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Escaping Through Openings in a Biological Shield
--Application to the HRT

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FROM: H. C. Claiborne and T. B. Fowler

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SUMMARY

A method was developed for calculating shield induced gamma radiation escaping through openings in a biological shield. The method was applied to the HRT and the results indicated that the contribution to the dose from induced activity in the HRT shield was around 0.1 r/hr and was insignificant in comparison to other mechanisms contributing to the escape of gamma rays through shield openings.

INTRODUCTION

Maintenance of the HRT or other reactor types will require openings in the biological shield. An estimate of the radiation escaping through these maintenance portholes is necessary for designing temporary shielding and developing maintenance procedures.

As previously discussed,⁽³⁾ the radiation escaping from maintenance portholes may occur in four ways: 1) line of sight from equipment; 2) scatter off the inner porthole walls, cell walls and equipment; 3) line of sight from induced activity in the shield; 4) air scatter within the reactor cell.

A method of calculating the air scatter contribution to the gamma dose outside a cell due to leakage through a porthole was previously reported.⁽³⁾ In this memorandum a method of estimating the gamma dose contribution due to induced activity in the biological shield is developed and applied to the HRT. The contributions due to the other two mechanisms will be treated in a future memorandum.

DERIVATION OF EQUATIONS

Activity is induced in the shield by capture of thermal neutrons and subsequent emission of gamma photons. The gamma emission rate at any point in the biological shield is a function of the thermal flux at that point; the number of gammas emitted per capture, the neutron irradiation time and the time interval after irradiation. If the irradiation time and the time interval after irradiation are specified, the gamma emission rate per unit volume may be represented by $K\phi$. The value of K for a gamma photon of any particular energy may be estimated by analytical methods or measured experimentally.

Thermal Flux

The biological shield for the HRT is clad with steel on the inside. For estimating the thermal flux as a function of distance into the shield, the problem is resolved into a two-group, two-region calculation for an infinite slab.

The two-group, two-region diffusion equations with no fast neutron source (no fissionable material in the shield) are for region one (steel),

$$\nabla^2 \phi_{1F} - \frac{\phi_{1F}}{\tau_1} = 0 \quad (1)$$

$$\nabla^2 \phi_{1S} - \frac{\Sigma_{1S} \phi_{1S}}{D_{1S}} + \frac{D_{1F} \phi_{1F}}{D_{1S} \tau_1} = 0 \quad (2)$$

and for region two (concrete).

$$\nabla^2 \phi_{2S} - \frac{\phi_{2F}}{\tau_2} = 0 \quad (3)$$

$$\nabla^2 \phi_{2S} - \frac{\Sigma_{2S} \phi_{2S}}{D_{2S}} + \frac{D_{2F} \phi_{2F}}{D_{2S} \tau_2} = 0 \quad (4)$$

where the first subscript refers to the region and the second to the neutron group; S is for thermal and F for fast.

The general solutions of equations (1) and (2) are

$$\phi_{1F} = c_1 e^{-\frac{x}{\sqrt{\tau_1}}} + c_2 e^{\frac{x}{\sqrt{\tau_1}}} \quad (5)$$

$$\phi_{1S} = c_3 e^{-\lambda_1 x} + c_4 e^{\lambda_1 x} + c_1 S_1 e^{-\frac{x}{\sqrt{\tau_1}}} + c_2 S_2 e^{\frac{x}{\sqrt{\tau_1}}} \quad (5a)$$

where $\lambda = \sqrt{\frac{\Sigma_S}{D_S}}$

The form of the solution for the second region is the same as for the first. As a very close approximation, however, the second region may be considered infinite in extent since biological shields are around 5 feet of barytes concrete; therefore,

$$\phi_{2F} = c_5 e^{-\frac{x}{\sqrt{\tau_2}}} \quad (6)$$

$$\phi_{2S} = c_6 e^{-\lambda_2 x} + c_5 S_3 e^{-\frac{x}{\sqrt{\tau_2}}} \quad (7)$$

For this system the usual conditions of equal fluxes and currents at the interface apply. At $x = t$ (interface),

$$\phi_{1F} = \phi_{2F} \quad (8)$$

$$\phi_{1S} = \phi_{2S} \quad (9)$$

$$D_{1F} \left(\frac{d\phi_{1F}}{dx} \right) = D_{2F} \left(\frac{d\phi_{2F}}{dx} \right) \quad (10)$$

$$D_{1S} \left(\frac{d\phi_{1S}}{dx} \right) = D_{2S} \left(\frac{d\phi_{2S}}{dx} \right) \quad (11)$$

In applying a boundary condition to the inner face of the shield, it is assumed that the fast and thermal leakage from the reactor and the fast contribution from delayed neutrons emitted from piping and equipment may be expressed as an average fast and average thermal neutron current entering the inner face of the shield. Therefore, at $x = 0$

$$I_{WF} = \left(\frac{\phi_{1F}}{4} \right) - \frac{D_{1F}}{2} \left(\frac{d\phi_{1F}}{dx} \right) \quad (12)$$

$$I_{WS} = \left(\frac{\phi_{1S}}{4} \right) - \frac{D_{1S}}{2} \left(\frac{d\phi_{1S}}{dx} \right) \quad (13)$$

where I_W is the estimated entering neutron current. Applying these boundary conditions to equations (5) through (7) and solving the arbitrary constants become

$$C_2 = \frac{4 I_{WF} \left[\left(\frac{D_{2F}}{D_{1F}} \right) \sqrt{\frac{\tau_1}{\tau_2}} - 1 \right]}{\left(1 - \frac{2 D_{1F}}{\tau_1} \right) \left(1 - \frac{D_{2F}}{D_{1F}} \sqrt{\frac{\tau_1}{\tau_2}} \right) - e^{\sqrt{\frac{2t}{\tau_1}}} \left(\frac{D_{2F}}{D_{1F}} \sqrt{\frac{\tau_1}{\tau_2}} + 1 \right)} \quad (15)$$

$$C_1 = \frac{4 I_{WF} - C_2 \left(1 - \frac{2 D_{1F}}{\sqrt{\tau_1}} \right)}{1 + \frac{2 D_{1F}}{\sqrt{\tau_1}}} \quad (16)$$

$$S_1 = S_2 = \frac{D_{1F}}{\tau_1 \Sigma_{1S} - D_{1S}} \quad (17)$$

$$C_5 = \frac{C_2 \left[e^{\frac{2t}{\sqrt{\tau_1}}} - 1 + \frac{2 D_{1F}}{\sqrt{\tau_1}} \right] + \frac{4 I_{WF}}{1 + \frac{2 D_{1F}}{\sqrt{\tau_1}}}}{\left(\frac{1}{\sqrt{\tau_1}} - \frac{1}{\sqrt{\tau_2}} \right) t} \quad (18)$$

$$C_4 = \frac{K_2 + K_3 K_4 + \frac{K_1 (K_4 - 1)}{1 + 2 D_{1S} \lambda_1}}{\left(1 - K_4 \right) \left(\frac{1 - D_{1S} \lambda_1}{1 + 2 D_{1S} \lambda_1} \right) + \left(1 + K_4 \right) e^{2t \lambda_1}} \quad (19)$$

where

$$K_1 = 4 I_{W2} - S_1 C_1 \left(1 + \frac{2 D_{1S}}{\sqrt{\tau_1}} \right) - S_2 C_2 \left(1 - \frac{2 D_{1S}}{\sqrt{\tau_1}} \right) \quad (20)$$

$$K_2 = \frac{\lambda_1 t}{e} \left[\frac{S_1 C_1 e^{-\frac{t}{\sqrt{\tau_1}}}}{\sqrt{\tau_1}} - \frac{S_2 C_2 e^{\frac{t}{\sqrt{\tau_1}}}}{\sqrt{\tau_1}} \left(\frac{D_{2S}}{D_{1S}} \right) \frac{S_3 C_5 e^{-\frac{t}{\sqrt{\tau_2}}}}{\sqrt{\tau_2}} \right] \quad (21)$$

$$K_3 = \left[S_3 C_5 e^{-\frac{t}{\sqrt{\tau_2}}} - S_1 C_1 e^{-\frac{t}{\sqrt{\tau_1}}} - S_2 C_2 e^{\frac{t}{\sqrt{\tau_1}}} \right] e^{\lambda_1 t} \quad (22)$$

$$K_4 = \left(\frac{D_{2S}}{D_{1S}} \right) \left(\frac{\lambda_2}{\lambda_1} \right) \quad (23)$$

$$C_6 = \left(C_3 + C_4 e^{2t \lambda_1} - K_3 \right) e^{(\lambda_2 - \lambda_1) t} \quad (24)$$

The symbols for the nuclear constants are as follows:

D = diffusion coefficient, cm; Σ_s = macroscopic cross section, cm^{-1} ; τ = Fermi Age, cm^2

Dose at Outer Edge of Porthole

For isotropic emission of gammas arising from thermal neutron absorption in a biological shield, the dose at the outer edge of shield can be expressed by

$$\bar{D} = k \int_V \frac{K \phi B e^{-\mu \rho}}{4 \pi r^2} dv \quad (25)$$

The buildup factor, B, can be approximated by an equation of the form⁽⁶⁾

$$B = A e^{-\alpha \mu \rho} + (1 - A) e^{-\beta \mu \rho} \quad (26)$$

when A, α , and β are constants which are functions of the material and energy of the emitted gammas. Gamma flux is converted to dose by the conversion constant, k, which is a function of the energy. As long as portholes are several centimeters removed from intersections of the walls of the biological shield, the infinite slab approximation can be used, and the volume element (see Fig. 1) becomes

$$dV = 2 \pi r^2 \sin \theta d\theta dr \quad (27)$$

The thermal flux as given by equations (5) or (7) must be transformed by the following substitution for use in the coordinate system selected (see Fig. 1)

$$x = (t + L) - r \cos \theta \quad (28)$$

To simplify the solution, the shield is considered divided into three regions (see Fig. 1) of gamma emission. In the first region gammas are born and attenuated in steel only; in the second region gammas are

born in steel but are also attenuated in concrete; and in the third region gammas are born in and attenuated by concrete only. The total dose is the sum of the contributions from the three gamma regions.

First Gamma Region --

For this region the attenuation length (See Fig. 2) is

$$\rho = r - \frac{R}{\sin \theta} \quad (29)$$

and the thermal flux is given by equation (5a).

Combining equations (6) and (25) through (28) an expression for the dose is obtained that contains eight terms, each term being of the same form. Expressing as a general term,

$$D_1 = \frac{kK}{2} \sum_{n=1}^{n=8} C_n \int_{\theta_1}^{\theta_2} \int_{r_1}^{r_2} C_n \left[\frac{a_n R}{\sin \theta} + b_n (L+t) \right] e^{-(a_n + b_n \cos \theta)r} dr \quad (30)$$

$$\text{where } r_1 = \frac{R}{\sin \theta}, r_2 = \frac{R+t}{\cos \theta}, \theta_1 = \tan^{-1} \frac{r}{(L+t)}, \theta_2 = \tan^{-1} \left(\frac{r}{L} \right)$$

and the index n refers to the term number of the expanded equation. The corresponding values of the constants for each term are given below in Table I.

TABLE I

Values of Generalized Constants for Gamma Region 1

n	a	b	c
1	$(\alpha + 1) \mu$	$-\lambda_1$	AC_3
2	$(\alpha + 1) \mu$	λ_1	AC_4
3	$(\alpha + 1) \mu$	$-1/\sqrt{\tau_1}$	$AC_1 S_1$
4	$(\alpha + 1) \mu$	$1/\sqrt{\tau_1}$	$AC_2 S_2$
5	$(\beta + 1) \mu$	$-\lambda_1$	$(1 - A) C_3$
6	$(\beta + 1) \mu$	λ_1	$(1 - A) C_4$
7	$(\beta + 1) \mu$	$-1/\sqrt{\tau_1}$	$(1 - A) C_1 S_1$
8	$(\beta + 1) \mu$	$1/\sqrt{\tau_1}$	$(1 - A) C_2 S_2$

Integrating equation (30) with respect to r and transforming to a more convenient algebraic form by letting $z = \cos \theta$,

$$D_1 = \frac{kK}{2} \sum_{n=1}^{n=8} \int_{z_1}^{z_2} \left[\frac{b_n(L+t) - \frac{b_n R z}{\sqrt{1-z^2}}}{a_n + b_n z} \right]$$

$$\left[\frac{(a_n + b_n x) \left[\frac{R}{\sqrt{1-z^2}} - \frac{L+t}{z} \right]}{1-e} dz \right] \quad (31)$$

$$\text{where } z_1 = \cos \left[\tan^{-1} \left(\frac{R}{L} \right) \right]$$

$$z_2 = \cos \left[\tan^{-1} \left(\frac{R}{L + t} \right) \right]$$

An analytical solution of equation (31) is not possible, but particular solutions can be obtained by a simple numerical or graphical method. When $a_n = -b_n x$, which actually occurs in some cases, the denominator of equation (31) equals zero; however, for this condition the numerator is also zero and the resultant indeterminate possesses a finite value.

Second Gamma Region :-

In this region all gammas born in the steel between the boundary of the first gamma region and infinity are considered. Attenuation occurs both in the steel and in the concrete located between the target and point of the gamma emission. Except for certain extreme cases, the choice of the proper buildup factor for attenuation through two adjacent media of different composition is difficult. The most proper method is the equivalent Z (atomic number) concept which has been applied⁽¹⁾ with apparent success to a similar calculation. Another method is to take the total buildup factor as the product of the buildup factors for the given thickness of each medium. This method generally is not recommended, but is adequate in some cases for design purposes. For example, when a high Z material follows a low Z material, the dose calculated with a product of buildup factors will be high⁽⁵⁾ and result in a conservative shield design. The most conservative method is to use only the higher buildup factor of the two media throughout the entire system. Actually for the HRT shield the average atomic number of the two media are fairly close together, 31 for barytes concrete and 26 for steel. Consequently, these methods will all produce nearly the same result.

For this region, Equation (25) is modified to

$$D_2 = k \int_V \frac{K_s \phi (B_s B_c) e^{-\mu_c \rho_c} e^{-\mu_s \rho_s}}{4\pi r^2} dV \quad (32)$$

where the subscripts c and s refer to concrete and steel respectively. In the equivalent Z method or where the higher buildup factor only is used, the product $B_s B_c$ is replaced by a single value of B .

The attenuation lengths (See Fig. 2) are

$$\rho_c = \frac{L}{\cos \theta} - \frac{R}{\sin \theta} \quad (33)$$

$$\rho_s = r - \frac{L}{\cos \theta} \quad (34)$$

Combining equations (5), (27), (28), (32), (33), and (34) and utilizing the same procedure as for the first gamma region, the generalized term expression for the dose is

$$D_2 = \frac{k K_s}{2} \sum_{n=1}^{n=16} \int_0^1 \frac{e^{\left(b_n t + \frac{c_n R}{\sqrt{1-z^2}} - \frac{cL}{z}\right)}}{(a_n + b_n z)} \left[1 - e^{-\frac{(a_n + b_n) t}{z}} \right] dz \quad (35)$$

The corresponding values of the constants for each term are given below in Table II for the method using the product of the individual buildup factors. For use in the equivalent Z method or the higher buildup factor only method, terms 2, 4, 6, 8, 10, 12, 14 and 16 are dropped and A_s set equal to one in the remaining terms. The α_s and α_c , β_s and β_c , and A_c are then replaced by the equivalent values or values based on the higher buildup factor material.

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TABLE II

Values of Generalized Constants for Gamma Region 3

n	a	b	c	C
1	$(\alpha_s+1)\mu_s$	$-\lambda_1$	$(\alpha_c+1)\mu_c$	$A_s A_c C_3$
2	$(\beta_s+1)\mu_s$	$-\lambda_1$	$(\beta_c+1)\mu_c$	$(1-A_s)(1-A_c)C_3$
3	$(\alpha_s+1)\mu_s$	$-\lambda_1$	$(\alpha_c+1)\mu_c$	$A_s(1-A_c)C_3$
4	$(\beta_s+1)\mu_s$	$-\lambda_1$	$(\beta_c+1)\mu_c$	$A_c(1-A_s)C_3$
5	$(\alpha_s+1)\mu_s$	λ_1	$(\alpha_c+1)\mu_c$	$A_s A_c C_4$
6	$(\beta_s+1)\mu_s$	λ_1	$(\beta_c+1)\mu_c$	$(1-A_s)(1-A_c)C_4$
7	$(\alpha_s+1)\mu_s$	λ_1	$(\alpha_c+1)\mu_c$	$A_s(1-A_c)C_4$
8	$(\beta_s+1)\mu_s$	λ_1	$(\beta_c+1)\mu_c$	$A_c(1-A_s)C_4$
9	$(\alpha_s+1)\mu_s$	$-1/\sqrt{\tau_1}$	$(\alpha_c+1)\mu_c$	$A_s A_c C_1 S_1$
10	$(\beta_s+1)\mu_s$	$-1/\sqrt{\tau_1}$	$(\beta_c+1)\mu_c$	$(1-A_s)(1-A_c)C_1 S_1$
11	$(\alpha_s+1)\mu_s$	$-1/\sqrt{\tau_1}$	$(\alpha_c+1)\mu_c$	$A_s(1-A_c)C_1 S_1$
12	$(\beta_s+1)\mu_s$	$-1/\sqrt{\tau_1}$	$(\beta_c+1)\mu_c$	$A_c(1-A_s)C_1 S_1$
13	$(\alpha_s+1)\mu_s$	$1/\sqrt{\tau_1}$	$(\alpha_c+1)\mu_c$	$A_s A_c C_2 S_2$
14	$(\beta_s+1)\mu_s$	$1/\sqrt{\tau_1}$	$(\beta_c+1)\mu_c$	$(1-A_s)(1-A_c)C_2 S_2$
15	$(\alpha_s+1)\mu_s$	$1/\sqrt{\tau_1}$	$(\alpha_c+1)\mu_c$	$A_s(1-A_c)C_2 S_2$
16	$(\beta_s+1)\mu_s$	$1/\sqrt{\tau_1}$	$(\beta_c+1)\mu_c$	$A_c(1-A_s)C_2 S_2$

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Third Gamma Region --

All gammas born in the concrete from the edge of the porthole to infinity are considered in this region. The general form of the equation is identical with that for the first region (equation (31)) except the limits of integration are from zero to z_2 and only four terms are necessary since the neutron flux is defined by equation (7). The values of the generalized constants are given below in Table III. (See Fig. 3).

TABLE III

Values of Generalized Constants for Gamma Region 3

n	a	b	c
1	$(\alpha_c + 1)\mu_c$	$-\lambda_2$	$A_c C_6$
2	$(\beta_c + 1)\mu_c$	$-\lambda_2$	$(1 - A_c) C_6$
3	$(\alpha_c + 1)\mu_c$	$-1/\sqrt{\tau_1}$	$A_c C_5 S_3$
4	$(\beta_c + 1)\mu_c$	$-1/\sqrt{\tau_1}$	$(1 - A_c) C_5 S_3$

APPLICATION TO THE HRT

The contribution to the dose at the outer edge of a porthole in the HRT biological shield due to induced activity in the shield was estimated for three different porthole sizes using the method developed in the previous section.

Source Term

The basis for estimating the thermal flux in the shield was the neutron leakage from the inside surface of the HRT pressure vessel as estimated by

Edlund and Wood,⁽⁴⁾ 5.1×10^{16} fast neutrons/sec and 1.6×10^{17} slow neutrons/sec. By applying a two-group, two-region calculation for attenuation and slowing down through the pressure vessel wall, the blast shield and the thermal shield, and attenuating geometrically to the biological shield, the fast and slow neutrons currents entering the shield were estimated. The delayed neutrons liberated outside the reactor were estimated⁽⁷⁾ to be 24% of the total delayed neutrons. Assuming that the reactor cell may be represented approximately by a 23-ft sphere, the delayed neutron contribution, when uniformly apportioned, amounts to a fast current of 2×10^9 n/cm² sec at the biological shield. The total estimated fast current entering the biological shield was 6.9×10^9 and the slow current 6.1×10^7 n/cm² sec.

The nuclear properties of the shield used for estimating the thermal flux were based on values given by Tobias⁽⁸⁾ or estimated by the usual approximate methods.⁽⁹⁾ The actual values of the nuclear parameters were:

$$\tau_1 = 214 \text{ cm}^2, \tau_2 = 237 \text{ cm}^2, \lambda_1 = 0.769 \text{ cm}^{-1},$$

$$\lambda_2 = 0.296 \text{ cm}^{-1}, D_{1F} = 0.36 \text{ cm}, D_{1S} = 0.39 \text{ cm}$$

$$D_{2F} = 2.0 \text{ cm and } D_{1F} = 0.25 \text{ cm}$$

Using these values and taking the average thickness of the steel cladding as 5/8 in., the arbitrary constants as calculated by equations (15) through (22) are

$$c_1 = 5.098 \times 10^{10}, c_2 = -2.808 \times 10^{10}, c_3 = -2.026 \times 10^8,$$

$$c_4 = 2.818 \times 10^8, c_5 = 1.602 \times 10^{10}, c_6 = -7.792 \times 10^9,$$

$$s_1 = s_2 = 7.966 \times 10^{-3}, s_3 = 0.4070$$

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These constants give a thermal flux of 2.6×10^8 n/cm² sec at the inside edge of the biological shield. For estimating induced activity in the cell equipment, this may be assumed to exist throughout the reactor cell.

Gamma sources (K values) were estimated from experimental data⁽²⁾ on activity of steel and barytes concrete after neutron irradiation. The experimental values reported were normalized to 1.25 mev gammas, which was assumed to be the average energy of the emitted gammas. Based on one year of operation at 5 megawatts and a 4-hour interval after shutdown, the K values were estimated to be

$$K_s = 1.3 \times 10^{-3} \text{ photons/cm}^3 \text{ unit neutron flux}$$

$$K_c = 9.6 \times 10^{-5} \quad " \quad " \quad " \quad "$$

$$\text{For 1.25 mev gammas, } k = 2.2 \times 10^{-6} \frac{\text{roentgens}}{\text{hr unit gamma flux}}$$

Attenuation Properties

The attenuation coefficients for 1.25 mev gammas and the constants for the buildup factor equation used in these calculations were taken essentially from the Shielding Design Manual⁽⁶⁾ and are as follows:

$$\mu_s = 0.416, \mu_c = 0.192, \alpha_s = -0.084, \alpha_c = -0.082$$

$$\beta_s = 0.035, \beta_c = 0.038, A_s = 8.07, A_c = 8.8$$

Note that the constants for concrete and steel are close enough so that the dose would not be significantly dependent on the method of handling the buildup factor.

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Results

The results obtained by numerical integration of the dose equations for the three regions are shown in Table IV. Examination of Table IV shows that the contribution to the dose from induced activity in the HRT shield is only of the order of 0.1 r/hr and is negligible even when compared to air scattering.⁽³⁾ Another significant point is that only region three is of importance in estimating the dose. Consequently, for any additional calculations the contribution from the steel cladding may be neglected for thicknesses in the order of 1/2 in.

TABLE IV

Dose* From Induced Activity in HRT Shield

Region	L = 3' 2" R = 8"	L = 3' 2" R = 7"	L = 5' 6-1/2" R = 4"
1	3.6×10^{-4}	2.8×10^{-4}	1.7×10^{-5}
2	7.8×10^{-3}	5.6×10^{-3}	5×10^{-7}
3	0.135	0.118	1.12×10^{-3}
Total	0.144	0.124	1.13×10^{-3}

*Dose in r/hr. For 4 hours after shutdown

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Fig. 1 Diagrammatic Representation of Shield

Fig. 2 Details of Geometry for Each Gamma Region

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