \frac{Q_t(\text{Mw})}{V_s(\text{inches}^3)} \times \frac{3.1 \times 10^{16}(\text{fissions})}{(\text{Mw sec})} \times \frac{5.9(\text{mev of } \gamma \text{ energy})}{(\text{fission})} \quad (4)$$

where V_s is the total volume of fuel system, core and external circuit. At 600 Mw of heat and with a total volume of 452 ft^3, S_γ(delayed) = 0.141 x 10^{15} mev/$inches^3$ sec. This estimate takes no account of the possible removal of volatile fission products before their decay.

The spectral distribution of the gamma radiation from fission products has been studied by Peelle et al[5]. Measurements on gamma photons having energies lying between about 0.3 and 6 mev were reported. With reasonable extrapolation, the spectrum appears to be adequately described for present purposes by Equation (3), with $N^o = 1.14$ and $E_\gamma^o = 0.752$ for E_γ in the range $0.1 < E_\gamma < 8$ mev.

Capture Gamma Source in Core - The estimation of the gamma-source strength due to radiative capture of neutrons is rather more difficult. In principle, one may write:

$$S_\gamma(\text{capture}) = \int_0^\infty \phi_n(E_n,r) \sum B^i \Sigma_c^i(E_n)\, dE_n \,(\text{mev/cm}^3 \text{ sec}) \qquad (5)$$

where $\phi_n(E_n,r)$ is the energy distributed neutron flux at r, E_n is the neutron energy, B^i is the binding energy for a neutron in a nucleus of the i-th type, and Σ_c^i is the corresponding cross section for radiative capture. The flux data is available, and the calculation, although tedious, could be performed for each space point. However, an examination of the flux plots reveals that they are all quite similar geometrically, and are sufficiently similar to the fission density distribution that one may, for present purposes, assume the neutron capture distribution is similar to the fission density distribution, and that the distribution of the captures among the various nuclides

does not change with position. One may then base the estimation of S_γ(capture) on average conditions within the core. In Table III are listed the allocations of neutrons to the various nuclides, together with the corresponding energies taken from Reference 6.

Table III

Nuclide	Fraction of neutrons absorbed in radiative capture	Binding Energy (mev/neutron)
Li	0.051 (mostly F)	0*
Be		6.81
F		6.60
U^{235} (captures)	0.169	6.43
U^{238}	0.018	4.86
Th	0.145	5.12
U^{235} (fissions)	0.404	

* Capture by Li releases negligible γ radiation

Multiplying the binding energy for each nuclide by the corresponding fraction of neutron captures, summing, and dividing by 0.404 (the fraction of neutrons causing fission), one finds Q_γ(capture) to be 5.58 mev of gamma energy per fission. Using the fission density distribution given above, it follows that:

$$S_\gamma(\text{capture}) = 1.18 \times 10^{15}\ S_c(r)\ (\text{mev of gamma energy/inches}^3\ \text{sec})$$

The spectral distribution of the capture gamma rays from these elements is available only for U^{238}. Kenney and Mattingly[7] report lines at 4.0, 5.9, and 7.5 mev, and continuous radiation increasing monotonically with decreasing gamma

energy below 3 mev. Since the binding energy in U^{238} is only 4.9 mev, the gammas at 5.9 and 7.5 are spurious and will be ignored. The total cross section for thermal neutrons in U^{238} is 2.7 barns, the cross section for the 4 mev gamma is 1.3. Thus about 2 mev of the binding energy is liberated in the form of 4 mev gammas, the remainder (about 3 mev) is liberated below 3 mev (say, at 0.5 mev). U^{235} and Th are, in the absence of experimental data, assumed to behave similarly. Thus, the 5.1 mev binding energy in Th^{232} is arbitrarily resolved into 2 mev of 4 mev gammas and 3 mev of 0.5 mev gammas, and the 6.4 mev binding energy in U^{235} is resolved into 2.5 mev of 5 mev gammas and 4 mev of 0.5 mev gammas. The light elements F and Be are assumed to belong to Mittleman's Class 1 and to emit one 6.6 mev gamma per capture[8]. Summing the groups for the gamma energies gives the spectral distribution, viz:

Table IV

Assumed Capture Gamma Spectrum for Core Salt

Photon energy, mev	Fraction of photons
0.5	0.909
4	0.037
5	0.034
6.6*	0.020

*Includes Be radiation

Gamma source from Inelastic Scattering of Neutrons in Core - The only nuclides in the core having appreciable cross sections for inelastic scattering of neutrons are fluorine, uranium, and thorium. By a calculation similar to that which follows, it can be shown that the contributions to the gamma source from uranium and thorium scattering are negligible. Accordingly, they will be ignored. Freeman[9] reports four gamma rays in the spectrum of radiation

from F^{19} nuclei excited by fast neutrons. These have energies of 0.111, 0.197, 1.24, and 1.37 mev. The cross sections, in barns, for production of the first two are given for neutron energies up to 1 mev, and relative cross sections for all four up to 2.2 mev. These data were averaged roughly (with reasonable extrapolations) over the neutron energy groups, for which estimates of the fast flux were available from the multi-group calculation. The results are given in Table V, together with the volume-integrated, relative fast flux in each group.

Table V

Gamma Rays from F^{19} Excited by Inelastic Scattering of Fast Neutrons

Neutron Group No. j	Lower Limit Energy, mev E_j	Integrated Fast Flux* $\phi_{n,j}$	Gamma Ray Energy, E_γ mev			
			0.111	0.197	1.24	1.37
			Group Average Inelastic Scattering Cross Sections, $\bar{\sigma}_j$ (E_γ) barns/atom			
0	10.00	-	-	-	-	-
1	6.06	0.302	(0.5)**	(0.8)	(0.2)	(0.2)
2	3.68	1.54	(0.5)	(0.8)	(0.2)	(0.2)
3	2.23	4.20	(0.5)	(0.8)	0.2	0.2
4	1.35	7.30	0.6	0.9	0.0	0.0
5	0.821	9.46	0.6	0.9		
6	0.1831	10.60	1.3	0.9		
7	0.0090	7.29	0.2	0.0		

* The units of $\phi_{n,j}$ are neut-cm per neutron born in core.

** Values in parenthesis estimated by extrapolation.

Rigorously, the gamma source should be estimated by evaluating, for each gamma ray at each space point, the integral,

$$S(E_\gamma,r) = \int_0^\infty \phi_n(E_n,r)\ N_F\ \sigma_F(E_n,E_\gamma)\ E_\gamma dE_n\ \frac{\text{mev of gamma energy}}{\text{cm}^3\ \text{sec}}$$

where E_n denotes neutron energy, $\phi_n(E_n,r)$ is the energy-distributed neutron flux at space point r, N_F is the number of fluorine atoms per cc (assumed uniform), and $\sigma(E_n,E_\gamma)$ the cross section in F^{19} for the production of photons of energy E_γ by inelastic scattering of neutrons of energy E_n. However, as with the capture gamma source and for the same reasons, variations in the neutron spectrum are ignored and it is assumed that the distribution of the gamma source due to inelastic scattering is similar to the fission-rate density distribution. It then is sufficient merely to estimate the gamma source Q_γ in mev per fission and multiply by the fission-rate density. The volume-integrated, relative neutron flux $\phi_{n,j}$ in each neutron energy group is readily obtained from the multi-group diffusion calculation. This is given in Table V and is defined by the relation,

$$\phi_{n,j}\ \frac{\text{neutron-cm}}{\text{neutron born in core}} = \int_{V_c} \int_{E_n=E_j}^{E_n=E_{j+1}} \phi_n'\ (E_n,r)\ dE_n\ dV \tag{6}$$

where V_c is the volume of the core, and $\phi_n'\ (E_n,r)$ is the relative neutron flux in neutron-cm/cm^3 sec mev per neutron born in core. One then has,

$$Q_\gamma(E_\gamma) = \sum_{j=1}^{j=31} \phi_{n,j}\ \bar{\sigma}_j(E_\gamma)\ N_F\ E_\gamma\ \nu \tag{7}$$

where $\bar{\sigma}_j(E_\gamma)$ is the cross section for the production of photons of energy E_γ averaged over the j-th neutron energy group, and ν is the average number

of neutrons produced per fission. From the data in Table I, $N_F = 0.0479 \times 10^{24}$ atoms of F per cc. Setting $\nu = 2.47$ (for U^{235}), and using the data in Table V, $Q_\gamma(E_\gamma)$ was computed for each of the four gamma rays emitted by fluorine. The results are given in Table VI, together with the consequent spectral distribution given as fractions.

Table VI

Neutron Inelastic Scattering-Gamma Source and Spectrum

Photon Energy E_γ, mev	Gamma Source Strength $Q_\gamma(E_\gamma)$, mev/fission	Spectral Distribution Fraction of Photons
0.111	0.37	0.470
0.197	0.67	0.490
1.24	0.18	0.020
1.37	0.20	0.020
	1.42	1.000

The gamma source distribution therefore takes the form,

$$S_\gamma(\text{I.S.}) = 0.301 \times 10^{15}\ S_c(r) \text{ mev of gamma energy/inches}^3 \text{ sec}$$

Capture Gamma Source in Core Vessel Wall - The isotopic composition of nickel, together with the corresponding binding energies, are listed in Table VII, taken from Reference (6).

Table VII

Composition and Binding Energies in Natural Nickel

Isotope Atomic Mass	Percent Abundance	Binding Energy for Additional Neutron, mev
58	67.76	9.014
60	26.16	8.548
61	1.25	11*
62	3.66	9*
64	1.16	9*

*Estimated

The excitation (binding energy plus kinetic energy) resulting from the capture of a neutron of the j-th group in nickel is found by weighting the binding energies given in Table VII with the capture cross section and percent abundance of the corresponding isotope, summing the five products, dividing by the mean capture cross section, and adding the kinetic energy $E_{n,j}$. The resulting excitation energies should then be multiplied by the number of neutrons captured in the j-th group, and the thirty-one products summed to give the total energy available. This procedure must be repeated at each space point in the core vessel. However, in view of the approximate nature of other parts of this calculation, notably a lack of detailed information about the distribution of neutron captures and spectrum in the core vessel, this tedious procedure is not justified and will not be followed. Instead, a suitable approximation will be made. First, the average excitation energy per neutron capture is assumed to be ~ 9 mev. Second, it is assumed that the spatial distribution of neutron captures in the core vessel wall is uniform. It follows that,

$$S_\gamma(\text{C.V.C.}) = \frac{9 \text{ mev of gamma energy}}{\text{neutron capture in C.V.}} \times \frac{Z \text{ captures in C.V.}}{\text{neutron born in core}}$$

$$\times \frac{Q_t \text{ Mw of heat produced}}{4\pi R^2 \text{ T inches}^3} \times \frac{3.1 \times 10^{16} \text{ fissions}}{\text{Mw sec}} \times \nu \frac{\text{neutrons}}{\text{fission}}$$

where R is the core vessel radius and T the thickness. From the multi-group diffusion calculation, it was estimated that 0.010 of all neutrons were absorbed in the core vessel. Setting $Q_t = 600$, $\nu = 2.47$, $Z = 0.010$, $R = 36$ inches, $T = 1/3$-inch, one finds $S_\gamma(\text{C.V.C.}) = 0.762 \times 10^{15}$ mev/inches^3 sec.

Braid[10] lists five different "capture" gamma rays from nickel with energies ranging from 0.45 to 2.48 mev, and gives the frequency of emission. Kinsey[11] lists fifteen more between 5.3 and 9 mev. The total energy per

neutron captured thus accounted for amounts to 7.1, which is appreciably less than the assumed excitation energy of 9 mev. The gap in the measurements between 2.68 and 5.3 mev could conceivably contain about 0.5 mev of, say, 3.5 mev gammas, bringing the total to 7.6 mev. The remainder probably consists of low energy radiation below 5.3 mev, and will be approximated by taking 1.3 mev of 0.2 mev gammas. On this basis, the spectrum given in Table VII was computed.

Table VII

Spectrum of Capture Gamma Rays from Nickel

Photon Energy E_γ, mev	Fraction of Gamma Rays Emitted at E_γ
0.2	(0.852)*
0.45	0.0105
0.86	0.00393
1.24	0.00262
2.06	0.00393
2.68	0.00262
3.5	(0.01875)*
5.31	0.00131
5.70	0.000524
5.82	0.00393
5.99	0.000393
6.10	0.00131
6.34	0.000787
6.58	0.00262
6.84	0.0118
7.05	0.000656
7.22	0.000656
7.53	0.00524
7.82	0.00852
8.12	0.00367
8.53	0.01835
9.00	0.0459

* Assumed values

Capture Gamma Source in Blanket - Since there are negligibly few fissions (mostly in thorium) in the blanket, "prompt" and "delayed" gammas may be neglected. Further, since the "capture" gamma source in the blanket will be small relative to the total gamma source in the core, and since the gamma energy from inelastic scattering of neutrons in the blanket will be an order of magnitude smaller than the capture gamma source, the gammas arising from inelastic scattering in the blanket will be neglected.

The number of captures in lithium in the blanket is negligibly small. It was estimated from the multi-group calculation that the thorium in the blanket captured 0.189 of all neutrons, and the fluorine 0.005. Thus, approximately (neglecting the kinetic energy of the captured neutrons)

$$Q_\gamma \text{ (B.C.)} = \left[\frac{0.189 \text{ captures in Th}}{\text{neutron born in core}} \times \frac{5.12 \text{ mev of gamma energy}}{\text{capture in thorium}} + \frac{0.005 \text{ captures in F}}{\text{neutron born in core}} \times \frac{6.6 \text{ mev of gamma energy}}{\text{capture in fluorine}}\right] \div \left[0.189 + 0.005\right] \frac{\text{captures in blanket}}{\text{neutron born in core}}$$

$$= 5.16 \text{ mev of gamma energy/capture in blanket}$$

The relative distribution of neutron captures in thorium in the blanket, estimated from the multi-group calculation, is given in Table VIII.

Table VIII

Relative Distribution of Neutron Captures in Blanket

Radial Position r, inches	Relative Capture Rate captures/inch^3 sec, $S_b(r)$
36-1/3	1.000
37	0.636
38	0.524
40	0.355
42	0.242
44	0.163
46	0.110
50	0.050
54	0.019
60	0.000

Little error is introduced by assuming the distribution of captures in fluorine is the same. The relative distribution must be proportioned with respect to the total absorptions in the blanket.

$$N_b \int_{36\frac{1}{3}}^{60} S_b(r)\, 4\pi r^2\, dr = (0.189 + 0.005)\, \frac{\text{captures}}{\text{neutron born in core}} \times 600 \text{ Mw of heat}$$

$$\times \frac{3.1 \times 10^{16} \text{ fissions}}{\text{Mw sec}} \times \frac{2.47 \text{ neutrons born}}{\text{fission}}$$

Where N_b = proportionality factor, it follows,

$$N_b = 0.115 \times 10^{15}$$

Accordingly,

$$S_\gamma(\text{B.C.}) = 0.594 \times 10^{15}\, S_b(r) \text{ mev/inch}^3 \text{ sec}$$

As with the core captures, the spectrum of the "capture" radiation from thorium is assumed to consist of 0.5 gammas of energy 4 mev and 6 gammas of energy 0.5 mev.

Calculation of the Gamma Heating

For the purpose of this calculation, the straight-ahead-scattering, integral-spectrum approximation will be used. This procedure has been described in a previous paper[12]. Suffice it to say here that in the physical model on which the treatment is based, photons lose energy in Compton collisions, but are not deflected thereby. Further, it is assumed that the loss of photons from a given energy group by scattering and absorption is exactly compensated by the scattering from higher energy groups. Thus, the spectrum of the radiation is not a function of distance from the source. These assumptions are rather crude, of course. Their justification is, first, that they permit of analytical solutions from which numerical results of the correct order of magnitude may be obtained

with an amount of labor not unreasonably great. Second, in many instances, the various errors are somewhat compensatory, and the result is in rather better agreement with more rigorous methods than one might suppose.

In the approximation, the heating G_γ at a space point whose vector coordinates are denoted by $\vec{\rho}$ due to an isotropic, volume distributed gamma source S_γ at the space point $\vec{\rho}_s$ is formulated as follows[12]:

$$d\, G_\gamma(\vec{\rho}) = \frac{S_\gamma(\vec{\rho}_s)\, dV(\vec{\rho}_s)\, \exp(-\sum_h \bar{\mu}_{e,i}\Delta\rho_i)\, \bar{\mu}_{e,h}}{4\pi\rho^2} \tag{8}$$

where $dV(\vec{\rho}_s)$ is an element of volume of gamma source, $\bar{\mu}_{e,i}$ is the mean gamma-energy absorption coefficient (defined below) in the i-th medium between points $\vec{\rho}_s$ and $\vec{\rho}$, $\bar{\mu}_{e,h}$ the same coefficient for the material at $\vec{\rho}$, $\Delta\rho_i$ is the line-of-sight path-length in the i-th medium, and ρ the scalar distance between the points $\vec{\rho}_s$ and $\vec{\rho}$.

The mean gamma-energy absorption coefficients are defined, for continuous distributions, by the integral,

$$\bar{\mu}_e = \frac{1}{\bar{E}_\gamma} \int_0^\infty \mu_e(E_\gamma)\, E_\gamma\, P_\gamma(E_\gamma)\, dE_\gamma \tag{9}$$

where $P_\gamma(E_\gamma)\, dE_\gamma$ is the fraction of photons having energies lying in the range dE_γ, $\mu_e(E_\gamma)$ is the energy-absorption coefficient for photons of energy E_γ in the medium in which they are traveling, and $\bar{E}_\gamma$ is the mean photon energy. A method for computing μ_e is given in Reference 13.

The gamma heating at a selected point is obtained by integrating Equation (8) over all gamma sources. A little reflection shows that the heating

rate in the core vessel is probably a maximum at the inner surface adjacent to the gamma sources in the core fluid. Accordingly, the heat release at that point will be estimated. Further, in order to obtain compact analytical solutions, the core geometry will be assumed to be spherically symmetrical. This assumption should be valid for points in the lower end of the core vessel, opposite the inlet nozzle, and is conservative in that the neutron flux dependent gamma source adjacent to the wall in that region is probably higher than in regions near the inlet.

For the purposes of integrating Equation (8) over the gamma sources, it is convenient to separate these into four groups, viz: A. The "delayed" gamma source, due to radioactive decay of the fission products, which is uniform throughout the core fluid; B. The sum of the "prompt" and "capture" gamma sources plus the gammas from inelastic scattering of neutrons - this group is distributed similarly to $S_c(r)$, the fission density distribution; C. Gammas resulting from neutron captures in the core vessel wall - this source is assumed to be uniform throughout the wall; and D. Gammas resulting from neutron capture in thorium in the blanket - distributed according to $S_b(r)$, the blanket capture density distribution given in Table VIII. These groups are summarized in Table IX.

Table IX

Gamma Source Groups in Spherical Core

Group	Source Function	Limits
A	$S_\gamma(A) = 0.141 \times 10^{15}$ mev/inch^3 sec	$r \leq 36$
B	$S_\gamma(B) = 3.07 \times 10^{15}\ S_c(r)$	$r \leq 36$
C	$S_\gamma(C) = 0.762 \times 10^{15}$	$36 \leq r \leq 36\frac{1}{3}$
D	$S_\gamma(D) = 0.594 \times 10^{15}\ S_b(r)$	$36\frac{1}{3} \leq r \leq 60$

The heat release at the inner surface of the core vessel due to each of the groups of sources will be estimated separately and then summed to obtain the total heat release rate.

Group A: Equation (8) takes the form:

$$G_\gamma(A) = \int_{V_c} \frac{0.141 \times 10^{15}\ dV(\vec{\rho}_s)\ \exp\left(-\bar{\mu}_{e,s}(A)\ \rho\right) \bar{\mu}_{e,m}(A)\ \times \text{C.F.}}{4\pi\rho^2} \tag{10}$$

where $G_\gamma(A)$ is the heating due to source group A, V_c is the volume of the core, $dV(\vec{\rho}_s)$ an element of core volume, $\bar{\mu}_{e,s}(A)$ the mean energy-absorption coefficient of the core fluid with respect to the spectral distribution of the radiation in Group A (Table IX) as defined by Equation (9), $\bar{\mu}_{e,m}(A)$ is the same coefficient in the nickel, and C.F. is the conversion factor 1.60×10^{-13} watts sec/mev. Storm et al[14] have obtained an analytical expression for integrals of the type appearing in Equation (10). Consider a uniform, spherical source of gamma radiation of radius r and strength S_γ imbedded in an infinite matrix of absorbing material characterized by an energy-absorption coefficient $\bar{\mu}_e$. Let the heat release at some point (radial position R) be designated $G_\gamma(R)$. Then,

$$G_\gamma(R)/S_\gamma = \int_{V(r)} \frac{\bar{\mu}_e\ \exp(-\bar{\mu}_e\rho)\ dV}{4\pi\rho^2} = I(\bar{\mu}_e r, \bar{\mu}_e R) \tag{11}$$

Storm's expressions for the function I may be put into the form:

$$\begin{aligned} 4\ \bar{\mu}_e R\ I(\bar{\mu}_e r, \bar{\mu}_e R) = {} & \left[\bar{\mu}_e R + \bar{\mu}_e r - 1\right] \exp(-\bar{\mu}_e R + \bar{\mu}_e r) - \left[\bar{\mu}_e R - \bar{\mu}_e r - 1\right] \times \\ & \exp(-\bar{\mu}_e R - \bar{\mu}_e r) - \left[(\bar{\mu}_e R - \bar{\mu}_e r)(\bar{\mu}_e R + \bar{\mu}_e r)\right] \times \\ & \left[E_1(\bar{\mu}_e r - \bar{\mu}_e R) - E_1(\bar{\mu}_e R + \bar{\mu}_e r)\right] \end{aligned} \tag{12}$$

when $R \geqslant r$, and

$$4\,\bar{\mu}_e R\left[I(\bar{\mu}_e r,\bar{\mu}_e R) - 1\right] = -\left[\bar{\mu}_e r + \bar{\mu}_e R + 1\right]\exp(-\bar{\mu}_e r + \bar{\mu}_e R) + \left[\bar{\mu}_e r - \bar{\mu}_e R + 1\right]\times \exp(-\bar{\mu}_e r - \bar{\mu}_e R) + \left[(\bar{\mu}_e r - \bar{\mu}_e R)(\bar{\mu}_e r + \bar{\mu}_e R)\right]\times \left[E_1(\bar{\mu}_e r - \bar{\mu}_e R) - E_1(\bar{\mu}_e r + \bar{\mu}_e R)\right] \tag{13}$$

when $R \leqslant r$, and E_1 denotes the exponential function tabulated by Placzek[17]. Applying Equations (11) and (12) to Equation (10) with $r = R = 36$ inches gives,

$$G_\gamma(A) = 0.141 \times 10^{15} \times 1.60 \times 10^{-13}\,\frac{\bar{\mu}_{e,m}}{\bar{\mu}_{e,s}}\,I(36\,\bar{\mu}_{e,s}, 36\,\bar{\mu}_{e,s})\,\frac{\text{watts}}{\text{inch}^3} \tag{14}$$

It remains to evaluate $\bar{\mu}_{e,m}$ and $\bar{\mu}_{e,s}$ for the spectrum of Group A photons by the method of Reference 13. The spectrum will be cut off at 0.1 mev, for which low level the "low energy cut-off coefficient", f_o, may be taken equal to zero with negligible error. Using values of attentuation coefficients published recently by Grodstein[15], energy-absorption coefficients in units of cm^2/gm were computed for Be, O, and U. Data for Li, F, and Th are not available; however, an examination of the trends shows that the absorption coefficient in units of cm^2/gm for oxygen will be very close to that of fluorine, that of uranium to that of thorium, and that of lithium, though appreciably different from that of beryllium, is sufficiently close for present purposes. The results are shown in Table X.

Table X

Gamma-Energy Absorption Coefficient for Core Fluid and Core Vessel Wall

Element	(Li)Be	O(F)	U(Th)	Fe(Ni)	Core Salt	Metal
Concentration ρ_i, gm/cc	0.441	1.51	0.232	8.9		
	Energy Absorption Coefficient, $\mu_e \frac{cm^2}{gm}$				$\sum_i \mu_{e,i}\rho_i$	
E_γ mev					μ_e cm^{-1}	μ_e cm^{-1}
0.1	0.0167	0.0200	0.962	0.233	0.261	2.07
0.1161	(0.0177)*	(0.0210)*	3.99**	0.0788***	0.963	0.702***
0.2	0.0228	0.0264	1.35	0.0479	0.363	0.426
0.4	0.0264	0.0297	0.208	0.0306	0.1046	0.272
0.6	0.0264	0.0294	0.0970	0.0288	0.0783	0.256
0.8	0.0258	0.0292	0.0630	0.0277	0.0701	0.247
1.0	0.0248	0.0280	0.0483	0.0263	0.0644	0.234
1.5	0.0219	0.0257	0.0346	0.0242	0.0571	0.215
2.0	0.0182	0.0249	0.0331	0.0240	0.0549	0.214
3.0	0.0165	0.0212	0.0331	0.0223	0.0477	0.198
4.0	0.0142	0.0196	0.0354	0.0224	0.0451	0.199
6.0	0.0128	0.0170	0.0419	0.0232	0.0416	0.207
8.0	0.0118	0.0154	0.0432	0.0240	0.0389	0.214

* Interpolation

** K - shell cut-off

*** at 0.15 mev

The concentrations of the components Li-Be, F, and U-Th in gm/cc were then computed from the data of Table I and are listed in Table X. The products of the concentrations and the individual absorption coefficients were then summed for each gamma energy; these are listed in Table X in the sixth column. The units there are reciprocal centimeters.

Combining these data with the spectrum of Group A photons ("delayed"), and applying to Equation (9) gives $\bar{\mu}_{e,s}(A) = 0.197\ \text{inch}^{-1}$. Similarly,

$\bar{\mu}_{e,m}(A) = 0.602$ inch^{-1}. Substituting into Equation (12) with r = R = 36 inches; I = 0.465. Putting this into Equation (14), $G_\gamma(A) = 32.1$ watts/inch^3 (1.94 watts/cc).

Group B: With this group of photons, the variation of the source strength with radial position must be taken into account. In order to do this, the core region is conceptually resolved into thin, concentric shells. Consider the heat release in the core vessel due to the gamma source in a single shell whose mean radius is $\bar{r}_k$, whose thickness is Δr, and in which the mean source strength is approximately $S_\gamma(\bar{r}_k)$. Clearly, the heat release in the core vessel effected by gammas from this thin shell may be approximated by subtracting the heat that would be generated by a uniform source of strength $S_\gamma(\bar{r}_k)$ and radius $\bar{r}_k - \frac{\Delta r}{2}$ from the heat that would be generated by a uniform source of the same strength and radius $\bar{r}_k + \frac{\Delta r}{2}$, i.e.,

$$\Delta G_\gamma = G_\gamma \left[S_\gamma(\bar{r}_k), \bar{r}_k + \frac{\Delta r}{2}\right] - G_\gamma \left[S_\gamma(\bar{r}_k), \bar{r}_k - \frac{\Delta r}{2}\right] \tag{16}$$

From Equation (11) it follows that,

$$\Delta G_\gamma = S_\gamma(\bar{r}_k) \frac{\bar{\mu}_{e,m}}{\bar{\mu}_{e,s}} \left\{ I \left[\bar{\mu}_{e,s}(\bar{r}_k + \frac{\Delta r}{2}) \bar{\mu}_{e,s} R\right] - I \left[\bar{\mu}_{e,s}(\bar{r}_k - \frac{\Delta r}{2}), \bar{\mu}_{e,s} R\right] \right\} \tag{17}$$

Now, by going to the limit as Δr approaches zero, one obtains a differential equation which may be integrated over the entire core region to give the heating in the core vessel wall due to Group B photons.

$$G_\gamma(B) = \frac{\bar{\mu}_{e,m}(B)}{\bar{\mu}_{e,s}(A)} \int_{r=0}^{r=R} S_\gamma(B)\, dI(\bar{\mu}_{e,s} r, \bar{\mu}_{e,s} R) \times \text{C.F.} \tag{18}$$

The integral is conveniently evaluated graphically by plotting $S_\gamma(B)$ from Table IX versus I. But, first, $\bar{\mu}_{e,s}$ and $\bar{\mu}_{e,m}$ must be computed for the spectrum of Group B photons. This spectrum is conveniently obtained by weighting the spectra of the three sub-components of the B group ("prompt", "capture", and "inelastic scattering") by the energy available per fission in each subgroup $Q_{\gamma,i}$, according to the equation,

$$P_\gamma(E_\gamma,B) = \frac{\sum_i Q_{\gamma,i} P_{\gamma,i}(E_\gamma)}{\sum_i Q_{\gamma,i}} \tag{19}$$

where i is a subgroup index. Similarly, the mean photon energy $\bar{E}_\gamma(B)$ is given by,

$$\bar{E}_\gamma(B) = \frac{\sum_i Q_{\gamma,i}\ \bar{E}_{\gamma,i}}{\sum_i Q_{\gamma,i}} \tag{20}$$

Substituting these into Equation (9) gives,

$$\bar{\mu}_e(B) = \frac{\sum_i Q_{\gamma,i} \int_0^\infty \mu_{e,i}\ E_\gamma P_{\gamma,i}(E_\gamma)\ dE_\gamma}{\sum Q_{\gamma,i}\ \bar{E}_{\gamma,i}} \tag{21}$$

The integrals are readily evaluated from the individual spectra of the sub-groups, as are the $\bar{E}_{\gamma,i}$. The results are given in Table XI.

Table XI

Components of the Spectrum of Group B Photons

Sub-group	Energy, Q_γ mev/fission	Mean Photon Energy $\bar{E}_{\gamma,i}$ mev	Value of Integral in Eq.(21), mev/cm	
			Salt	Nickel
Prompt	7.5	1.0	0.0695	0.215
Capture	5.54	0.904	0.0591	0.209
Inelastic Scattering	1.42	0.201	0.0525	0.136

Substituting these data into Equations (20) and (21) gives $\bar{\mu}_{e,s}(B) = 0.181$ inch^{-1}, $\bar{\mu}_{e,m}(B) = 0.591$ inch^{-1}, and $\bar{E}_{\gamma}(B) = 0.881$ mev. Applying this value of $\bar{\mu}_{e,s}$ to Equation (12), with R = 36, values of I given in Table XII were computed.

Table XII

The Function I for $\bar{\mu}_{e,s} = 0.181$ inch^{-1}, R = 36 inches

Radial Position, r inches	$I\left[\bar{\mu}_{e,s}r, \bar{\mu}_{e,s}R\right]$
0	0.00000
5	0.00001
10	0.00011
15	0.00058
20	0.00260
25	0.01085
30	0.04710
32	0.08824
34	0.17615
35	0.26295
36	0.46163

Substituting from Table IX into Equation (18) gives,

$$G_{\gamma}(B) = \frac{0.591}{0.181} \times 3.07 \times 10^{15} \int_{r=0}^{r=36} S_c(r) \frac{\text{mev}}{\text{inch}^3 \text{ sec}} \, dI \times 1.60 \times 10^{-13} \frac{\text{watt-sec}}{\text{mev}}$$

The integral is evaluated by combining Tables II and XII, and is found to be 0.1166, from which $G_{\gamma}(B) = 188$ watts/inch^3 (11.5 watts/cc).

Group C: An analysis of the flux distribution in the core vessel shows that the neutron capture rate is approximately 15 percent less at the outer surface than at the inner. In order to simplify the mathematical treatment, this variation will be ignored. The error introduced will be small because the contribution made by capture gammas emitted by the nickel to the heating at the inner surface is a small part of the total (about 10 percent). Since the thickness of the core vessel wall is small compared to the radius of the vessel, the curvature of the wall may be neglected. Thus, a sufficiently accurate model of the system consists in a Group C gamma source uniformly distributed between two infinite plane surfaces 1/3-inch apart. Let the origin of coordinates be taken at the inner surface of the core vessel wall with the x-axis directed outward and normal to the surface, and with the y-axis directed parallel to (and lying in) the inner surface. Consider the heat release rate $G_\gamma(x)$ as some point between the two surfaces, and apply Equation (9) together with the added relations:

$$dV(\vec{\rho_s}) = 2\pi y dy dx'$$

$$\rho^2 = y^2 + (x-x')^2$$

$$\rho d\rho = y dy; \quad (x' = \text{constant})$$

where x' is the variable of integration in the x-direction. There results,

$$G_\gamma(x) = \int_{x'=0}^{x'=T} \int_{\rho=|x-x'|}^{\infty} \frac{S_\gamma \exp\left[-\bar{\mu}_{e,m}(C)\right] \bar{\mu}_{e,m}(C) \, d\rho \, dx'}{2\rho} \tag{22}$$

where T = thickness of the core vessel. Integrals of this type have been treated by Foderaro and Obenshain[16], who present extensive graphs of the

function $F_1(t,a)$, defined as follows:

$$F_1(t;a) = \int_{y=0}^{y=t} e^{ay} \int_{x=y}^{\infty} t^{-1} e^{-t} dt\, dx \tag{23}$$

Putting Equation (22) into the form of Equation (23) results in,

$$G_\gamma(x) = \frac{S_\gamma}{2}\left\{ F_1\left[\bar{\mu}_{e,m}(C)x;0\right] + F_1\left[\bar{\mu}_{e,m}(C)(T-x);0\right]\right\} \tag{24}$$

At the inner surface of the core vessel, x = 0. Noting that $F_1(0;a) = 0$, taking $S_\gamma(C)$ from Table IX, and setting T = 1/3-inch, there results:

$$G_\gamma(C) = \frac{0.762}{2} \times 10^{15} \frac{\text{mev}}{\text{inch}^3\ \text{sec}}\ F_1\left[\bar{\mu}_{e,m}(C)/3;0\right] \times \text{C.F.} \tag{25}$$

where C.F. = 1.60×10^{-13} watt sec/mev. It remains to evaluate $\bar{\mu}_{e,m}$, the energy absorption coefficient for nickel, for the spectrum of Group C photons by applying the data of Tables X and VII to Equation (9). It was found that $\bar{\mu}_{e,m} = 0.627\ \text{inch}^{-1}$. Putting this into Equation (25), $G_\gamma(C) = 26.8$ watts/inch^3 (1.63 watts/cc).

Group D: The heating induced in the nickel at the inner surface of the core vessel by photons resulting from the capture of neutrons in the blanket may be treated similarly to that induced by Group B photons. Equation (8) again applies, but now the source function for Group D is used and the integration is carried out over the blanket region. However, a minor complication now arises in that part of the path of each photon reaching the inner surface of the core vessel lies in the core vessel wall. This will be accounted for approximately by conceptually replacing the core vessel wall with an "equivalent" thickness of blanket salt containing no gamma sources. The rule of equivalence used

requires that $T' \bar{\mu}_{e,b} = T \bar{\mu}_{e,m}$, where T' is the "equivalent"thickness and $\bar{\mu}_{e,b}$ the energy absorption coefficient of the blanket salt. With this modification, Equation (8) is readily transformed by the methods used for Group A and B photons into

$$G_\gamma(D) = \frac{\bar{\mu}_{e,m}}{\bar{\mu}_{e,b}} \int_{r=36\frac{1}{3}}^{r=60} 0.594 \times 10^{15}\ S_b(r)\ \text{mev/inch}^3\ \text{sec}\ dI(r) \times \text{C.F.} \qquad (26)$$

By combining the spectrum of Group D photons with the data of Table X according to Equation (9), it is found that $\bar{\mu}_{e,m}(D) = 0.608\ \text{inch}^{-1}$, and $\bar{\mu}_{e,b} = 0.704\ \text{inch}^{-1}$. Accordingly, the equivalent thickness $T' = (1/3) \times (0.608/0.704) = 0.288$, and $R' = 36\frac{1}{3} - 0.288 = 36.045$. Using this and $\bar{\mu}_{e,b}$ in Equation (13), the values of I given in Table XIII were computed.

Table XIII

The Function I for $\bar{\mu}_{e,b} = 0.704$, $R' = 36.045$

Radial Position r, inches	$I\left[\bar{\mu}_{e,b}r,\ \bar{\mu}_{e,b}R'\right]$
$36\frac{1}{3}$	0.7055
$36\frac{1}{2}$	0.7656
37	0.8705
38	0.9529
39	0.9812
40	0.9921

Using these data to evaluate the integral in Equation (26), it is found that $G_\gamma(D) = 15.9\ \text{watts/inch}^3$ (0.97 watts/cc).

Conclusion

The contributions to the gamma heating at the inner surface of the core vessel wall are summarized in Table XIV.

Table XIV

Group	Description	Contribution to G_γ, watts/cc
A	"Delayed" gammas from core	1.94
B	"Prompt", "capture", and "inelastic scattering" gammas from core	11.5
C	"Capture" gammas from core vessel wall	1.63
D	"Capture" gammas from blanket	0.97
	Total heat release rate	16.0

By similar procedures, the heating rate at the center and outer surface of the core vessel wall could be estimated. However, the accuracy of the method hardly justifies this labor, and it is sufficient and conservative to take the value of 16.0 watts/cc as the average value.

The magnitude and sign of the probable error in this calculation is not easily estimated. A more accurate result could be obtained by integrating the fundamental gamma heating equation numerically with respect to space and energy using appropriate build-up factors, but the extra labor does not seem justified unless it is suspected that the value obtained here is low by an order of magnitude, which does not seem likely. Since the straight-ahead-scattering method overestimates the penetration of gamma radiation, the result obtained tends to be high. On the other hand, the integral-spectrum assumption does not allow for any softening of the radiation, and it may be that the heavy weighting

of the spectrum by high energy capture gammas has resulted in an underestimate of the energy absorption coefficient. This would tend to decrease the heat release rate in spite of the concomitant overestimate of the flux. The uncertainty is perhaps as great as a factor of 50 percent. Neglected radiations (annihilation, etc.) would add a further contribution. A consideration of the various factors leads to the conclusion that the heat release rate is probably not more than 50 percent greater, and probably not less than 16.0 watts/cc.

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NOMENCLATURE

Symbol	Definition or Explanation	Units
A	Gamma source group as described in Table IX and preceding paragraph	
B	Gamma source(s). See A, above	
B^i	Binding energy for a neutron in a nucleus of the i-th type	mev
C	Gamma source(s). See A, above	
C.F.	Conversion factor; value = 1.60×10^{-13}	$\frac{\text{watt-sec}}{\text{mev}}$
D	Gamma source. See A, above	
E_j	Kinetic energy of neutrons at lower limit of j-th group	mev
E_n	Neutron energy	mev
E_γ	Energy of gamma photon	mev
E_γ^o	Constant used for obtaining dimensional homogeneity in Eq. (3)	mev
$\bar{E}_\gamma$	Mean photon energy	mev
$F_1(t,a)$	Function defined by Eq. (23)	dimensionless
G_γ	Gamma-induced heating	$\frac{\text{watts}}{\text{inch}^3}$
$G_\gamma(A,\text{etc})$	Gamma-induced heating due to source group A (or B, C, or D)	$\frac{\text{watts}}{\text{inch}^3}$, $\frac{\text{watts}}{\text{cc}}$
$G_\gamma(\vec{\rho})$	Gamma-induced heating at space point $\vec{\rho}$	$\frac{\text{watts}}{\text{inch}^3}$, $\frac{\text{watts}}{\text{cm}^3}$
I	Function defined by Eq. (12) and (13)	
N^o	Constant in Eq. (3)	dimensionless
N_b	Proportionality constant for blanket capture distribution. See Table VIII et seq.	dimensionless
N_c	Proportionality factor for fission distribution. See Table II et seq.	dimensionless

Nomenclature (continued)

Symbol	Definition or Explanation	Units
N_F	Number of fluorine atoms per unit volume	$\frac{\text{atoms}}{\text{cm}^3}$
$P_\gamma(E_\gamma)$	Probability, per mev of energy range, that a photon has the energy E_γ	mev^{-1}
Q_γ	Gamma source strength	$\frac{\text{mev}}{\text{fission}}$
$Q_\gamma(\text{B.C.})$	Gamma source strength from neutron captures	$\frac{\text{mev}}{\text{fission in core}}$
Q_t	Total reactor heat energy output	Mw
R	Radial position at which gamma heating is to be calculated	inches
R'	Radius defined for Table XII	
r	Radial coordinate, distance from center of core	inches
r_n	Mean radius of elemental gamma-source shell	inches
$S_b(r)$	Relative neutron capture rate density in blanket (See Table VIII)	$\frac{\text{neutron captures}}{\text{inch}^3\ \text{sec}}$
$S_c(r)$	Relative fission rate density in core (See Table II)	$\frac{\text{fission}}{\text{sec inch}^3}$
S_γ	Gamma-source density	$\frac{\text{mev of } \gamma \text{ energy}}{\text{inch}^3\ \text{sec}}$
$S_\gamma(\text{B.C.})$	Gamma-source density in blanket due to radiative capture	$\frac{\text{mev}}{\text{inch}^3\ \text{sec}}$
$S_\gamma(\text{C.V.C.})$	Gamma-source density due to neutron capture in core vessel wall	$\frac{\text{mev of } \gamma}{\text{inch}^3\text{sec}}$
$S_\gamma(\text{I.S.})$	Gamma-source density due to neutron inelastic collisions in core	$\frac{\text{mev of } \gamma}{\text{inch}^3\text{sec}}$
$S_\gamma(\vec{\rho}_s)$	Gamma-source density at space point $\vec{\rho}_s$	$\frac{\text{mev of } \gamma}{\text{inch}^3\text{sec}}$
T	Core vessel thickness	inches
T'	"Equivalent core vessel thickness" as defined for Eq. (26) et seq.	inches
V_c	Volume enclosed by core vessel	inches^3

Nomenclature (continued)

Symbol	Definition or Explanation	Units
V_s	Total volume of salt in fuel system	$inches^3$
x, x'	Radial coordinates in core vessel wall; distance from inner surface	inches
y	Transverse coordinate parallel to core vessel wall	inches
z	Neutron captures in core per neutron born in core	
μ_e	Gamma-energy absorption coefficient defined by Eq. (9)	cm^{-1}
$\bar{\mu}_e$	Mean gamma-energy absorption coefficient defined by Eq. (21)	cm^{-1}
ν	Fission yield	$\frac{\text{neutrons}}{\text{fission}}$
$\vec{\rho}$	Scaler-distance between space points $\vec{\rho}_s$ and $\vec{\rho}$.	inches
$\vec{\rho}$	Vector coordinates of a space point	
$\vec{\rho}_s$	Vector coordinates of an elemental gamma source	
$\Delta\rho_i$	Line-of-sight path-length in the i-th medium	inches
Σ	Macroscopic neutron absorption cross section Also: mathematical summation symbol	cm^{-1}
Σ_c^i	Macroscopic cross section of a nucleus of the i-th type for radiative capture of neutrons	cm^{-1}
$\sigma_F(E_n, E_\gamma)$	Microscopic cross section of F^{19} for production of photons of energy E_γ by inelastic scattering of neutrons of energu E_n	$\frac{\text{barns}}{\text{atoms}}$
$\bar{\sigma}_j(E_\gamma)$	Microscopic cross section for production of photons of energy E_γ by inelastic scattering, averaged over the j-th neutron group	$\frac{\text{barns}}{\text{atom}}$
$\phi_n(E_n, r)$	Energy distributed neutron flux at r	$\frac{\text{neutron-cm}}{cm^3 \text{sec mev}}$
$\phi_{n,j}$	Volume integrated relative neutron flux in j-th neutron energy group	$\frac{\text{neutron-cm}}{\text{neutron born in core}}$

SUBSCRIPTS

b	"Blanket; of blanket salt"
h, i, j, k	Summation indices
m	"Metal; of metal"
n	"Neutron(s); of neutron(s)"
s	"Salt(s); of salt(s)"
t	"Total"
γ	"Gamma photon(s); of gamma photon(s)"

SUPERSCRIPTS

All superscripts with other than standard mathematical meaning are defined where used.

Distribution

1-3. DTIE, ORO
4. M. J. Skinner