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SUBJECT: Calculation of Air Scattered Gamma Radiation Escaping Through a Shield Opening -- Application to the HRT

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CALCULATION OF AIR SCATTERED GAMMA RADIATION ESCAPING THROUGH A SHIELD OPENING -- APPLICATION TO THE HRT

SUMMARY

A method was developed for calculating air-scattered gamma-radiation escaping through openings in a biological shield. The method was applied to the HRT and the results indicated that air scattering was insignificant compared to the other mechanisms contributing to the escape of gamma-rays through shield openings.

INTRODUCTION

Maintenance of the HRT 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.

After reactor shutdown, the sources of radiation in the reactor cell are induced activity in the biological shield and equipment, and fission products adhering to the inner surfaces of the equipment and piping. The radiation escaping from a maintenance porthole occurs 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 shield; 4) air scatter within the reactor cell.

In this memorandum, a method of computing the gamma dose outside the cell due to leakage through a porthole as the result of air scattering only is developed and applied to the HRT. The other mechanisms contributing to the dose will be treated in future memoranda.

DERIVATION OF EQUATION

Consider a cell surrounded by a thick biological shield with numerous sources of gamma radiation distributed throughout the cell volume. It is assumed that all radiation sources may be represented by point isotropic sources of known coordinates. For gamma scattering by air, absorption may be neglected and only single scattering need be considered.(4) For single scattering, only that scattering occurring between the angles θ_1 and θ_2 (see Fig. 1) has a probability of reaching a detector located in the center of the porthole at the outer edge of the shield. The dose (in roentgens/hr) at this point as registered on an isotropic counter for an isotropic point source for air scattering only is

$$D = \int_V \frac{SNF(E)}{4\pi R_1^2} \frac{\left(\frac{d\sigma}{d\Omega}\right)}{R_2^2} \, dV \qquad (1)$$

Where $F(E)$ is the dose per unit gamma flux as a function of energy E, $\left(\frac{d\sigma}{d\Omega}\right)$ is the differential cross section per unit solid angle Ω or the probability for Klein-Nishina scattering through any scattering angle by a single electron, S is the source in photons/sec, and N is the number of electrons/c.c. The symbols relating to geometry are denoted in Fig. 1. For a scattering angle $(\theta + \psi)$,(5)

$$\frac{d\sigma}{d\Omega} = 1.409 \times 10^{-13} \left(\frac{E}{E_o}\right) \left[1 - \left(\frac{E}{E_o}\right) \sin^2 (\theta + \psi) + \left(\frac{E}{E_o}\right)^2\right] \qquad (2)$$

When a photon of initial energy E_o undergoes compton scattering, the energy of the scattered photon is(5)

$$E = \frac{E_o}{1 + \frac{E_o}{0.51}\left[1 - \cos\left(\theta + \psi\right)\right]} \qquad (3)$$

The function F(E) can be closely represented by a polynomial of two or three terms over a wide-energy range. However, for the range below 1.5 mev, F(E) is closely approximated by(3)

$$F(E) = kE \qquad (4)$$

Substituting the volume element and equations (2), (3), and (4) into (1) will produce a cumbersome expression which cannot be evaluated analytically, and a numerical solution of the triple integral would be extremely tedious. Consider, however, the radiation entering the annulus generated by revolving the hole in the biological shield about the axis connecting the receptor and the point of emission of the radiation (see Fig. 1). Now the volume element is

$$dV = \left(2\pi R_1 \sin\psi\right)\left(R_1\, d\psi\right) d R_1 \qquad (5)$$

By the law of sines,

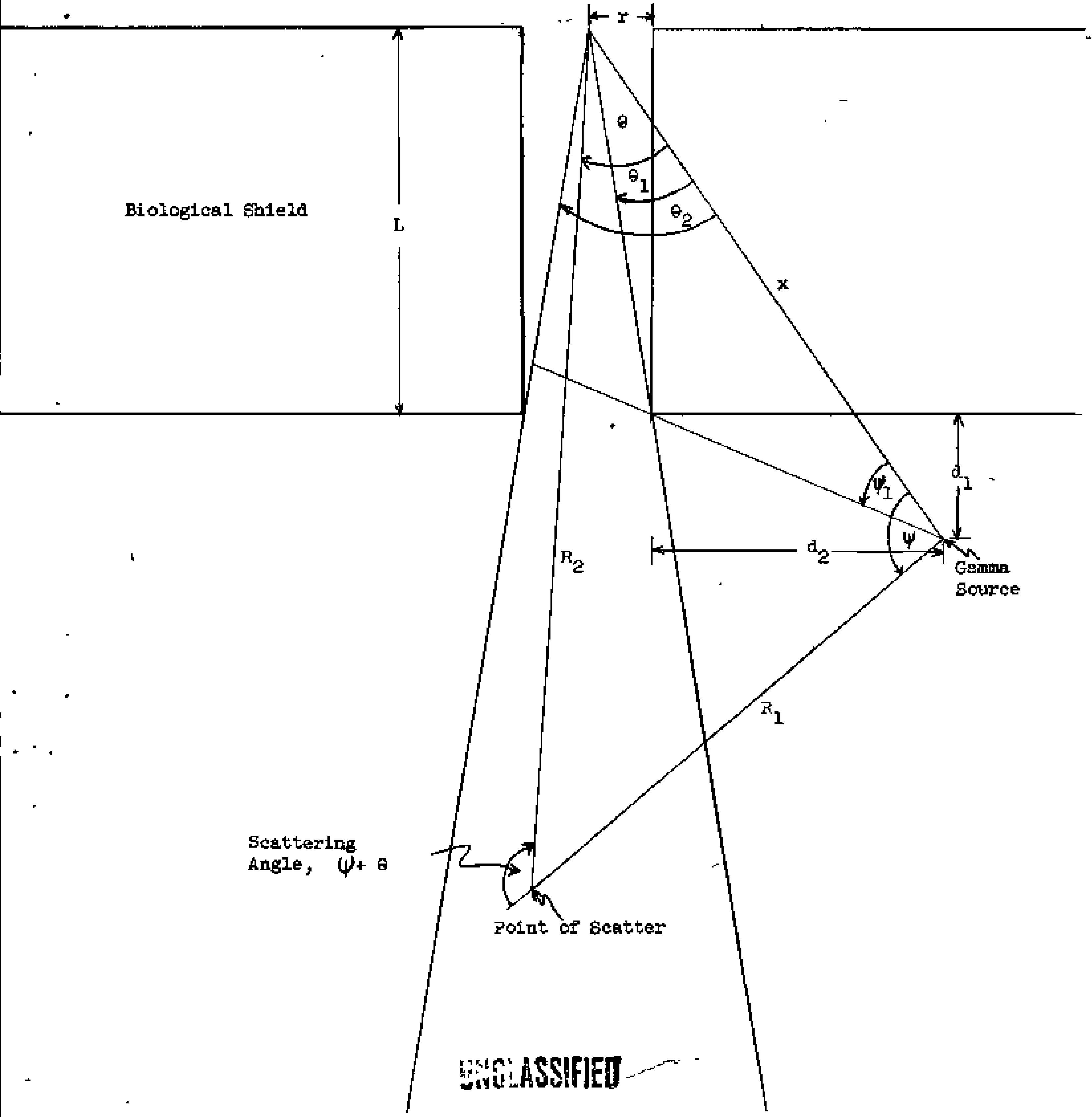
$$\frac{R_1}{\sin\theta} = \frac{R_2}{\sin\psi} = \frac{x}{\sin\left(\theta + \psi\right)} \qquad (6)$$

and by differentiating equation (6) it can be shown that

$$d R_1 = \frac{{R_2}^2}{x \sin\psi}\, d\theta \qquad (7)$$

FIG. 1

DIAGRAMMATIC REPRESENTATION OF AIR SCATTERING THROUGH SHIELD PORTHOLE



If equations (4), (5), and (7) are substituted into (1), an expression is obtained for the gamma dose at the rear of the annular opening. This is approximately corrected to the porthole dose by multiplying by f, the ratio of the porthole area to the annulus area. Therefore,

$$D = \frac{SfN}{2\ x} \int_{\theta_1}^{\theta_2} \int_{\psi_1}^{\pi\theta} kE \left(\frac{d\sigma}{d\Omega}\right) d\ \psi\, d\theta \tag{8}$$

where

$$f = \frac{rx}{4L\ (d_2 +\ r)} \tag{9}$$

This neglects the effect of the wall; i.e., it is assumed that the cell is infinitely deep. As long as the bottom wall is a few feet from the porthole, this assumption is quite good for air scatter only. The actual scatter from the wall will be treated in a future memorandum.

Thus, by an approximation, a reduction of the volume integral to a double integral was obtained. An analytical solution of equation (8) is also impossible, and a numerical solution still tedious. However, if the problem is divided into two regions, as determined by the scattering angle, $\theta + \psi$, it is possible to represent equation (3) quite well for each region by a function of the form

$$E = m(\theta + \psi) + b \tag{10}$$

and equation (2) by a function of the form

$$\frac{d\sigma}{d\Omega} = ae^{-n(\psi + \theta)} \tag{11}$$

for any particular value of E_o.

If equations (10) and (11) are substituted into (8) and the integral split into two regions, for scattering angles greater than α and for scattering angles less than α, the dose is approximated by

$$D = \frac{SNkf}{2x} \left\{ \int_{\theta_1}^{\theta_2} \int_{\psi_1}^{\alpha-\theta} a_1 e^{-n_1(\psi+\theta)} \left[m_1(\theta+\psi) + b_1 \right] d\psi \, d\theta \right.$$

$$\left. + \int_{\theta_1}^{\theta_2} \int_{\alpha-\theta}^{\pi-\theta} a_2 e^{-n_2(\psi+\theta)} \left[m_2(\theta+\psi) + b_2 \right] d\psi \, d\theta \right\} . \qquad (12)$$

Equation (12) is now simple to integrate, even if F(E) were represented by a polynominal expression. Selection of the scattering angle, α, is dependent on the energy of the source gammas. Generally, a best fit to equation (2) is obtained with α around $\frac{\pi}{2}$. For high energy gammas best fits$^{(5)}$ are obtained for $\alpha < \frac{\pi}{2}$, but for low energy gammas $\alpha > \frac{\pi}{2}$.

Integrating equation (12),

$$D = \frac{SNkf}{2x} \left[I_1 + I_2 \right] \qquad (13)$$

where

$$I_1 = \frac{a_1}{n_1^2} \left[e^{-n_1(\psi_1+\theta_1)} \left\{ \left[m_1(\theta_1+\psi_1) + \frac{2m_1}{n_1} + b_1 \right] \left[1 - e^{-n_1\Delta\theta} \right] \right. \right.$$

$$\left. \left. - m_1\Delta\theta \, e^{-n_1\Delta\theta} \right\} - \left\{ n_1 b_1 + m_1(n_1\alpha + 1) \right\} e^{-n\alpha} \Delta\theta \right] \qquad (14)$$

$$I_2 = \frac{a_2}{n_2}\left[\left(e^{-n_2\alpha} - e^{-n_2\pi}\right)\left(b_2 + \frac{m_2}{n_2}\right) + m_2\left(\alpha e^{-n_2\alpha} - \pi e^{-n_2\pi}\right)\right] \qquad (15)$$

and

$$\Delta\theta = \theta_2 - \theta_1 = 2\tan^{-1}\left(\frac{r}{L}\right) \qquad (16)$$

$$\theta_1 = \tan^{-1}\left[\frac{r + d_2 - d_1\left(\frac{d_2 + r}{d_1 + L}\right)}{L}\right] - \tan^{-1}\frac{r}{L}$$

$$\psi_1 = \tan^{-1}\left(\frac{d_2}{d_1}\right) - \tan^{-1}\left(\frac{d_2 + r}{d_1 + L}\right) \qquad (18)$$

The individual scatter dosages for each energy group of gammas from each point source are calculated with equation (13) and the sum of all contributions gives the total dose.

APPLICATION TO THE HRT

The relative contributions to the dose at the outer edge of the shield due to air scattering only within the HRT cell was estimated for three different porthole sizes. The actual dose will be a function of the location and strength of the source.

Source Term

Aven(1) has indicated that induced activity in the piping and equipment of the HRT is insignificant compared to the activity of fission products that may adhere to surfaces exposed to the fuel solution.

The gamma emission rate of the fission products may be approximated by(2)

$$1.9 \times 10^{-6}\ t^{-1.2} \text{ photons/sec fission}$$

where t is the time after fission in days.

For long-time operation,

$$\text{gammas/sec ft}^2 = \frac{2.6 \times 10^{16} P}{A\, T^{0.2}} \tag{19}$$

where P = power, megawatts; T = time after shutdown, days; A = inside area of piping and equipment, ft^2.

Since the gammas come from fission products adhered to equipment surfaces, the sources will be attentuated by the thickness of the steel. Assuming the buildup factor as linear for around one relaxation length,

$$\text{Attentuation} = (1 + 0.52\, y)\, e^{-0.553y} \tag{20}$$

where y is the thickness of the equipment. Combining equations (19) and (20),

$$S = \frac{2.6 \times 10^{16} P\, (1 + 0.52y)\, e^{-0.553y}}{AT^{0.2}} \tag{21}$$

Taking y = 1/2 in, P = 5 megawatts, T = 4 hrs, A = 450 ft.^{2},(6) and assuming only 50% of the fission product poisons adhere to the surfaces,

$$S = 1.76 \times 10^{14} \text{ photons/ft}^2 \tag{22}$$

Properties

The fission product poisons emit gammas of several energies. However, as a reasonable approximation, the average(2) energy will be taken as 0.7 mev. Thus E_o = 0.7, for air $N = 9.7 \times 10^{23}$ and $k = 2.03 \times 10^{-6}$.

For 0.7 mev gammas reasonable fits to equations (2) and (3) are obtained with $\alpha' = \frac{\pi}{2}$, therefore

for $\alpha < \frac{\pi}{2}$

$m = -0.258$

$b = 0.7$

$a = 9 \times 10^{-26}$

$n = 1.34$

and for $\alpha > \frac{\pi}{2}$

$m = -0.0682$

$b = 0.401$

$a = 1.2 \times 10^{-26}$

$n = 0$ (since $\frac{d\sigma}{d\Omega}$ is about constant)

For $\alpha > \frac{\pi}{2}$ with $n = 0$, equation (13) becomes indeterminate. Evaluation of the indeterminate or rederiving for a constant $\frac{d\sigma}{d\Omega}$,

$$D = \frac{SWkf}{2c} \left[\frac{a\pi}{2} \left(\frac{3m\pi}{4} + b \right) \Delta\theta \right] \qquad (23).$$

Results

The relative doses at the rear edge of the shield from point sources at various coordinates within the cell were determined for three porthole sizes. Since the contribution due to air scattering only is insignificant compared to scattering off the porthole surfaces (results to be published in future memorandum), only a sampling of results for the largest porthole size considered (14-in. diameter, 3-ft 2-in length) is shown in Table I. These results are for the source term given by equation (22) which is based on one ft^2 of equipment surface and 50% deposition of fission poisons. For a point source approximated by a different area or percentage of poisons, the results are changed in direct proportion.

TABLE I

Dose at Outer Edge of Porthole in HRT Shield[a]

d_1 \ d_2[b]	Contributions to Dose, roentgens/hr			
	1	2	3	7
1	0.28	0.11	0.06	0.02
2	0.47	0.17	0.09	0.03
3	0.59	0.24	0.12	0.03
5	0.73	0.33	0.18	0.04
9	0.86	0.45	0.27	0.07
11	0.90	0.48	0.30	0.08
15	0.94	0.52	0.33	0.10
19	0.96	0.55	0.36	0.10

[a] Diameter = 14 in., Length = 3 ft., 2 in.

[b] d_2 = perpendicular distance from porthole edge, ft.

d_1 = perpendicular distance from wall with porthole, ft.

REFERENCES

1. Aven, R. E., ORNL CF 56-9-35.

2. Glasstone, S., "Principles of Nuclear Reactor Engineering," p. 118, Van Nostrand (1955).

3. Homogeneous Reactor Experiment, Quarterly Progress Report for Period Ending November 30, 1950 (ORNL 925), p. 52.

4. Rockwell, T., "Reactor Shielding Design Manual," (TID-7004), p.319, (1950).

5. Stephenson, R., "Introduction to Nuclear Engineering," pp 193-5, McGraw-Hill (1954).

6. Van Winkle, R., ORNL CF 56-5-89.