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Escaping Through a Shield Opening -- Application to the HRT

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

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SUMMARY

A simplified method was developed for calculating wall-scattered gamma radiation escaping through a shield opening. The method was applied to the HRT and the results showed that next to the line of sight contribution, scattering off the wall of the shield opening was the main contribution to the dose at the rear edge of the shield. Design charts were prepared that give the dose as a function of the gamma source locations with the reactor cell.

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,⁽¹⁾ the escape of radiation through shield openings may occur in four ways: 1) line of sight from equipment; 2) scatter off the porthole wall, cell walls and equipment; 3) line of sight from induced activity in the shield; 4) air scatter within the reactor cell.

The methods of estimating the contributions to the dose due to the last two mechanisms were previously reported.^(1,2) In this memorandum a rather simplified method for scattering from porthole wall and cell walls is developed and applied to the HRT.

The problem of scattering from thick absorbers is considerably more complicated than for no absorption such as is virtually the case with air scatter. Analysis of thick absorber scattering is usually complicated by

the necessity for considering multiple scattering, which is quite involved and requires too much effort for ordinary design purposes. A method that shows promise⁽³⁾ for calculating scattered radiation from "thick" surfaces involves the application of albedo theory, but this is still in a preliminary stage of development. Essentially, this method consists of calculating albedos (ratio of emergent to incident radiation) with automatic electronic computers by a Monte Carlo technique. A long time and great effort would be required to prepare tables of albedos as a function of incident angle and photon energy for application to design problems.

Generally speaking, in low density media such as air and with low-energy-photon sources, single scattering effects predominate; in heavier media and with high energy sources multiple-scattering effects are more important.⁽³⁾ The case under consideration is an in-between one; moderately high density and low photon energy (around 0.7 mev average). A simplified calculation procedure based on single scatter only is devised in the following sections and applied to the HRT. It is recognized that a single scatter calculation will be subject to appreciable error. However, for the conditions imposed (taking into consideration a buildup factor) the results should be within a factor of two of the correct values. In view of the large number of unknown connected with the geometry and source strength, more involved calculations are unwarranted for design purposes.

DERIVATION OF EQUATIONS

Consider a cell surrounded by a thick biological shield with numerous sources of gamma radiation distributed throughout the cell. It is assumed that all radiation sources may be represented by point isotropic sources of known coordinates. When an opening is made in the shield, gamma radiation can escape due to scatter off the porthole walls as well as from walls of the reactor cell.

It is assumed that the attenuation before and after a scattering collision may be represented by the product of the buildup factor and exponential attenuation factor and that the total attenuation is a function of their products.⁽³⁾ For single scattering, the air scatter equation⁽¹⁾ must be altered by inclusion of the buildup factor and the exponential attenuation factor. For these conditions, the dose from wall scatter as measured by an isotropic counter located in the center of the porthole at the outer edge of the shield is

$$D = \int_V \frac{SN \left(\frac{d\sigma}{d\Omega} \right) F(E) B_1 e^{-\mu_1 \rho_1} B_2 e^{-\mu_2 \rho_2}}{4 \pi R_1^2 R_2^2} dV \quad (1)$$

where subscript 1 refers to conditions before a scattering collision and subscript 2 after a scattering collision and $F(E)$ is the dose per unit gamma flux as a function of energy E , $\left(\frac{d\sigma}{d\Omega} \right)$ is the probability for scattering through any scattering angle by a single electron, S is the source in photons/sec, and N is the number of electrons/cc. The symbols relating

to geometry are denoted in Figures 1 and 2. Since B_2 and μ_2 are functions of the scattering angles (because of the energy spectrum existing after scattering), an analytical solution of equation (1) is impossible. Numerical evaluation of the triple integral for the possible conditions would be an extremely tedious task. Fortunately, it is possible to reduce equation (1) to a single integral, which is considerably easier to evaluate numerically, by making an approximation which will not significantly change the results.

The product of the buildup factor and the attenuation factor may be represented⁽³⁾ by an equation of the form

$$B = \left[A e^{-\alpha \mu \rho} + (1 - A) e^{-\beta \mu \rho} \right] \quad (2)$$

and

$$B e^{-\mu \rho} = A e^{-(\alpha + 1) \mu \rho} + (1 - A) e^{-(\beta + 1) \mu \rho} \quad (3)$$

An examination of the plots of α , β and A ⁽³⁾ as functions of energy show that in the region of interest the following equations represent a fair approximation.

$$A_2 = A_1 \left(\frac{E_0}{E} \right) \quad (4)$$

$$\alpha_2 = \alpha_1 \left(\frac{E_0}{E} \right) \quad (5)$$

$$\beta_2 = \left(\frac{E}{E_0} \right) \beta_1 \quad (6)$$

$$\mu_2 = \left(\frac{E_0}{E} \right) \mu_1 - a(E_0 - E) \quad (7)$$

Combining equations (2) through (7),

$$\begin{aligned}
 B_1 e^{-\mu_1 \rho_1} \cdot B_2 e^{-\mu_2 \rho_2} &= \frac{A^2 E_0}{E} \exp - \left\{ (\alpha + 1) \mu \rho_1 + \left[\frac{\alpha E_0}{E} + 1 \right] \left(\frac{E_0}{E} \right) \mu - a (E_0 - E) \rho_2 \right\} \\
 &+ A \left(1 - \frac{AE_0}{E} \right) \exp - \left\{ (\alpha + 1) \mu \rho_1 + \left[\frac{\beta E}{E_0} + 1 \right] \left(\frac{E_0}{E} \right) \mu - a (E_0 - E) \rho_2 \right\} \\
 &+ \frac{AE_0}{E} (1 - A) \exp - \left\{ (\beta + 1) \mu \rho_1 + \left[\frac{\alpha E_0}{E} + 1 \right] \left(\frac{E_0}{E} \right) \mu - a (E_0 - E) \rho_2 \right\} \\
 &+ (1 - A) \left(1 - \frac{AE_0}{E} \right) \exp - \left\{ (\beta + 1) \mu \rho_1 + \left[\frac{E\beta}{E_0} + 1 \right] \left[\frac{E_0}{E} \right] \mu - a (E_0 - E) \rho_2 \right\} \quad (8)
 \end{aligned}$$

The general form of each term is $C_i \exp - [g_i \rho_1 + h_i \rho_2]$ with the coefficients as functions of the energy, E , and the subscript i referring to the term number of equation (8).

For all cases under consideration (Fig. 1 through 4), ρ_2 is replaced by a function of ρ_1 . From the geometry it is evident that

$$\rho_2 = R_2 - Z_2 = \left(R_1 \frac{\sin \psi}{\sin \theta} \right) - Z_2 = (Z_1 + \rho_1) \frac{\sin \psi}{\sin \theta} - Z_2 \quad (9)$$

and furthermore that

$$\rho_2 = \rho_1 \frac{\sin \psi}{\sin \theta} + \frac{(m + 2r)}{\sin (\gamma + \psi)} \frac{\sin \psi}{\sin \theta} - \frac{r}{\sin (\theta - \gamma)} \quad (10)$$

$$\text{since } Z_1 = \frac{(m + 2r)}{\sin (\gamma + \psi)} \quad (11)$$

$$Z_2 = \frac{r}{\sin (\theta - \gamma)} \quad (12)$$

Substituting equation (10) into (8) and expressing as a general term,

$$B_1 e^{-\mu_1 \rho_1} B_2 e^{-\mu_2 \rho_2} = \sum_{i=1}^{i=4} C_i \exp - \left\{ \left(g_i + h_i \frac{\sin \psi}{\sin \theta} \right) \rho_1 + h_i \left[\frac{(m + 2r)}{\sin(\gamma + \psi)} \frac{\sin \psi}{\sin \theta} - \frac{r}{\sin(\theta - \gamma)} \right] \right\} \quad (13)$$

When a photon of initial energy, E_o , undergoes Compton scattering the energy of the scattered photon as a function of the scattering angle, $\theta + \psi$, is⁽³⁾

$$E = \frac{E_o}{1 + \frac{E_o}{0.51} [1 - \cos(\theta + \psi)]} \quad (14)$$

The probability for scattering through any solid angle, $\frac{d\sigma}{d\Omega}$, is given by the Klein-Nishina formula.⁽³⁾

$$\frac{d\sigma}{d\Omega} = 3.97 \times 10^{-26} \left(\frac{E}{E_o} \right) \left[1 - \left(\frac{E}{E_o} \right) \sin^2(\theta + \psi) + \left(\frac{E}{E_o} \right)^2 \right] \quad (15)$$

In the region of interest the function $F(E)$ may be approximated closely by

$$F(E) = kE \quad (16)$$

If equations (1), (13), (14), (15) and (16) are combined, the general expression for the dose in form of a volume or triple integral is obtained. This equation is general and holds for scatter off the porthole wall or walls of the reactor cell, but numerical evaluation would be too time-consuming for practical use.

Scatter Off Porthole Walls

Consider a point source located outside of the line of sight region as defined by the outer edge of the porthole (See Fig. 1). As was done for the air scatter case,⁽¹⁾ the volume integral is reduced to a double integral by an approximation. Consider the radiation entering the annular opening generated by revolving the hole in the biological shield about the axis connecting the receptor and the point of emission of the radiation. Now the volume element is

$$dV = (2\pi R_1 \sin \psi) (R_1 d\psi_1) dR_1 \quad (17)$$

By the law of sines

$$\frac{R_1}{\sin \theta} = \frac{R_2}{\sin \psi} = \frac{x}{\sin(\theta + \psi)} \quad (18)$$

and by differentiating equation (18) it can be shown that

$$dR_1 = \frac{R_2^2}{x \sin \psi} d\theta \quad (19)$$

Combining equation (1) with equations (13) through (19) and making a change of variable ($dR_1 = d\rho_1$), an expression is obtained for the gamma dose at the annular opening, which is approximately corrected to the porthole dose by multiplying by f , the ratio of the porthole area to the annular area.

$$D = \frac{SNfk}{2} \int_{\psi_1}^{\psi_2} \int_0^{\rho_1} \left[\sum_{i=1}^4 C_i \exp - \left\{ \left(g_i + h_i \frac{\sin \psi}{\sin \theta} \right) \rho_1 \right. \right. \\ \left. \left. + h_i \left[\frac{(m + 2r)}{\sin(\gamma + \psi)} \frac{\sin \psi}{\sin \theta} - \frac{r}{\sin(\theta - \gamma)} \right] \right\} \right] \left[\frac{E \frac{d\sigma}{d\Omega} \sin^2(\psi + \theta)}{x^2 \sin} \right] d\rho_1 \cdot d\psi \quad (20)$$

$$\text{where } f = \frac{rx}{4L(m+r)} \quad (21)$$

An analytical solution of equation (30) is, of course, impossible since ρ_1 is a function of θ . A numerical solution is possible, but it is a tedious job even with the use of an electronic computer such as the Oracle.

The linear attenuation coefficients for concrete and other shield materials are large enough to attenuate gammas by an order of magnitude in a few centimeters of travel for gammas around one mev. In this case only about the first 3 centimeters are of importance. Therefore, for portholes several inches in diameter, θ may be considered constant for integration with respect to ρ_1 since the variation of θ in the region of significance will be small for any particular value of ψ , and E and $\frac{d\sigma}{d\Omega}$ will be a sensitive function of ψ only. It also follows that the upper limit of ρ_1 may be set equal to infinity as long as the source cannot "see" the porthole wall nearer than a few centimeters from the outside edge of the shield. Actually, the approximation is fair up to the edge of the porthole since the last few centimeters contribute only a relatively small portion of the dose.

Performing the first integration (neglecting the variation of θ with ρ_1),

$$D = \frac{SNfk}{2x^2} \int_{\psi_1}^{\psi_2} \left[\sum_{i=1}^4 \frac{C_i}{\left(g_i + h_i \frac{\sin \psi}{\sin \theta}\right)} \exp \left\{ h_i \frac{(m+2r)}{\sin(\gamma+\psi)} \frac{\sin \psi}{\sin \theta} \right. \right. \\ \left. \left. - \frac{r}{\sin(\theta-\gamma)} \right\} \right] \left[\frac{E \frac{d\sigma}{d\Omega} \sin^2(\psi+\theta)}{\sin \psi} \right] d\psi \quad (22)$$

The variation of θ with ψ is, of course, significant and cannot be neglected. From equation (18),

$$\sin \theta = \frac{R_1}{R_2} \sin \psi = \frac{(Z_1 + \rho_1)}{(Z_2 + \rho_2)} \sin \psi \quad (23)$$

Since $Z_1 \gg \rho_1$ and $Z_2 \gg \rho_2$ for the region of significance,

$$\sin \theta \cong \frac{Z_1}{Z_2} \sin \psi = \frac{(m + 2r) \sin (\theta - \gamma) \sin \psi}{r \sin (\gamma + \psi)} \quad (24)$$

Solving for $\sin \theta$,

$$\sin \theta \cong \frac{\sin \gamma}{\sqrt{1 + \left(\frac{r}{m + 2r}\right)^2 \frac{\sin^2(\psi + \gamma)}{\sin^2 \psi} - \left(\frac{2r}{m + 2r}\right) \frac{\cos \gamma \sin (\gamma + \psi)}{\sin \psi}}} \quad (25)$$

where (see Fig. 1)

$$x = \sqrt{(L + d)^2 + (m + r)^2} \quad (26)$$

$$\sin \gamma = \frac{(m + r)}{x} \quad (27)$$

$$\cos \gamma = \frac{(L + d)}{x} \quad (28)$$

A further simplification of equation (22) is possible; the exponent approaches zero for all values of ψ in the region of significance. Replacing $\sin \psi / \sin \theta$ by using equation (18) and recalling that $R = Z + \rho$, the exponent becomes

$$\text{exponent} = -h_i \left[\frac{(m + 2r)}{\sin (\gamma + \psi)} \cdot \frac{(Z_2 + \rho_2)}{(Z_1 + \rho_1)} - \frac{r}{\sin (\theta - \gamma)} \right] \quad (29)$$

$$\text{and} \quad \frac{Z_2 + \rho_2}{Z_1 + \rho_1} \cong \frac{Z_2}{Z_1} \quad (30)$$

Substituting for Z_1 and Z_2 as given by equations (11) and (12) and applying the condition of equation (30), equation (29) is identically zero. The final approximate equation for the dose becomes

$$D = \frac{SNfk}{2x^2} \int_{\psi_1}^{\psi_2} \left[\sum_{i=1}^4 \frac{C_i}{g_i + h_i \frac{\sin \psi}{\sin \theta}} \right] \left[\frac{E \left(\frac{d\sigma}{d\Omega} \right) \sin^2(\psi + \theta)}{\sin \psi} \right] d\psi \quad (31)$$

The limits (See Fig. 1) of integration are

$$\psi_1 = \tan^{-1} \left(\frac{m}{d} \right) - \tan^{-1} \left(\frac{m+r}{d+L} \right) \quad (32)$$

$$\psi_2 = \tan^{-1} \left(\frac{m+2r}{d} \right) - \tan^{-1} \left(\frac{r+m}{L+d} \right) \quad (33)$$

The final integral is still cumbersome and cannot be evaluated analytically, but it is a function of ψ only when combined with equations (14) and (15). Consequently, a numerical or graphical solution is possible with a reasonable effort. This relation for the dose does not hold if the point source can "see" the opening; i.e., the point source lies within the core generated by straight lines connecting alternate interior and exterior edges of the rectangles created by passing planes through the axis of the porthole.

Consider the case where the source lies along the axis of the port-hole and "sees" the entire opening at the rear of the biological shield. This is a completely symmetrical case that is also represented by equation (31)

with the following changes (See Fig. 2). Set $f = 1$ and

$$\psi_1 = \tan^{-1} \left(\frac{r}{L+d} \right) \quad (34)$$

$$\psi_2 = \tan^{-1} \left(\frac{r}{d} \right) \quad (35)$$

$$x = (L + d) \quad (36)$$

$$\sin \theta \approx \frac{1}{\sqrt{\left[\frac{(L+d)}{r} - 2 \frac{\cos \psi}{\sin \psi} \right] \frac{(L+d)}{r} + \frac{1}{\sin \psi}}} \quad (37)$$

The modified equation is, of course, only for scatter off the porthole walls; the line of sight dose is obtained separately.

In calculating a dose from sources located between the axis and the limit-of-use of equation (31), the simplest procedure is to assume that the variation of the dose with m is linear in this region. Since the line of sight contribution will be the largest single component of the dose, small errors in the porthole wall scatter contribution are of no consequence.

Scatter from Cell Walls

When single scatter only (See Fig. 3) is considered, only gammas striking the wall opposite the porthole within the line of sight region have a chance of leaking from the reactor cell. This contribution to the dose is relatively small, but may become the dominant contribution as the distance (m) between the source and shield opening gets large.

Equation (31) can also be used as an approximation in this case when the following changes (See Fig. 3) are made.

$$\sin \theta \approx \frac{1}{\sqrt{1 + \left[\frac{(L+H)}{(H-d)} \frac{\cos(\psi + \gamma)}{\sin \psi \cos \gamma} + \frac{\sin \gamma}{\cos \gamma} \right]^2}} \quad (38)$$

and the limits of integration are now

$$\psi_1 = \pi - (\gamma + \phi) \quad (39)$$

$$\psi_2 = \pi - (\gamma + \delta) \quad (40)$$

where

$$\phi = \tan^{-1} \left[\frac{\frac{r}{L} (L + H) + (m + r)}{(H - d)} \right] \quad (41)$$

$$\delta = \tan^{-1} \left[\frac{(m + r) - \frac{r(L + H)}{L}}{(H - d)} \right] \quad (42)$$

The geometry, along with the limits of integration chosen, actually neglects a small area of contribution (cross-hatched area in Fig. 3); percentage wise this is small, however, and the increase in difficulty of solution does not warrant inclusion of this portion.

When $m < \frac{rH}{L}$ equations (40), (42), and (43) do not hold. (δ passes through zero). For $\frac{rd}{L} < m < \frac{rH}{L}$ the modifications necessary for these equations are

$$\psi_2 = \pi + \delta - \gamma \quad (43)$$

$$\phi = \tan^{-1} \left[\frac{2r(L + H)}{L(H - d)} \right] \quad (44)$$

$$\delta = \tan^{-1} \left[\frac{\frac{r(L + H)}{L} - (m + r)}{(H - d)} \right] \quad (45)$$

For a point source located along the axis of the porthole (Fig. 4), the limits of integration are changed to

$$\begin{aligned}\psi_1 &= 0 \\ \psi_2 &= -\tan^{-1} \left[\frac{r(L+H)}{2(H-d)} \right]\end{aligned}\quad (46)$$

and

$$\sin \theta = \frac{1}{\sqrt{1 + \left(\frac{L+H}{H-d} \right)^2 \frac{\cos^2 \psi}{\sin^2 \psi}}}\quad (47)$$

$$x = L + d \quad (48)$$

$$f = 1 \quad (49)$$

In this case an overestimate of the dose made by an amount equivalent to the shaded area in Figure 4. Again the error may be neglected since it is very small compared to the total dose.

APPLICATION TO THE HRT

Design Chart Preparation and Use

The relative contributions to the dose at the outer edge of the shield due to scatter off porthole walls and cell walls that confine the HRT were estimated for three different porthole sizes by using the equations developed in a previous section. To this was added the air scatter contribution (virtually negligible) and the line of sight contribution where applicable. The actual dose will be a function of the location and strength of the source. Using a point source of 1.8×10^{14} photons⁽¹⁾ (equivalent of one ft² of inside surface), design charts (See Fig. 5, 6, 7) were prepared that give the dose as a function of the gamma source location.

The results as shown are for the following conditions:

1. Reactor operating several weeks at 5 Mw before shutdown.
2. Half the total fission products adhere to surfaces in contact with fuel solution.
3. Time interval after reactor shutdown, 4 hr.
4. The point sources are the equivalent of one sq. ft. of surface in contact with fuel solution.
5. All radiation is attenuated through 1/2 in. of steel (roughly an average thickness of piping and equipment).

In using these design charts, it is necessary to reduce all equipment and pipes to equivalent point sources and to locate these sources in terms of two distances; the perpendicular distance from the porthole axis and the perpendicular distance from the wall containing the opening. The

number of equivalent point sources to use in representing a piece of equipment or piping will depend on the size and location and will be a matter of judgment to a certain extent. The actual choice will be dictated by the desired accuracy; the greater the number of sources, the higher the accuracy (within limitations of the assumptions) but the greater the effort. The total dose at the outer edge of a porthole is obtained by adding all the individual contributions from the selected equivalent point sources.

To use these charts for other than the stipulated conditions, the total dose is corrected by the following equation:

$$D_2 = D_1 (2p) \left(\frac{P}{5} \right) \left(\frac{4}{t} \right)^{0.2}$$

where

p = fraction of fission products adhering to
equipment and piping surfaces

P = operating power, megawatts

t = time after shutdown, hr.

In calculating doses at points removed from the shield opening, the total dose as determined for the rear edge of the porthole must be attenuated by the appropriate geometrical factor. If the dose primarily results from scatter contribution, as a first order approximation, the opening may be considered as a hemispherical emitter and attenuated by the inverse square law; i.e., multiplying the dose by $\left(\frac{r}{s} \right)^2$ where r is the porthole radius and s is the distance to the new point. For large distances away from the opening, the directional nature of the escaping radiation should be taken into account.

Scatter from Porthole Walls and Cell Wall

Some of the results used in preparing the design charts (Fig. 5, 6, and 7) are shown in Tables I and II for a porthole of 14 in. diameter and 3 ft 2 in. length. The bases are the same as enumerated in the previous section.

TABLE I

Dose From Porthole Wall Scatter

*d	**(m + r)	roentgens/hr					
		0	1-2/3	2-2/3	3-2/3	5-2/3	11-2/3
1		1000	69	17	6.7	2.0	0.24
2		460	130	33	14	3.9	0.46
3		250	120	46	19	5.7	0.68
5		92	63	50	26	-	1.1
7		43	36	31	27	10	1.4
11		14	13	13	13	12	2.0

* d = perpendicular distance from wall with porthole, ft

** (m + r) = perpendicular distance from porthole axis, ft

TABLE II

Dose From Cell Wall Scatter

roentgens/hr							
*d \ ** (m + r)	0	1-2/3	2-2/3	3-2/3	5-2/3	11-2/3	
1	10	5.0	4.2	3.6	2.8	1.4	
2	11	5.4	4.5	3.8	2.9	1.4	
3	12	5.9	4.8	4.0	3.0	1.4	
5	16	7.0	5.5	4.5	3.3	1.4	
7	20	8.0	6.2	5.0	3.5	1.3	
11	30	9.7	7.2	5.7	3.6	1.2	

*d = perpendicular distance from wall with porthole, ft

** (m + r) = perpendicular distance from porthole axis, ft

Line of Sight

Where applicable, line of sight calculations were made by the usual equation for geometric attenuation of isotropic point sources, i.e.,

$$D = \frac{S}{4 \pi s^2}$$

where S is distance between the source and receptor.

TABLE III

Line of Sight Dose Along Porthole Axis

d	0	1	2	3	5	11
r/hr	2140	1230	802	563	321	207

On comparing Table I with Tables II and III, it becomes obvious that the line of sight contribution predominates and that the total dose will decrease abruptly as the sources move out from the line of sight region. This is graphically illustrated by the design charts (Fig. 5, 6, and 7). Consequently, a small error in location of a source existing near the limit of the line of sight region can lead to an order of magnitude error in the estimated dose.

Effect of Steel Cladding on Porthole Walls

The porthole walls of the HRT actually will be clad with 1/8 to 1/4-in. sheet steel. The method of calculation, however, does not take into account two different regions of gamma attenuation. Fortunately, scatter off thick absorbers is not a sensitive function of the material. With increase in density scattering per unit volume increases, but this increase is practically nullified by the increase in the attenuation coefficient. This is demonstrated by comparing Table IV below with Table I. The values in Table IV are for porthole walls of barytes concrete only and the other tables are for walls of steel only. All calculations for the design charts assumed that the walls were composed only of steel, which is a reasonable assumption on the basis that barytes concrete or steel gave nearly the same results. Further justification of the assumption results from the fact that steel occupies the more important region of gamma scattering and will produce slightly higher calculated dose than concrete.

TABLE IV

Scattering From Barytes Concrete Portholes

Dose, roentgen/hr

*d \ ** (m + r)	1-2/3	2-2/3	3-2/3	5-2/3	7-2/3	11-2/3
1	65	16	6.4	1.9	0.83	0.24
2	128	32	13	3.8	1.6	0.47
3	-	46	19	5.7	2.4	0.69
5	-	-	26	-	3.7	1.1
7	-	-	28	10	-	1.5
11	-	-	-	11	5.8	-

* d = perpendicular distance from wall with porthole, ft

** (m + r) = perpendicular distance from porthole axis, ft

Properties

The values of the constants used in the calculations are as follows:

For barytes concrete:

$$A = 11.5, \alpha = -0.102, \beta = 0.018, \mu_1 = 0.260 \text{ cm}^{-1},$$

$$N = 0.967 \times 10^{24} \text{ electrons/c.c.}, a = 0.25$$

For steel:

$$A = 9.4, \alpha = -0.092, \beta = 0.020, \mu_1 = 0.598 \text{ cm}^{-1}$$

$$N = 2.20 \times 10^{24} \text{ electrons/c.c.}, a = 1.0$$

For both (independent of material):

$$H = 20 \text{ ft}, E_0 = 0.7 \text{ mev}, S = 1.8 \times 10^{14} \text{ photons/sec}$$

$$k = 2.03 \times 10^{-6} \text{ roentgens/hr-unit gamma flux}$$

Fig. 1 Scatter Off Porthole Walls -- Asymmetric Case

Fig. 2 Scatter Off Porthole Walls -- Symmetric Case

Fig. 3 Scatter From Cell Wall -- Asymmetric Case

Fig. 4 Scatter from Cell Wall -- Symmetric Case

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Fig. 6 : GAMMA LEAKAGE THROUGH SHIELD PORTHOLE -
DOSE AT OUTER EDGE OF SHIELD FROM INTERIOR
POINT SOURCES

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