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THE SPLIT SCATTER SHIELD FOR SPACE APPLICATIONS

THESIS

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By

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Preface

This report is an attempt to establish the value of dividing the shield of a space vehicle into sections and separating these sections. I hope to show that this shield would be much more effective for uses in the space environment than the presently-planned shields, and that the split shield is feasible for future development. The methods of calculation that I have used are simplified so that the computations could be readily handled without resorting to computer programs. However, a Monte Carlo program for the split shield problem is presently under development by the Propulsion Laboratory, WADD under the direction of Mr. R.L. Verga. The results of this study are expected to be published in the near future and these results should do much to either substantiate or disprove the results I have presented here.

A list of the symbols used in the report is given on page vii.

I wish to acknowledge the many helpful suggestions that I have received in the preparation of this report from Mr. R.L. Verga of the Propulsion Laboratory, Mr. R.E. Malenfant formerly of the Propulsion Laboratory and Major A.F. Vetter of the Air Force Institute of Technology.

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Abstract

The split scatter shield consists of multiple shield sections which are separated from each other. When this type of shield is used outside the atmosphere, radiation scattering in each section has a high probability of escaping the shield system without re-scattering. Consequently, this shield has been proposed as a replacement for the normal shield of unit construction for space applications. The split shield is compared with a unit shield of the same weight and material in a hypothetical problem situation by computing the radiation attenuation by each. The problem is computed using point and circular source geometries assuming the sources to emit gamma rays only. The calculations are performed using simplifying assumptions so that computer programs are not necessary. A geometrical parameter study is performed for the split shield to determine the optimum number of sections, the optimum separation distance between sections, and the maximum flux attenuation. The major assumptions and the problem dimensions are modified to determine their effect upon the results of the previous parameter study. The results indicate that a split shield is capable of greater flux attenuation by a factor of more than four than a unit shield of the same weight.

List of Symbols

S	radiation source
D	radiation detector
x	total separation distance between the source and the detector
R	radius of the shield and of the circular source
x_o	thickness of the shield or shield sections
μ_t	total macroscopic attenuation coefficient for gamma rays
$\mu_t x_o$	shield thickness, in mean-free paths
ϕ_{us}	radiation flux reaching the detector through a unit shield
ϕ_{ss}	radiation flux reaching the detector through a split shield
d_1	distance from the source to the first section of a split shield
d_2	distance from the detector to the final section of a split shield
a	separation distance between the shield-sections of a two-section split shield or between the shield-section of any split shield when sections are equally separated
a_1	separation distance between the first two sections of a three-section split shield
a_2	separation distance between the final two sections of a three-section split shield
B	build-up factor for all scattered radiation
B'	build-up factor for all radiation scattered more than twice in a two-section split shield (point source)
B''	build-up factor for all radiation scattered more than twice

in a three-section split shield (point source)

B''' build-up factor for all radiation scattered more than twice in a four-section split shield (point source)

θ angle subtended by the source radius at a point along the axis of the source

I_0 source strength for a point source

S_0 source strength for a circular source

$E_1(\mu_t x_0)$ exponential integral $= \int_{\mu_t x_0}^{\infty} \frac{e^{-y}}{y}\,dy$

B_c' build-up factor for all radiation scattered more than twice in a two-section split shield (circular source)

B_c'' build-up factor for all radiation scattered more than twice in a three-section split shield (circular source)

THE SPLIT SCATTER SHIELD FOR
SPACE APPLICATIONS

I. Introduction

Space vehicles powered by nuclear devices must contain shielding material to protect the internal components from radiation damage. The normal shield used for this purpose consists of a unit shadow shield placed between the source of radiation and the area to be protected. Such a shield attenuates the radiation (neutrons and gamma-rays) primarily by absorption. This type of shield may contribute a large percentage to the total weight of a space vehicle. In one conceptual design for a manned space vehicle, the shield weight is 20% of the total powerplant weight (Ref. 3:1).

Drs. Carl Klahr and Kalman Held of Technical Research Group, Inc., have proposed and have performed some calculations on a shield for space vehicles that would consist of multiple, separated sections of shielding material (Ref. 6). This shield would attenuate the radiation primarily by scattering into space rather than by absorption. Such a method of shielding is considered feasible because there will be no back-scattering of the radiation by air. This report will attempt to compare the effectiveness of the split scatter shield proposed above with that of the unit shadow shield of the same weight and material, and it will perform a parameter study on the sections of a split shield to establish the most favorable geometrical arrangement of these sections. The selection of the shielding material will not be considered by this report.

This report will analyze the comparison problem by computing the reduction in the radiation flux arriving at a selected area (the detector), first, through a unit shadow shield and, then, through a split shield. The positions of the split-shield sections will be varied to determine the maximum reduction in the flux and to determine the optimum separation distances between the sections. Then, other parameters of the shield sections will be varied in an attempt to further reduce to minimum flux arriving at the detector. The maximum savings that is possible by use of the split shield will be the ratio of the minimum flux from the split shield to the flux from a unit shield.

The radiation that any shield is designed to attenuate consists of gamma rays and neutrons. This report will consider the attenuation of gamma rays, only, but since the formulae describing the attenuation of both forms are similar, the results should be generally applicable to neutron shields (Ref. 5:243). Because of the complexity of the computations for shielding problems, it will be necessary to make several simplifying assumptions so that the computations can be performed without the aid of a computer program.

The computations for the gamma-ray attenuation will be based upon a problem situation with arbitrarily-selected dimensions. These dimensions are not meant to represent any actual project or vehicle under development but merely to represent a general situation. It is believed, however, that these dimensions do represent values that are reasonable.

This report will discuss, in the following order; (1) a description of the problem situation and the assumptions to be used, (2) a detailing of the method of analysis, (3) a description of the parameter studies, (4) a discussion of the results of these studies, and (5) a description of the conclusions drawn.

II. Problem Description and Assumptions

The comparison between the unit shield and the split scatter shield is accomplished by placing both shields in the same problem situation and then comparing the effectiveness of each in attenuating a radiation flux. This section will describe the selected problem and will examine the assumptions necessary to solve the problem.

Problem Description

The problem situation selected for the analysis of the shields is shown by Fig. 1. The source of the radiation (S) and the detector (D) are separated by a distance x and the unit shield is represented by a circular slab of radius R placed midway between the source and the detector. Specific units are not applied to the

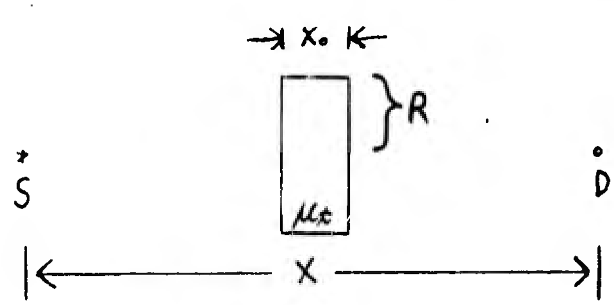

Fig. 1

Cross-section of Shielding Problem Situation dimensions x and R since these parameters are used in ratio to each other.

The thickness of the unit-shield slab is shown as x_0 and the total macroscopic attenuation coefficient for gamma rays of the shielding material is μ_t. The thickness of the shield is used in the computations in terms of mean-free-path lengths for gamma-rays ($\mu_t x_0$). Thus, while the actual thickness (x_0) may vary depending upon the shield material, the number of mean free paths is held fixed.

The detector is considered to be a point isotropic detector for all the computations in this report, and although the source is shown to be a point source in Fig. 1, it will also be considered to be a circular disc source of radius R for later computations.

Assumptions

As mentioned previously, it is necessary to make some general simplifying assumptions to conveniently solve the shielding problem. These assumptions are described here and an attempt is made to describe their effect upon the results of the comparison problem.

It is assumed throughout this report that the thickness of the shield (x_0) is small in relation to the total source-to-detector separation distance. This assumption should be generally true since the total length of most space vehicles is large in comparison to the shield thickness (Ref. 3:15). The effect of a large value for x_0

is examined in Section III of this report.

Since this problem is computed for operations in the space environment, it is assumed that any photon which is directed away from a shield or the detector will escape from the system. This assumption neglects any shielding function by the structural material and it neglects the effect of scattering from the structure. Since the structural material will normally be thin and the probability of scattering small, this assumption is considered valid.

The source of radiation is assumed to emit mono-energetic gamma rays isotropically. As mentioned in the Introduction, the assumption of gamma rays, only, is valid since the basic formulae describing the attenuation of radiation apply to both neutrons and photons. The assumption of mon-energetic photons being emitted isotropically should have little effect upon the final results since these assumptions have nearly the same effect on both the unit and the split shields.

The photons are assumed to scatter isotropically within the shielding material. Although this assumption is not generally true, it is made in order to simplify the computations. The effect of this assumption is shown in Section III of this report.

The photons are assumed to scatter within the shielding material without the loss of energy. Once again, this assumption is not generally true but the effect upon the results is of a conservative nature. This is true since the degradation of energy suffered by a photon increases the total attenuation coefficient when the photon energy is below about three Mev (Ref. 5:154). It should be noted that a mean free path in the later portion of a shield represents a smaller shield thickness (x_0) than does a mean free path near the front of the shield. It is also assumed that any photon scattering back toward the source will be lost, since the probability of rescattering back toward the detector and passing again through the shield is very small.

The previously-mentioned assumptions are the more general of the simplifying assumptions used in this report. Other assumptions that are needed for specific instances in the computations will be described as they occur.

III. Method of Analysis

This section describes the method of analysis for the comparison between a unit shield and a multiply-split scatter shield. The comparison is conducted for the problem situation as shown by Fig. 1 where the source may be either a point or a circular source. The problem is first analyzed for the point source and then for the circular source.

Point-source Computations

The initial computations on the two types of shields are performed assuming a point-isotropic source of radiation. The basic equation describing the radiation attenuation from a point isotropic source is given by

$$\phi = \frac{B I_o e^{-\mu_t x_o}}{4\pi x^2} \tag{1}$$

where ϕ = the radiation flux reaching the detector,

B = the build-up factor for scattered radiation,

I_o = the source strength for a point source,

μ_t = the attenuation coefficient for gamma rays,

x_o = the shield thickness,

and x = the total separation distance between source and detector.

The attenuation of the radiation due to the shield thickness is given by $e^{-\mu_t x_0}$ and the distance attenuation is given by $1/4\pi x^2$.

The build-up factor (B) accounts for the scattering of the photons within the shield material. With B = 1, Eq (1) represents the radiation flux reaching the detector without interaction in the shield. However, many photons which are initially directed away from the detector may be scattered toward it and many which are first scattered away may be rescattered toward the detector. The build-up factor is used to account for this increase in the detector flux due to such scatterings. B is a function of the shield thickness in mean free paths ($\mu_t x_0$), the initial energy of the photons, and the shielding material used. This factor can be considered to be approximately a linear function of $\mu_t x_0$ and is roughly equal to $\mu_t x_0$ for gamma rays (Ref. 4:596). This is the value of B which is assumed for the problem examined in this report. This assumption is a conservative estimate of B for most gamma-ray problems although it is probably high for neutron shields. The effect upon the results will be examined in Section III.

Since the scatter shield is designed to eliminate the majority of the scattered radiation, Eq (1) with B = 1 represents the minimum detector flux that could be realized with a theoretically perfect scatter shield. This uncollided radiation will still reach the detector no matter how effectively the scatter shield acts. Thus, the maximum savings which can be realized by using the scatter shield is 1/B.

<u>Unit Shield</u>. In order to form a basis for comparison, the detector flux is first computed for the unit shield. Eq (1) is used for this purpose with $B = \mu_t x_o$ as described previously. This value of ϕ_{us} represents the detector flux for the situation shown in Fig. 1.

<u>Two-section Scatter Shield</u>. It is now assumed that the unit shield shown in Fig. 1 is divided into two equally-thick sections with a separation distance (a) between the sections. The sections are separated from the source and detector by distances of d_1 and d_2, respectively, as shown in Fig. 2 where $d_1 + a + d_2 = x$. The other dimensions of the problem are maintained the same as shown in Fig. 1 except that now the thickness of each shield section is one-

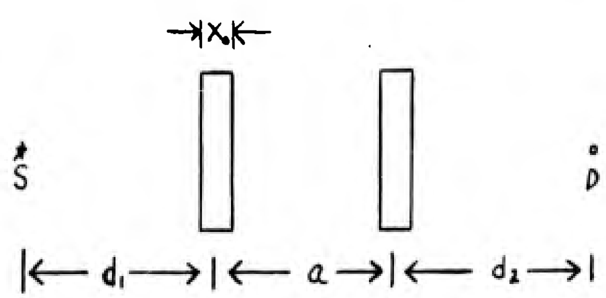

Fig. 2

Cross-section of the Two-section Split Shield half of the thickness of the unit shield.

The detector flux passing through the split shield is divided into the components representing the unscattered, the once-scattered, and the multiply-scattered fluxes. The probability that a photon passes through a shield section without interaction is given by $e^{-\mu_t x_0}$ and the probability that this photon reaches the detector is $1/4\pi x^2$. The probability that a photon reaches the first shield section is $\pi R^2/4\pi d_1^2$, the probability that it scatters in that section is $1 - e^{-\mu_t x_0}$, and the probability that it now reaches the detector is $e^{-\mu_t x_0}/4\pi \ (a + d^2)$, assuming isotropic scattering. The probability that a photon reaches the second section after scattering in the first is $\pi R^2/4\pi a^2$, the probability that it scatters again is $1 - e^{-\mu_t x_0}$, and the probability that it reaches the detector is now $1/4\pi d_2^2$. Where the term $\pi R^2/4\pi a^2$ is used to represent the probability of a photon reaching the next section from a scattering in the previous section, it is assumed that this scattering collision happened at the center of the previous shield. Although this assumption is not strictly accurate, it does represent a good average for all the scatterings that occur in the shield section. The probability of scattering $(1 - e^{-\mu_t x_0})$, given above, assumes that all interactions result in scattering collisions. This is a reasonable assumption for most materials when the photon energies are in the intermediate range.

Using these probabilities, it is possible to set up terms representing the detector flux from any number of scattering in the shield sections. However, if many scattering terms are used, the equations become unwieldy and difficult to use, so for the purpose of this study only terms representing the unscattered, once-scattered, and twice-scattered radiation are included. In order to represent the flux from more than two scatterings, the twice-scattered term is multiplied by an artificial build-up factor (B′).

With the use of the previously-described probabilities, the detector flux from a two-section split shield is given by:

$$\phi_{ss} = I_0 \left[\frac{e^{-2\mu_t x_0}}{4\pi x^2} + \frac{\pi R^2 (1 - e^{-\mu_t x_0}) e^{-\mu_t x_0}}{4\pi d_1^2 \, 4\pi (a + d_2)^2} + \frac{\pi R^2 (1 - e^{-\mu_t x_0}) e^{-\mu_t x_0}}{4\pi (d_1 + a)^2 4\pi d_2^2} + \frac{(\pi R^2)^2 (1 - e^{-\mu_t x_0})^2 B'}{4\pi d_1^2 \, 4\pi a^2 \, 4\pi d_2^2} \right] \quad (2)$$

where $x = d_1 + a + d_2$. The first term on the right of this equation represents the unscattered flux, the second and third terms represent the once-scattered flux, and the final term represents the multiply-scattered flux.

Before this equation can be used for any parameter studies, it is necessary to determine the value of B′. This is done by considering the separation distance between the two sections of the split shield to be zero and the sections to be centered between the source and the detector. With this configuration, the split shield is identical to the unit shield and the fluxes through each are the same. With $a = 0$, and $d_1 = d_2$, Eq (2) reduces to

$$\phi_{ss} = I_0\left[\frac{e^{-2\mu_t x_0}}{4\pi x^2} + \frac{2\pi R^2(1-e^{-\mu_t x_0})e^{-\mu_t x_0}}{(4\pi d^2)^2} + \frac{\pi R^2(1-e^{-\mu_t x_0})^2 B'}{2(4\pi d^2)^2}\right] \qquad (3)$$

where the probability of scattering in the first section and reaching the second section is now one-half instead of $\pi R^2/4\pi a^2$ as before. Another way of stating this is that when there is no separation between shield sections, half the photons will scatter into the next section and half will scatter away from it. The split shield flux from Eq (3) is set equal to the unit shield from Eq (1) and solved for B'. This value of B' can now be used to represent the build-up of multiply-scattered flux in Eq (2).

<u>Three-section Scatter Shield</u>. The unit shield is now considered to be divided into three equally-thick sections as shown by Fig. 3 where each section is one-third the thickness of the unit shield and $d_1 + a_1 + a_2 + d_2 = x$. As before, the detector flux passing through this shield is separated into the unscattered, once-scattered, and multiply-scattered portions by using the probabili-

ties described previously. The flux reaching the detector is given by

$$\phi_{ss} = I_o\left[\frac{e^{-3\mu_t x_o}}{4\pi x^2} + \frac{\pi R^2(1-e^{-\mu_t x_o})e^{-2\mu_t x_o}}{4\pi d_1^2\, 4\pi(a_1+a_2+d_2)^2} + \frac{\pi R^2(1-e^{-\mu_t x_o})e^{-2\mu_t x_o}}{4\pi(d_1+a_1+a_2)^2\, 4\pi d_2^2} + \right.$$

$$\frac{\pi R^2(1-e^{-\mu_t x_o})e^{-2\mu_t x_o}}{4\pi(d_1+a_1)^2\, 4\pi(a_2+d_2)^2} + \frac{(\pi R^2)^2(1-e^{-\mu_t x_o})^2 e^{-\mu_t x_o} B''}{4\pi d_1^2\, 4\pi a_1^2\, 4\pi(a_2+d_2)^2} +$$

$$\left.\frac{(\pi R^2)^2(1-e^{-\mu_t x_o})^2 e^{-\mu_t x_o} B''}{4\pi(d_1+a_1)^2\, 4\pi a_2^2\, 4\pi d_2^2} + \frac{(\pi R^2)^2(1-e^{-\mu_t x_o})^2 e^{-\mu_t x_o} B''}{4\pi d_1^2\, 4\pi(a_1+a_2)^2\, 4\pi d_2^2}\right] \quad (4)$$

where B'' is the build-up factor used to account for the flux reaching the detector after more than two scatterings. The first term of the right side of this equation represents the unscattered flux, the next three terms represent the once-scattered flux, and the final three terms represent the multiply-scattered flux.

So that the value of B'' may be determined, a_1 and a_2 are set equal to zero and d_1 is set equal to d_2. With these substitutions, Eq (4) reduces to

$$\phi_{ss} = I_o\left[\frac{e^{-3\mu_t x_o}}{4\pi x^2} + \frac{3\pi R^2(1-e^{-\mu_t x_o})e^{-2\mu_t x_o}}{(4\pi d^2)^2} + \frac{3\pi R^2(1-e^{-\mu_t x_o})^2 e^{-\mu_t x_o} B''}{2(4\pi d^2)^2}\right] \quad (5)$$

where the probability of scattering in one section and reaching the next is now one-half instead of $\pi R^2/4\pi a_1^2$ or $\pi R^2/4\pi a_2^2$. Since Eq (5) represents the same configuration of shield as the unit shield, Eq (5) is set equal to Eq (1) and solved for B″. This value of B″ is then used in Eq (4).

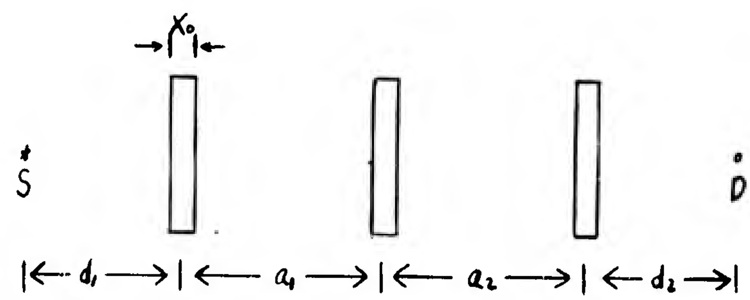

Fig. 3

Cross-section of the Three-section Split Shield

Four-section Scatter Shield. The unit shield is considered to be divided into four equally-thick sections and the same procedure is followed for this arrangement of shield sections as was followed for the two and three-section shields. The cross-section of this split shield is shown by Fig. 4 and the detector flux for this shield is given by

$$\phi_{ss} = I_0\Bigg[\frac{e^{-4\mu_t x_0}}{4\pi x^2} + \frac{\pi R^2(1-e^{-\mu_t x_0})e^{-3\mu_t x_0}}{4\pi d_1^2\, 4\pi(a_1+a_2+a_3+d_2)^2} + \frac{\pi R^2(1-e^{-\mu_t x_0})e^{-3\mu_t x_0}}{4\pi(d_1+a_1+a_2+a_3)^2\, 4\pi d_2^2} +$$

$$\frac{\pi R^2(1-e^{-\mu_t x_0})e^{-3\mu_t x_0}}{4\pi(d_1+a_1)^2\, 4\pi(a_2+a_3+d_2)^2} + \frac{\pi R^2(1-e^{-\mu_t x_0})e^{-3\mu_t x_0}}{4\pi(d_1+a_1+a_2)^2\, 4\pi(a_3+d_2)^2} +$$

$$\frac{(\pi R^2)^2(1-e^{-\mu_t x_0})^2 e^{-3\mu_t x_0} B'''}{4\pi d_1^2\, 4\pi a_1^2\, 4\pi(a_2+a_3+d_2)^2} + \frac{(\pi R^2)^2(1-e^{-\mu_t x_0})^2 e^{-3\mu_t x_0} B'''}{4\pi(d_1+a_1+a_2)^2\, 4\pi a_3^2\, 4\pi d_2^2} +$$

$$\frac{(\pi R^2)^2(1-e^{-\mu_t x_0})^2 e^{-3\mu_t x_0} B'''}{4\pi d_1^2\, 4\pi(a_1+a_2)^2\, 4\pi(a_3+d_2)^2} + \frac{(\pi R^2)^2(1-e^{-\mu_t x_0})^2 e^{-3\mu_t x_0} B'''}{4\pi(d_1+a_1)^2\, 4\pi(a_2+a_3)^2\, 4\pi d_2^2} +$$

$$\frac{(\pi R^2)^2(1-e^{-\mu_t x_0})^2 e^{-3\mu_t x_0} B'''}{4\pi d_1^2\, 4\pi(a_1+a_2+a_3)^2\, 4\pi d_2^2} + \frac{(\pi R^2)^2(1-e^{-\mu_t x_0})^2 e^{-3\mu_t x_0} B'''}{4\pi(d_1+a_1)^2\, 4\pi a_2^2\, 4\pi(a_3+d_2)^2}\Bigg] \qquad (6)$$

where B''' is the build-up factor for the multiply-scattered flux. The first term of this equation represents the unscattered flux, the next four terms represent the once-scattered flux, and the final six terms represent the multiply-scattered flux.

Once again, the shield section separation distances are set equal to zero, d_1 is set equal to d_2, and the probability of scattering from one section to an adjacent section is changed from $\pi R^2/4\pi a^2$ to one-half. With these substitutions, Eq (6) reduces to

$$\phi_{ss} = I_0\left[\frac{e^{-4\mu_t x_0}}{4\pi x^2} + \frac{4\pi R^2(1-e^{-\mu_t x_0})e^{-3\mu_t x_0}}{(4\pi d_2^2)^2} + \frac{6\pi R^2(1-e^{-\mu_t x_0})^2 e^{-3\mu_t x_0} B'''}{2\,(4\pi d_2^2)^2}\right] \qquad (7)$$

This equation is set equal to Eq (1), the value of B''' is determined, and this value is substituted into Eq (6).

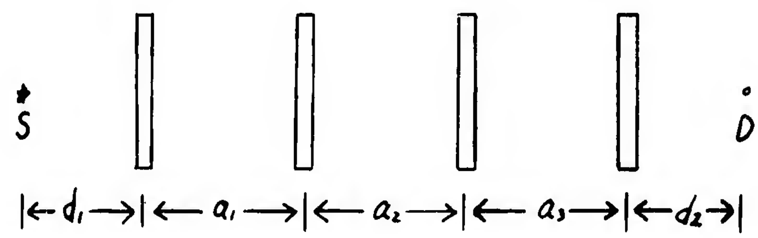

Fig. 4

Cross-section of the Four-section Split Shield

Circular-source Computations

The previous problem situation is modified by replacing the point source in Fig. 1 with a circular isotropic source of radius R, equal to the radius of the shield. This new problem is shown by Fig. 5 for the unit shadow shield. All other parameters and assumptions are maintained the same as before.

The equation for the flux reaching a point detector through a unit shield from a circular source is derived in the following manner. The differential flux ($d\phi$) at the detector is given by

$$d\phi = \frac{B S_a\, e^{-\mu_t x_o \sec\theta}}{4\pi (x \sec\theta)^2}\, dA \tag{8}$$

where B = the build-up factor,

S_a = the source strength in units of flux,

θ = the angle subtended by the source radius at the detector (See Fig. 5),

and dA = the differential area of the source.

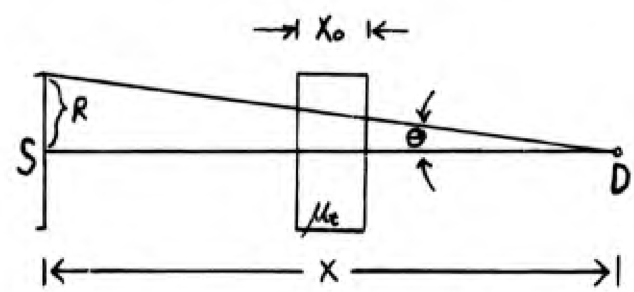

Fig. 5

Cross-section of the Unit Shield with a Circular Source

It may be noted that Eq (8) is similar to Eq (1) for the point source with the distance $x \sec\theta$ substituted for x. The differential area (dA) is $2\pi r\, dr$ and since $r = x \tan\theta$, dA becomes $2\pi x^2 \tan\theta \sec^2\theta\, d\theta$. When this is substituted into Eq (8), that equation becomes

$$\phi = \frac{BS_a}{2}\int_0^{\cos^{-1}\frac{\sqrt{x^2+R^2}}{x}} e^{-\mu_t x_o \sec\theta}\tan\theta\, d\theta$$

The variable of integration is now switched from θ to sec θ so that the flux equation becomes

$$\phi = \frac{BS_a}{2}\int_1^{\frac{\sqrt{x^2+R^2}}{x}} e^{-\mu_t x_o \sec\theta}\,\frac{d(\sec\theta)}{\sec\theta}$$

The substitution of $y = \mu_t x_o \sec\theta$ reduces this to

$$\phi = \frac{BS_a}{2}\int_{\mu_t x_o}^{\mu_t x_o\frac{\sqrt{x^2+R^2}}{x}} \frac{e^{-y}}{y}\,dy = \frac{BS_a}{2}\left[\int_{\mu_t x_o}^{\infty}\frac{e^{-y}}{y}\,dy - \int_{\mu_t x_o\frac{\sqrt{x^2+R^2}}{x}}^{\infty}\frac{e^{-y}}{y}\,dy\right]$$

Since the integrals in the previous equation are the familiar exponential integrals, this equation can be expressed as

$$\phi_{us} = \frac{BS_a}{2}\left[E_1(\mu_t x_o) - E_1\left(\mu_t x_o\frac{\sqrt{x^2+R^2}}{x}\right)\right] \qquad (9)$$

Unit Shield. The detector flux through a unit shield from a circular source is given by Eq (9) for the problem as shown by Fig. 5 where B is again assumed to be equal to $\mu_t x_o$. The flux computed from this equation forms the basis against which the flux from the split shields are compared.

Two-section Scatter Shield. The unit shield is again divided into two equally-thick sections separated by a distance a. The cross-section of this shield is shown by Fig. 2 except that the point source is replaced by a circular source of radius R. In developing the equation for this shield, the shield sections are maintained symmetrical about the mid-point between the source and the detector which means that $d_1 = d_2$ in Fig. 2. These distances are referred to as d for the circular-source computations.

The detector flux (ϕ_{ss}) is again divided into components representing the contributions of the unscattered, once-scattered, and multiply-scattered photons to the total flux. With B = 1, Eq (9) represents the unscattered flux.

The once-scattered flux is determined in a manner similar to that used for the point-source computations, but it is necessary to describe the distance attenuation of the photons from a circular source when there is no shielding material present. Referring to Fig. 6, the distance attenuation of photons from a differential area (dA) on the source is $1/4\pi(x\sec\theta)^2$ and the flux at a point (P)

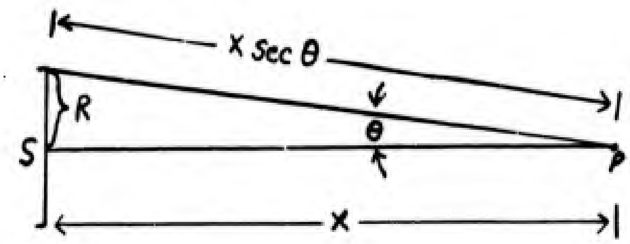

Fig. 6

Cross-section of the Distance Attenuation of the Flux from a Circular Isotropic Source

along the axis of the source is given by

$$\phi_P = \int_0^R \frac{S_a}{4\pi (x\sec\theta)^2}\, dA$$

When the substitutions of $dA = 2\pi r\, dr$ and $r = x\tan\theta$ are made, this equation reduces to

$$\phi_P = \frac{S_a}{2}\int_0^{\cos^{-1}\frac{x}{\sqrt{x^2+R^2}}} \tan\theta\, d\theta \quad .$$

Upon integration, this becomes

$$\phi_P = \frac{S_a}{2}\ln\frac{\sqrt{x^2+R^2}}{x} \qquad (10)$$

This equation represents the probability that a photon emitted from a circular source will reach a point along the axis of the source at a distance x. The probability of a photon scattering within a shield section is assumed to be $(1 - e^{-\mu_0 x_0})$ and, as derived previously, the attenuation in passing through a shield is given by Eq (9).

Since both Eq (9) and Eq (10) give the flux at a point on the axis of the shields, it is necessary to assume that this same flux is good for any point on the shield. Thus, it is assumed that the flux reaching a shield section is uniform over the entire face of that shield and that the shield section acts as a circular source of photons for the remaining sections. In order to estimate the accuracy of this assumption, the following problem is used.

This problem uses a square source plane, and a square shield with each square being 2 R on a side (See Fig. 7). These dimensions are assumed in order to simulate a circular source and shield with a radius R. Each of these squares is divided in 16 equal squares, and on the source plane, an isotropic point source is placed at the center of each small square. The flux at each corner point on the shield (a total of 25 points) is computed from each of the 16 sources using simple distance attenuation. These computations are performed for source-to-shield separation distances (x) of 15, 10, and 5 R. The ratio of the flux at one of the outer-

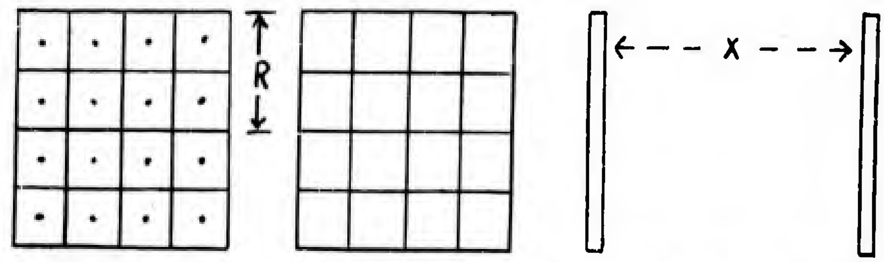

Fig. 7

Uniform Distribution from a Plane Source.

most corner points to the flux at the center of the shield is computed for each of the selected values of x. These ratios are 0.993, 0.980, and 0.931 for the values of x of 15, 10, and 5 R respectively. Judging from the results of this problem, the assumption of uniform dose over the shield face appears to be good for all except small ratios of the source radius to the separation distance.

With the previous probabilities and assumptions established, the equation to describe the passage of gamma rays from a circular source through the two-section split shield can now be written. As mentioned previously, the unscattered flux is given by Eq (9) with B = 1. The probability that a photon reaches the first section is given by Eq (10) with x replaced by d; the probability that it scatters in that section is $(1 - e^{-\mu_t x_0})$; and the probability that it then reaches the detector is given by Eq (9) with B = 1, x replaced by $a + d$, and S_a replaced by the product of the first two terms. Since a photon may scatter in either of the two sections, this term, representing the once-scattered flux, is doubled.

The twice-scattered flux is estimated by using the following probabilities. The probability of reaching the first section is given by Eq (10) with x replaced by d; the probability of scattering in that section is $(1 - e^{-\mu_t x_0})$; the probability of reaching the second section from the first is given by Eq (10) with x replaced by a ; once again, the probability of scattering in this section is $(1 - e^{-\mu_t x_0})$; and, finally, the probability of reaching the detector is given by Eq (10) with x replaced by d. This twice-scattered flux is now multiplied by an artificial build-up factor (B_c') to account for the flux from those photons which scatter more than twice.

When these probabilities are combined, the detector flux through the two-section split shield is given by

$$\phi_{ss} = \frac{S_a}{2}\left\{\left[E_1(\mu_t x_0) - E_1\left(2\mu_t x_0 \frac{\sqrt{x^2+R^2}}{x}\right)\right] + \ln\frac{\sqrt{d^2+R^2}}{d}\left(1-e^{-\mu_t x_0}\right)\left[E_1(\mu_t x_0) - E_1\left(\mu_t x_0 \frac{\sqrt{(a+d)^2+R^2}}{a+d}\right)\right] + \frac{B_c'}{4}\left(\ln\frac{\sqrt{d^2+R^2}}{d}\right)^2 \ln\frac{\sqrt{a^2+R^2}}{a}\left(1-e^{-\mu_t x_0}\right)^2\right\} \quad (11)$$

where the terms on the right side of the equation represent the unscattered, once-scattered, and multiply-scattered fluxes in that order. B_c' is determined by setting the separation distance between shield sections (a) equal to zero and equating the resultant equation to Eq (9). With $a = 0$, Eq (11) reduces to

$$\phi_{ss} = \frac{S_a}{2}\left\{\left[E_1(2\mu_t x_o) - E_1\left(2\mu_t x_o \frac{\sqrt{x^2+R^2}}{x}\right)\right] + \left[E_1(\mu_t x_o) - E_1\left(\mu_t x_o \frac{\sqrt{d^2+R^2}}{d}\right)\right] \ln\frac{\sqrt{d^2+R^2}}{d}\left(1-e^{-\mu_t x_o}\right) + \frac{B_c'}{4}\left(\ln\frac{\sqrt{d^2+R^2}}{d}\right)^2\left(1-e^{-\mu_t x_o}\right)^2\right\} \quad (12)$$

<u>Three-section Scatter Shield</u>. The detector flux through the three-section split shield from a circular source is determined using the previously-described probabilities. The cross-sectional view of the problem is shown by Fig. 3 except that the source is now considered to be a circular source. The problem is solved for only the symmetrical shield where $d_1 = d_2$ and $a_1 = a_2$. The unscattered flux is represented by the same term as in Eq (11) except that $2\mu_t x_o$ is replaced by $3\mu_t x_o$.

The once-scattered flux is described by the following probabilities. The probability of a photon reaching the first section is given by Eq (10) with x replaced by d, the probability of scattering in that section is ($1-e^{-\mu_t x_0}$), and the probability of reaching the detector is given by Eq (9) with x replaced by $2a$ + d. These probabilities describe those photons scattering once in the first section and they also describe the photons scattering once in the third section. The photons scattering once in the second section are given by the following group of probabilities. The probability of reaching the second section is given by Eq (9) with x replaced by a + d, the probability of scattering there is ($1-e^{-\mu_t x_0}$) and the probability of reaching the detector is again given by Eq (9) using a + d instead of x.

The twice-scattered flux is computed in the following manner. That portion which scatters once in either the first and second or the second and third sections is described as follows: the probability of reaching the first section is given by Eq (10) using d instead of x, the probability of scattering in that section is ($1-e^{-\mu_t x_0}$), the probability of reaching the second section is given by Eq (10) using a instead of x, the probability of scattering there is again ($1-e^{-\mu_t x_0}$), and the probability of reaching the detector is given by Eq (10), x replaced by a + d. The photons which scatter once in the first section and once in the third section are described as follows: the probabilities of reaching the first section and scattering there are given by Eq (10) using d instead of x and ($1-e^{-\mu_t x_0}$) respectively, the probability of reaching the third section from the first is given by Eq (9) with x replaced by $2a$, the probabilities of scattering in that section and reaching the detector are given by $(1-e^{-\mu_t x_0})$ and Eq (10) with x replaced by d. Since these terms represent only the twice-scattered radiation, they are multiplied by a build-up factor (B_c'') to obtain the multiply-scattered flux.

When these terms are combined, the equation for the detector flux through a three-section scatter shield becomes

$$\phi_{ss} = \frac{S_a}{2}\Bigg\{ \left[E_1(3\mu_t x_0) - E_1\left(3\mu_t x_0 \frac{\sqrt{x^2+R^2}}{x}\right)\right] + \ln\frac{\sqrt{d^2+R^2}}{d}\left(1-e^{-\mu_t x_0}\right)\left[E_1(2\mu_t x_0) - E_1\left(2\mu_t x_0 \frac{\sqrt{(2a+d)^2+R^2}}{2a+d}\right)\right] + \frac{1}{2}\left(1-e^{-\mu_t x_0}\right)\left[E_1(\mu_t x_0) - E_1\left(\mu_t x_0 \frac{\sqrt{(a+d)^2+R^2}}{a+d}\right)\right]^2 + \frac{B_c''}{2}\ln\frac{\sqrt{d^2+R^2}}{d}\ln\frac{\sqrt{a^2+R^2}}{a}\left(1-e^{-\mu_t x_0}\right)^2\left[E_1(\mu_t x_0) - E_1\left(\mu_t x_0 \frac{\sqrt{(a+d)^2+R^2}}{a+d}\right)\right] + \frac{B_c''}{4}\left(\ln\frac{\sqrt{d^2+R^2}}{d}\right)^2\left(1-e^{-\mu_t x_0}\right)^2\left[E_1(\mu_t x_0) - E_1\left(\mu_t x_0 \frac{\sqrt{(2a)^2+R^2}}{2a}\right)\right]\Bigg\} \quad (13)$$

where the first term represents the unscattered flux, the next two terms represent the once-scattered flux, and the final two terms represent the multiply-scattered flux.

B_c'' is determined by setting the shield-separation distances

(a) equal to zero and equating the resulting equation to the detector flux from the unit shield as given by Eq (9). When a = 0, Eq (13) reduces to

$$\phi_{ss} = \frac{S_a}{2}\Big\{ \Big[E_1(3\mu_t x_0) - E_1\Big(3\mu_t x_0 \frac{\sqrt{x^2+R^2}}{x}\Big)\Big] +$$

$$\frac{3}{2} \ln \frac{\sqrt{d^2+R^2}}{d}\left(1-e^{-\mu_t x_0}\right)\Big[E_1(2\mu_t x_0) - E_1\Big(2\mu_t x_0 \frac{\sqrt{d^2+R^2}}{d}\Big)\Big] +$$

$$\frac{B_c''}{2} \ln \frac{\sqrt{d^2+R^2}}{d}\left(1-e^{-\mu_t x_0}\right)^2\Big[E_1(\mu_t x_0) - E_1\Big(\mu_t x_0 \frac{\sqrt{d^2+R^2}}{d}\Big)\Big] +$$

$$\frac{B_c''}{4}\Big(\ln \frac{\sqrt{d^2+R^2}}{d}\Big)^2\left(1-e^{-\mu_t x_0}\right)^3\Big[E_1(\mu_t x_0) - E_1\Big(\mu_t x_0 \frac{\sqrt{x_0^2+R^2}}{x_0}\Big)\Big] \Big\} \quad (14)$$

The attenuation factor $[E_1(\mu_t x_0) - E_1(\mu_t x_0 \frac{\sqrt{(2a)^2+R^2}}{2a})]$ in the final term of Eq (13) approaches $E_1(\mu_t x_0)$ as a approaches zero. However, in Eq (14) the limiting value of a is considered to be the thickness of the shield section (x_0), so that this factor becomes

$$E_1(\mu_t x_0) - E_1\Big(\mu_t x_0 \frac{\sqrt{x_0^2+R^2}}{x_0}\Big)$$

Since μ_t and x_0 are used separately in this factor, it becomes a function of the shielding material used. If the shield is composed of a light-weight material having a low attenuation coefficient such as beryllium, this factor is small and the final term of Eq (14) is small in relation to the other terms. As the shield material is changed to higher-density substances, this factor approaches $E_1(\mu_t X_0)$, the limiting value for a shield section of zero thickness. This is the factor which is used in Eq (14) to determine B_c'' .

IV. Parameter Studies

This section of the report describes the actual dimensions used for the split scatter shield problem and the various parameter studies conducted on that shield. The initial studies are conducted for the variable a, the shield section separation distance, while later studies attempt to analyze the effect of changing other variables.

The problem situation, as illustrated by Fig. 1, is assumed to have the following dimensions: $B = \mu_t x_o$, $x = 30$, $R = 1$, and $\mu_t x_o = 6$, where the units of x and R are the same. The detector flux through the unit shield is computed from Eq (1) for the point source and from Eq (9) for the circular source. These fluxes represent the basis against which the fluxes from the various split shields will be compared.

Separation-distance Parameter Studies

Parameter studies are conducted on the separation distance between the shield sections of all the various split shields described in Section III. These parameter studies are intended to determine the minimum detector flux from each of the split shields and to locate the separation distance which gives this minimum flux. All variables in the equations are held constant except the distances between the shield sections. The total shield thickness is maintained at $\mu_t x_0 = 6$ for all of the split shields so that when the shield consists of two sections, each section has a thickness of $\mu_t x_0 = 3$ and when there are three sections, $\mu_t x_0 = 2$ for each section.

The parameter study for the two-section shield is conducted for the case of the point source using Eq (2). The initial study is performed for the symmetrical shield where $d_1 = d_2$. Then, the study is expanded to include all possible values of d_1, d_2, and a. The study on the two-section shield for the case of a circular source is conducted for the symmetrical shield only, using Eq (11).

The separation-distance parameter study for the three-section shield with a point source is again conducted for the symmetrical shield, first, and then, for all the possible arrangements of the shield sections. Eq (4) is used for both of these studies. The symmetrical shield arrangement was the only situation considered for the three-section shield with a circular source. The equation used for this study is Eq (13) with the value of B_c'' determined from Eq (14). The variance of one of the terms of Eq (14) with the shield material is described in Section III (see page 18). Because of this term, the value of B_c'' computed from Eq (14) varies slightly, depending on what shield material is used. The value of B_c'' for different materials is shown in Table I where the radius of the shield is assumed arbitrarily to be 100 cm. Since

Table I

Multiply-scattered Build-up Factor for a Three-section Split Shield for Various Shield Materials

Material	B_c''	μ_t(cm)*	ρ (gm/cm^3)
Be	26.035	0.1045	1.85
Al	24.855	0.1658	2.70
Fe	23.047	0.4677	7.86
W	23.037	1.235	19.30
--	23.037	∞	∞

* For 1.0 Mev Gamma-rays (From Ref 1:469)

this value of the radius is probably small compared to an actual situation, the effect on B_c'' shown here is over-estimated. The final entry in Table I represents a shield of zero thickness and infinite density, and it is the value of B_c'' used for the primary parameter study.

The four-section shield parameter study of the separation distance is conducted for the symmetrical shield arrangement only, using Eq (6) with $d_1 = d_2$ and $a_1 = a_2 = a_3$.

Other Parameter Changes

Certain other parameters of the split shield problem are now varied to observe the effect of these changes upon the results of the previous parameter study. These parameter changes are not studied through their entire range of variance, only through certain selected changes. The purpose of these changes is to give an indication of the direction of their effect upon the previous study.

The effect of a change in the total source-to-detector separation distance is the first parameter studied. This effect is studied first for the two-section shield with a point source by changing the ratio of R to x from 1/30 to 1/15, holding all other variables in Eq (2) constant. The shield-section separation distance (a) is varied slightly about the optimum value found previously to observe if this optimum separation distances changes. The same procedure is followed for the three-section shield with a point source except that the change in R/x is now from 1/30 to 1/20.

The effect of a change in the relative thicknesses of the shield sections is the next parameter studied. Previously, it was assumed that all sections of a split shield are equally thick. With the use of Eq (4) for the three-section shield with a point source, the minimum detector flux is determined for all possible combinations of section thicknesses where the section-thickness values are integers (i.e. $\mu_t x_o = 1, 2, 3$). The value of a used in these computations is that determined previously to be the optimum.

In the previous parameter studies, the build-up factor (B) was assumed to be equal to the unit-shield thickness in mean free paths ($\mu_t x_o$). This assumption is now modified so that the flux attenuation is computed for the two-section split shield with a point source using values of $B = 0.5\mu_t x_o$ and $B = 1.5\mu_t x_o$. It is necessary to determine a new value for the multiply-scattered build-up factor (B'), using Eqs (1) and (3) as described previously. Eq (2) is then used to determine the effect of changes in the build-up factor (B).

The total thickness of the shield sections has been assumed to be six mean free paths in all of the previous calculations. In an effort to calculate the effect of increasing this total shield thickness, computations are performed upon the two-section, three-section, and four-section split shields for values of $\mu_t x_o$ of eight and twelve, as well as the original six. The separation distance used for these computations is the optimum distance as determined previously, and the point source is used. The assumption of $B = \mu_t x_o$ was made in each case.

Changes in Assumptions

In Section II of this report, certain assumptions were made and their validities were discussed. It is the purpose of the remaining calculations to determine how more realistic values for these assumptions effect the results of the previous parameter studies.

The assumption was made previously that the thickness of the shield sections (x_o) were insignificant in relation to the source-to-detector separation distance. In order to determine the effect of a finite shield thickness, a value of x_o of 20% of the total distance (x) is assumed for the two-section shield with a point source. This value of x_o is selected because it is larger than any anticipated actual value, and the effect upon the results would represent a maximum.

In all of the previous parameter studies, it is assumed that the photons scatter isotropically in the shield and that the shield sections act as isotropic sources for the subsequent sections in the shield. Actually, it has been shown that the angular cross-sections for Compton scattering is anisotropic for high-energy photons (Ref 5:149). As a rough approximation to the angular distribution of the scattering photons, it is assumed that one-half of the gamma rays scatter in an angle between 0^o and 30^o to the angle of the incident rays, one-fourth between 30^o and 60^o, and one-eighth between 60^o and 90^o. This approximation is used for a two-section split shield with a point source. The result of this computation is not intended to be an accurate description of the scatter shield for any particular shielding material, but it will indicate the gross effect upon the effectiveness of the scatter shield due to anisotropic scattering of the photons.

V. Results

The results of the previously-described parameter studies are shown and discussed in this section of the report. These results are reported for the split scatter shield in reference to the unit shadow shield. The unit of comparison is defined to be the ratio of the flux reaching the detector through a scatter shield to that reaching the detector through a unit shield (ϕ_{ss}/ϕ_{us}).

Separation-distance Study

The parameter studies to determine the optimum separation distance between shield sections and the minimum value of ϕ_{ss}/ϕ_{us} are reported for the two, three, and four-section shields.

Two-section Scatter Shield. The results of the parameter studies on the two-section shield are shown in Fig. 8 for the point source and in Fig. 9 for the circular source. Both Fig. 8 and Fig. 9 represent the results for the symmetrically-arranged shield where $d_1 = d_2$. For the figures used in this section, the values of a shown are in relation to the total source-to-detector distance of 30. The results from both of these cases are nearly identical, with a minimum value of ϕ_{ss}/ϕ_{us} of 0.221 and an optimum separation distance of approximately 27% of the total source-to-detector distance for both. The detector flux from the split shield drops rapidly at first as the separation distance is increased, but then levels

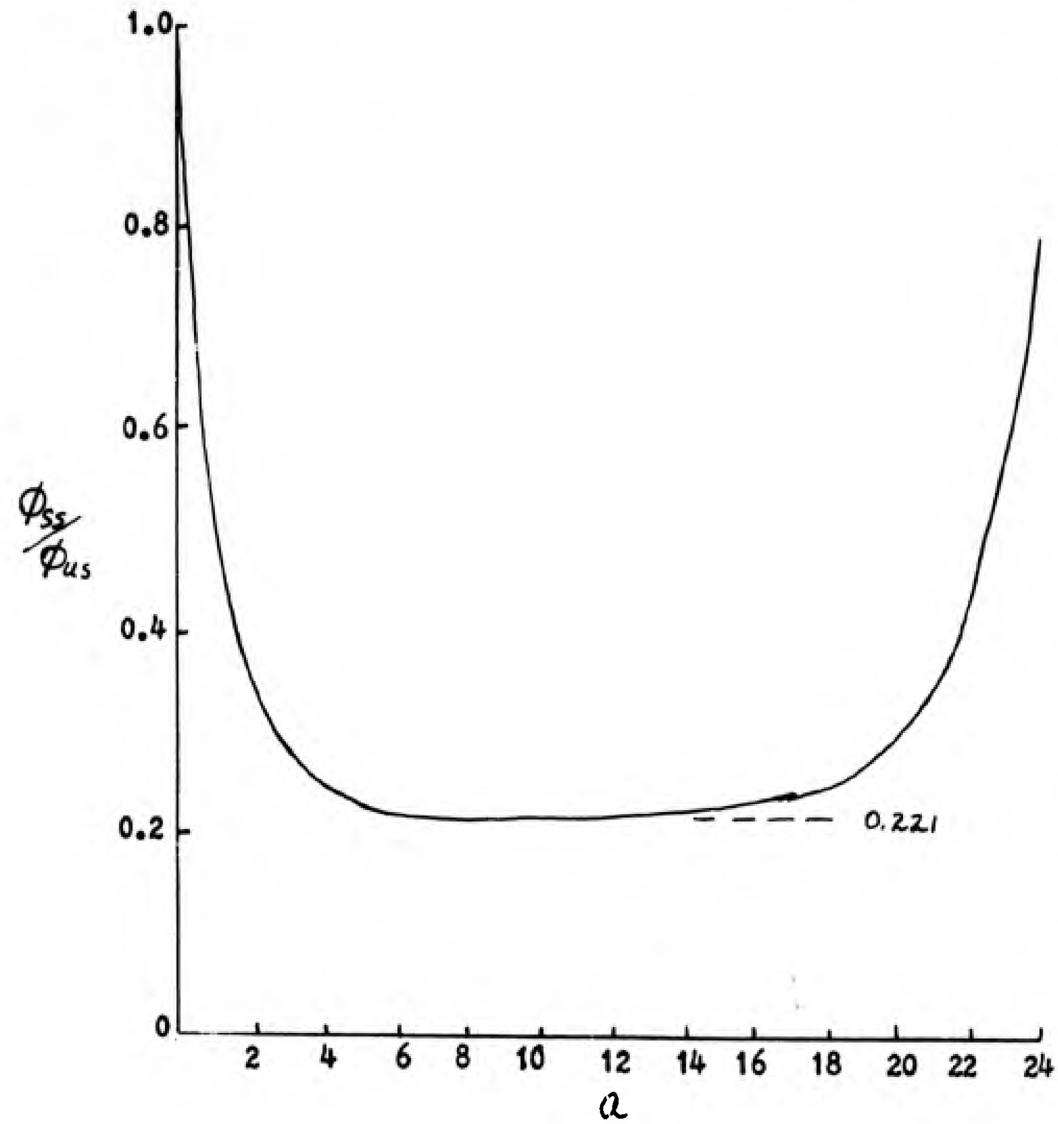

Fig. 8

Ratio of Split-shield Flux to Unit-shield Flux for a Two-section Shield (Point Source)

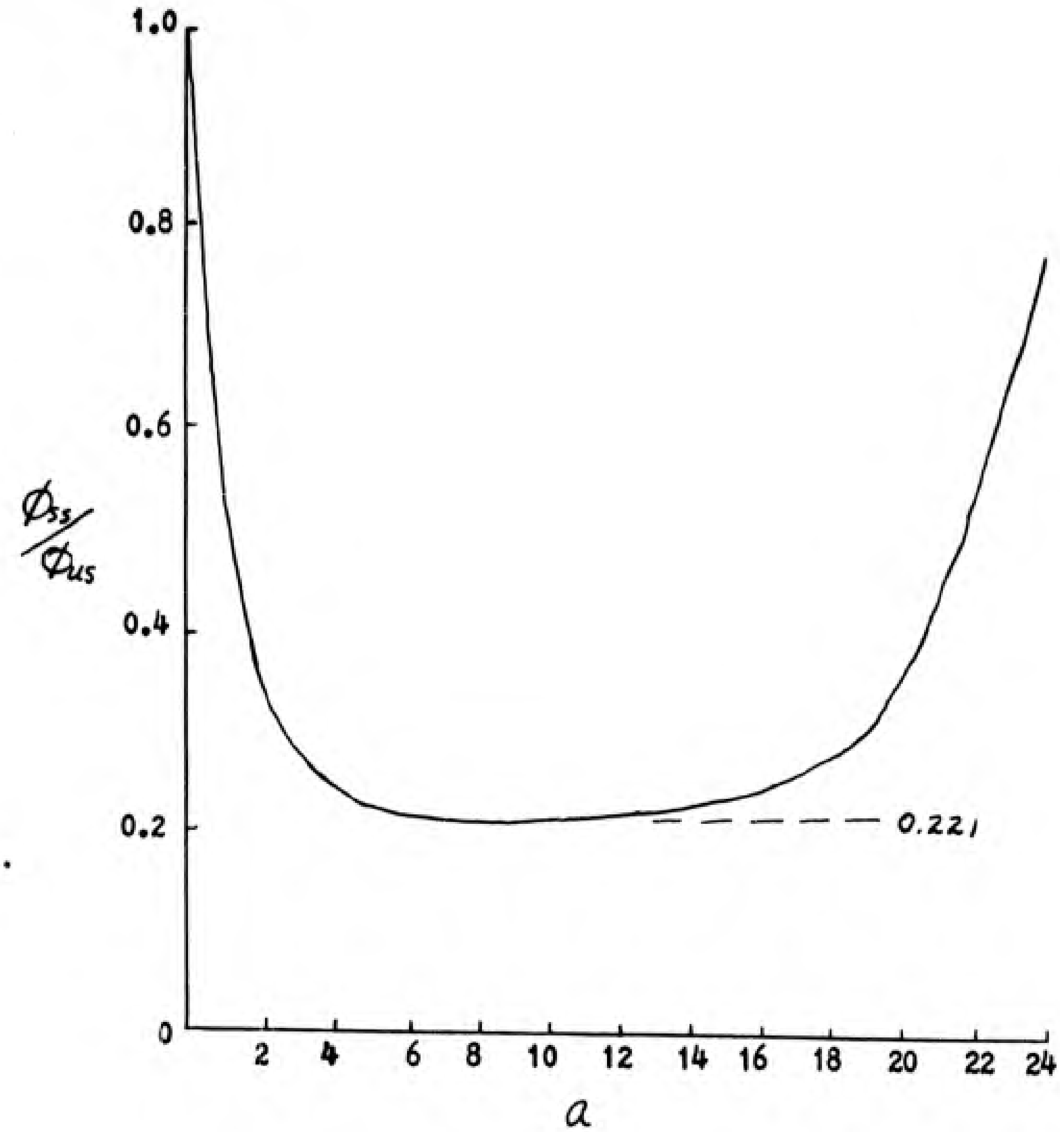

Fig. 9

Ratio of Split-shield Flux to Unit-shield Flux for a Two-section Shield (Circular Source) off over a wide range. Thus, the optimum value of the separation distance is not sharply defined.

The results of the study for the asymmetrical arrangement of shield sections is shown by Table II. This study was conducted only for the problem using a point source. The results of this study indicate that no further reduction in the flux attenuation through the two-section shield is achieved by any asymmetrical arrangement of the sections.

Three-section Scatter Shield. The results of the separation-distance parameter studies for the three-section split shield are shown by Fig. 10 for the point source and by Fig. 11 for the circular source. These results are for the symmetrically-arranged shield sections where $d_1 = d_2$ and $a_1 = a_2$ (see Fig. 3). The minimum value of ϕ_{ss}/ϕ_{us} for the shield with a point source is 0.213, and for the shield with a circular source, it is 0.220. Both of these minimums occur at the shield-section separation value (a) which is 20% of the total source-to-detector distance, but as before, no clearly-defined optimum exists.

As described previously, the minimum flux from the three-section shield with a circular source depends slightly upon the shielding material used (see Table I). The values plotted in Fig. 11 represent the limiting case of an infinitely thin shield, but if a light-weight material such as Be is used, the minimum

Table II

Flux Reduction Ratio for the Two-section Scatter Shield for

Asymmetrical Shield-section Arrangements

Shield-section Positions d_1	a	d_2		Shield-section Positions d_1	a	d_2	
16	2	12	0.335	11	4	15	0.244
	4	10	0.249		6	13	0.226
	6	8	0.238		8	11	0.221
	7	7	0.241		9	10	0.221
	8	6	0.250		10	9	0.224
15	2	3	0.330	10	4	16	0.248
	4	11	0.244		6	14	0.228
	6	9	0.232		8	12	0.221
	8	7	0.237		10	10	0.223
	10	5	0.265				
				9	6	15	0.237
14	2	14	0.328		8	13	0.224
	4	12	0.241		9	12	0.223
	6	10	0.228		10	11	0.224
	7	9	0.229		12	9	0.228
	8	8	0.229				
				8.5	6	15.5	0.234
13	4	13	0.241		8	13.5	0.226
	6	11	0.226		9	12.5	0.224
	7	10	0.224		10	11.5	0.224
	8	9	0.224		11	10.5	0.226
	9	8	0.228				

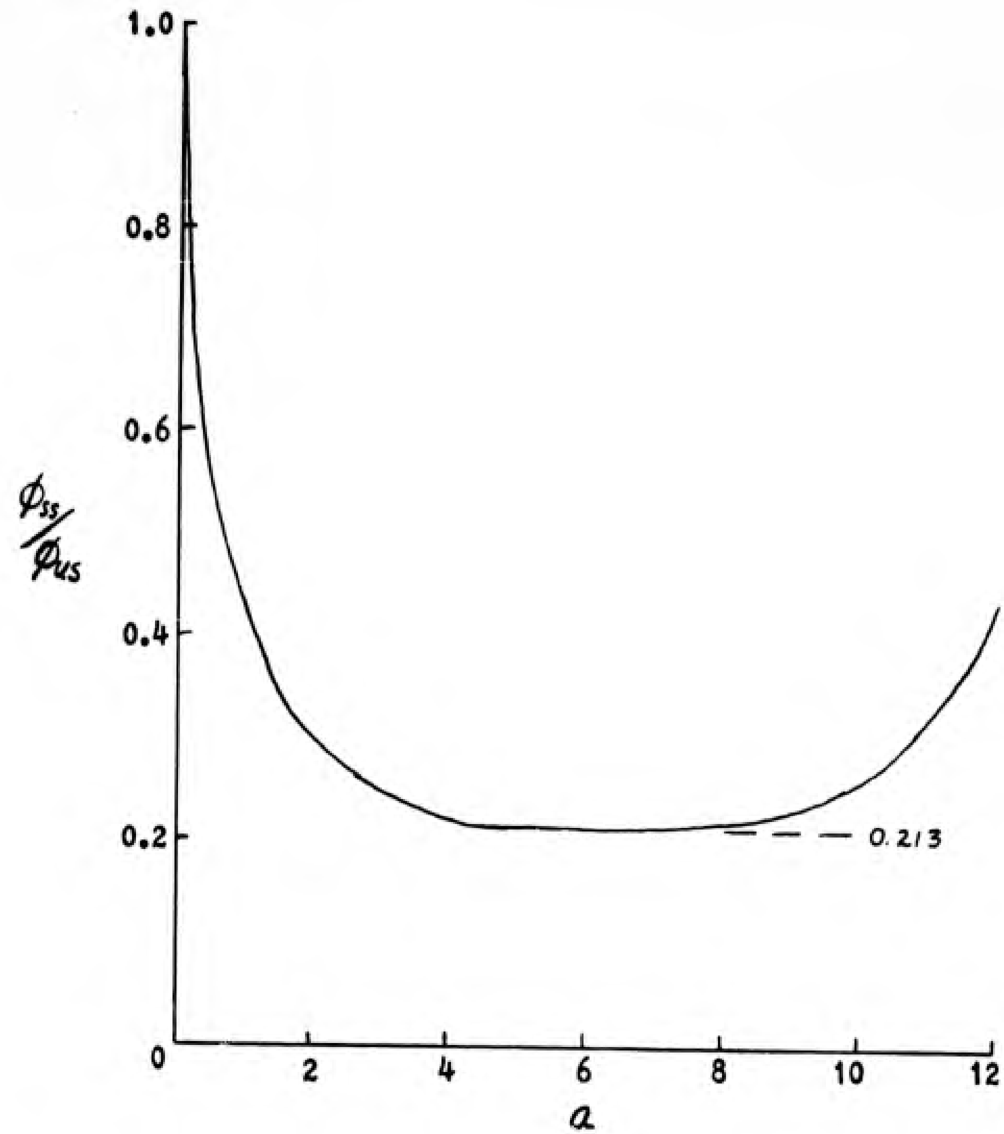

Fig. 10

Ratio of Split-shield Flux to Unit-shield Flux

for a Three-section Shield (Point Source)

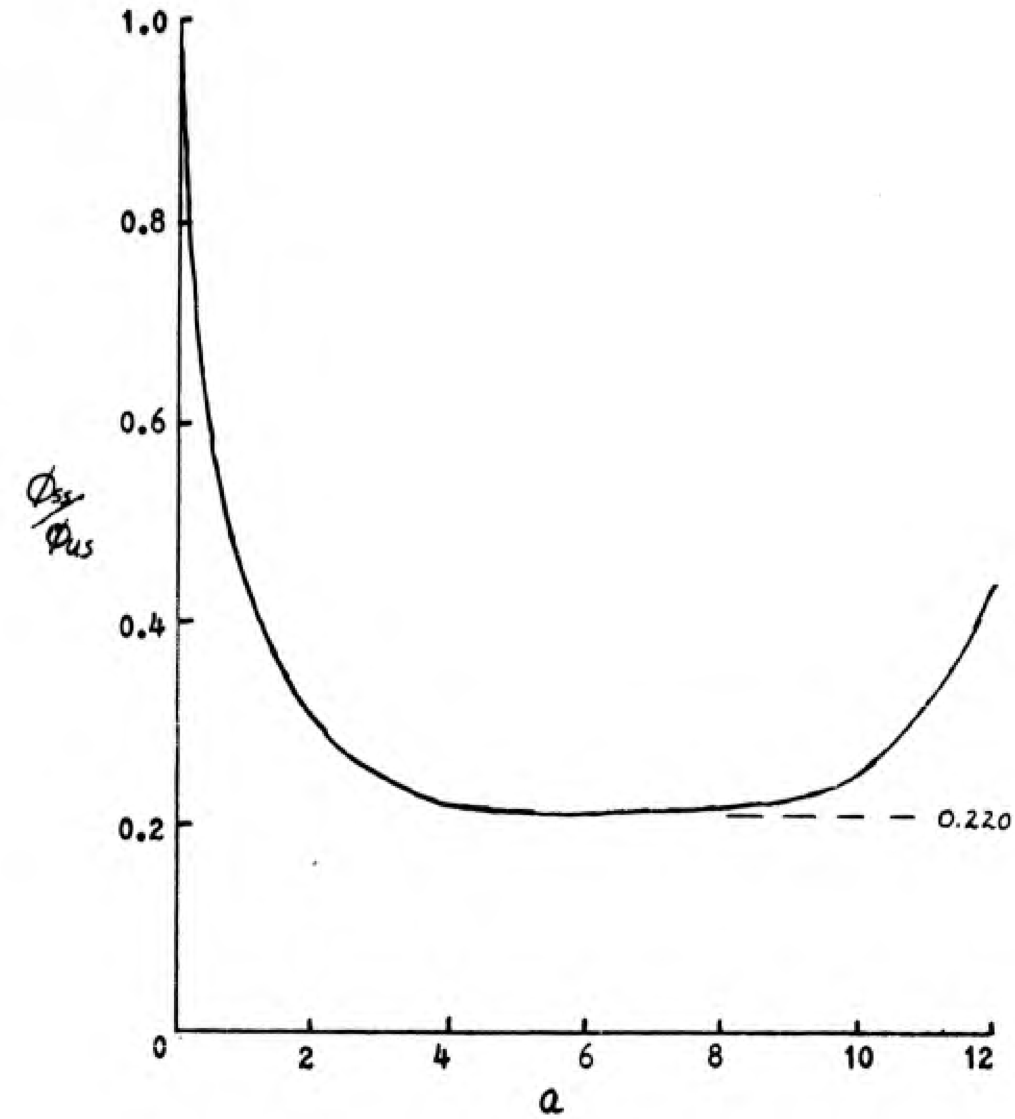

Fig. 11

Ratio of Split-shield Flux to Unit-shield Flux for a Three-section Shield (Circular Source) value of ϕ_{ss}/ϕ_{us} is increased only slightly to 0.224.

The results of the separation-distance parameter study are shown in Table III for the three-section shield with a point source. Once again, no reduction in ϕ_{ss}/ϕ_{us} is indicated by using any asymmetrical shield arrangement. Although this study was performed for all possible values of d_1, d_2, a_1, and a_2, Table III lists only those arrangements which give significant flux attenuations.

Four-section Scatter Shield. The results of the separation-distance parameter study are shown by Fig. 12. These results are for a symmetrical shield using point source calculations. Once again, the separation distance is slowly varying, with the minimum value of ϕ_{ss}/ϕ_{us} being 0.216 at a separation distance of 17% of the total source-to detector distance.

Other Parameter Changes

The effects upon the previous results due to changes in other parameters of the assumed problem are reported in the following paragraphs.

The effect of decreasing the total source-to-detector separation distance is a corresponding decrease in the effectiveness of the split shield. This is true because of the reduction in the spacing between shield sections which increases the probability of a photon scattering from one section to the next. When the ratio of the radius of the shield to the total distance was

Table III

Flux Reduction Ratio for the Three-section Scatter Shield for Asymmetrical Shield-section Arrangements

Shield-section Positions					Shield-section Positions				
d_1	a_1	a_2	d_2		d_1	a_1	a_2	d_2	
11	9	3	7	0.240		7	5	9	0.213
		4	6	0.234			6	8	0.213
	8	4	7	0.225		6	5	10	0.213
		5	6	0.226			6	9	0.213
	7	4	8	0.220			7	8	0.213
		5	7	0.218		5	5	11	0.214
	6	4	9	0.217			6	10	0.214
		5	8	0.215			7	9	0.214
	5	4	10	0.217					
		5	9	0.214	8	9	5	8	0.217
	4	5	10	0.216		8	5	9	0.214
		6	9	0.215			6	8	0.214
						7	5	10	0.214
10	8	4	8	0.220			6	9	0.213
		5	7	0.219			7	8	0.215
	7	5	8	0.215		6	6	10	0.213
		6	7	0.215			7	9	0.213
	6	5	9	0.213		5	6	11	0.215
		6	8	0.213			7	10	0.215
	5	6	9	0.213					
		7	8	0.213	7	10	5	8	0.220
	4	6	10	0.215		9	5	9	0.217
		7	9	0.215			6	8	0.217
						8	5	10	0.215
9	9	5	7	0.218			6	9	0.215
		6	6	0.219		7	6	10	0.214
	8	4	9	0.215			7	9	0.214
		5	8	0.214		6	6	11	0.216

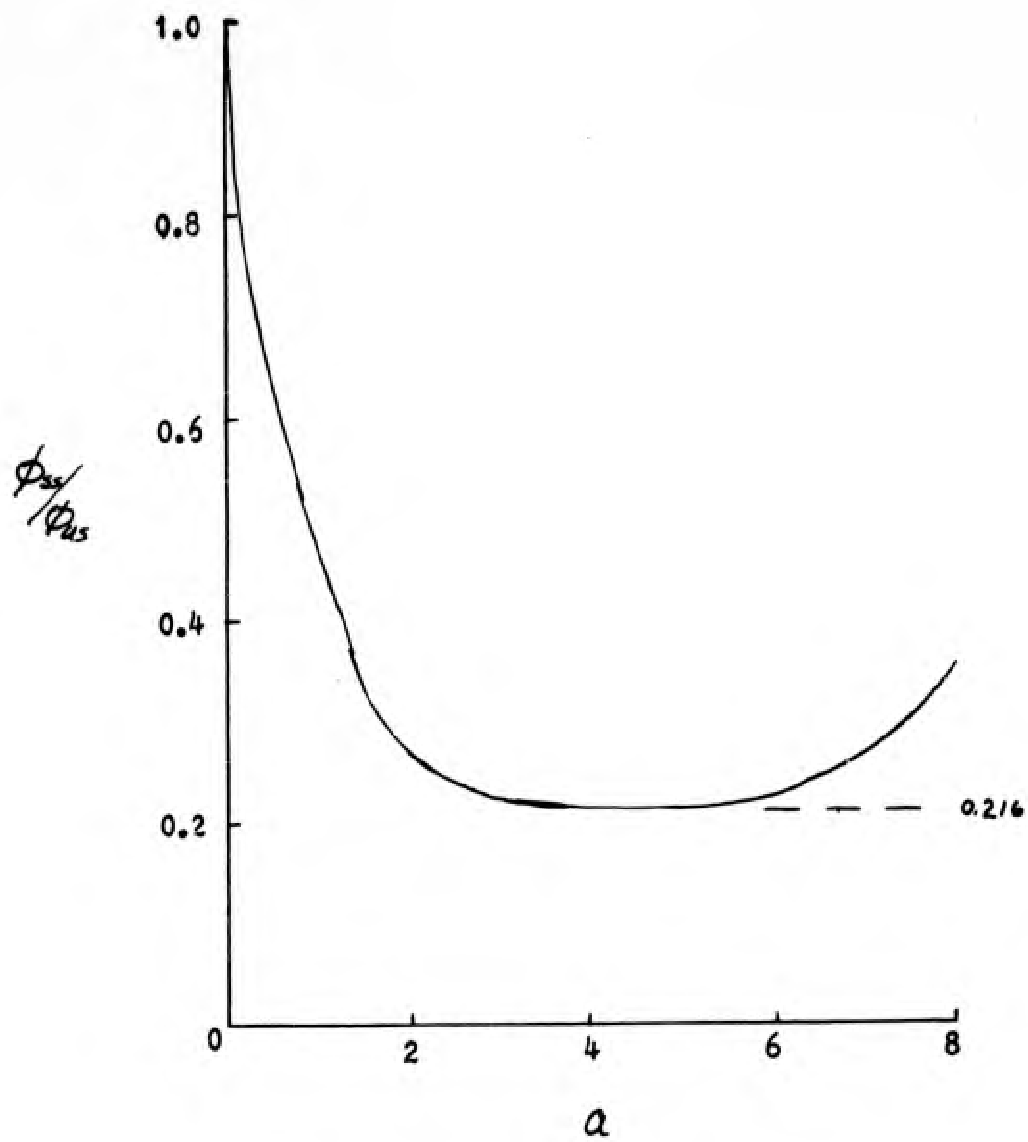

Fig. 12

Ratio of Split-shield Flux to Unit-shield Flux

for a Four-section Shield (Point Source) changed from 1/30 to 1/15 for the two-section shield, the value of ϕ_{ss}/ϕ_{us} increased from 0.221 to 0.732. When the value of R/x was changed from 1/30 to 1/20 for the three-section shield, ϕ_{ss}/ϕ_{us} increased from 0.213 to 0.271.

The results of using unequal section thicknesses was examined for the three-section shield. The results as shown in Table IV indicate the maximum effectiveness of the shield occurs when the sections are equally thick.

Table IV

Effect of Varying Shield-section Thicknesses

Shield-section Thickness ($\mu_t x_o$)			Minimum Value of ϕ_{ss}/ϕ_{us}
1st Section	2nd Section	3rd Section	
3	2	1	0.233
2	3	1	0.230
3	1	2	0.228
2	2	2	0.213
2	1	3	0.228
1	3	2	0.230
1	2	3	0.233

The effects of using different assumptions for the build-up factor (B) of the unit shield are shown in Table V. These results, computed for the two-section split shield, show that the effectiveness of a split shield is strongly dependent upon the build-up of radiation within a unit shield. Since the split shield gains its advantage by eliminating as much of the scattered radiation as possible, the theoretically perfect shield would have a value of ϕ_{ss}/ϕ_{us} equal to 1/B. Consequently, Table V also shows the results in terms of the percentage of 1/B actually obtained in each case.

Table V

Effect of Build-up Factor (B) on Split-shield Results

B	Minimum Value of ϕ_{ss}/ϕ_{us}	Max. Possible Reduction in Flux (1/B)	Percentage of 1/B Actually Obtained
$3(0.5\mu_t x_o)$	0.415	0.333	80.4%
$6(1.0\mu_t x_o)$	0.221	0.167	75.3%
$9(1.5\mu_t x_o)$	0.156	0.111	71.2%

The effect of increasing the total shield thickness was evaluated for the two, three, and four-section shields. The results of these changes are shown in Table VI.

Table VI

Effect of Total Shield-thickness Increase

Total Shield Thickness ($\mu_t x_o$)	Minimum Value of ϕ_{ss}/ϕ_{us} Two-sections	Three-sections	Four-sections
6	0.221	0.213	0.216
8	0.215	0.183	0.181
12	0.446	0.190	0.160

Assumption Modifications

The effects upon the previous results due to more realistic assumptions are given here. The first two assumptions represent cases where actual computations were performed while the final two are discussed qualitatively.

Finite Shield Thickness. The previous assumption of a small shield thickness was changed by assuming that the total shield occupied 20% of the total source-to-detector separation distance. The value of ϕ_{ss}/ϕ_{us} for the two-section split shield using this new assumption is 0.258. This is an increase over the previous value of 0.221, but it does not indicate any great error in using the previous assumption.

Anisotropic Scattering. The assumption of isotropic scattering within the shield sections was changed by assuming an angular distribution of scattering (see page 35). When this rough approximation for the scattering distribution is used, the minimum value of ϕ_{ss}/ϕ_{us} for the two-section shield increases to 0.485 and the optimum separation distance changes to approximately 20% of x. These results indicate that anisotropic scattering causes a large reduction in the relative value of the split scatter shield.

Throughout this report, it has been assumed that there is no energy degradation of the photons during scattering collisions. This, of course, is not true; and since the angular distribution of the scattered photons becomes more isotropic with lower energies, the later scatterings in a shield are more nearly isotropic (Ref 5:149). Also, if light-weight elements such as beryllium or hydrogen are used in the shield, the energy losses per collision are greater and the subsequent scatterings are again more isotropic. Thus, if the energy losses during scattering are considered, the previous assumption of isotropic scattering becomes better and the reduction in effectiveness of the split shield is not as large as indicated previously.

The scatter shield offers an additional advantage over a unit shield that has not been discussed previously. Because the scatter shield attenuates radiation primarily by scattering rather than by absorption, the heat generation problem in the shield will be greatly reduced. This is due not only to the smaller absorption of radiation, but, also, because the scatter shield offers a greater surface area for cooling than does the unit shield.

The results, as shown in this section, represent the values obtained using the method of analysis as described. This, of course, is not the only method possible and it is probable that with some modifications, the results would be changed somewhat. For example, it should be pointed out that placing the unit shield closer to the source, as is the case in most vehicles, would increase the advantage of the scatter shield. Also, if more scattering terms are included in the equations used for the parameter studies, the advantage of the scatter shield would probably be decreased slightly because of the different distance attenuation factors. However, even though the results shown here are not exact in nature, it is believed that they are representative of the values that can be expected in actual applications.

VI. Conclusions

The results of the studies on the various split shield configurations lead to the following conclusions,

(1) The split scatter shield offers a significant advantage in radiation attenuation over a unit shield of the same weight and material.

(2) The advantage of the split shield is dependent upon the required attenuation by the shielding system. As the required attenuation increases, the split shield offers greater advantages over the unit shield.

(3) The advantage of using the split scatter shield is strongly dependent upon the build-up of scattered radiation within the unit shield. Thus, when the build-up factor is small, the relative advantage of the split shield is not as great as when the build-up is large.

(4) The optimum number of sections in a split shield depends upon the required attenuation. For shields where only small attenuations are needed, a two-section split shield gives the maximum flux reduction, but for higher attenuations, the shield must be split into more sections for the maximum reduction.

(5) The optimum separation distance between any two shield sections varies with the total number of sections in the shield.

This distance is not sharply defined and no exact positioning of the shield sections is necessary.

(6) The split-shield sections give the maximum flux reduction when they are positioned symmetrically about the mid-point between the source and the detector as long as the photon scatterings are isotropic.

(7) The maximum advantage of the split shield depends upon the dimensions of the vehicle for which it is designed. When the distance between the source of radiation and the area to be protected is large in comparison to the lateral extent of the shield, the split shield gives a greater advantage over the unit shield than when this distance is small.

(8) The split shield effectiveness is strongly dependent upon the angular distribution of scattering within the shield.

Since the shield dimensions used in this report vary in only one direction, the thickness of the shield is proportional to the weight. Thus, the greater reduction in the flux through a scatter shield can be used in either of two ways. When weight is of primary importance, the scatter shield can be used to give a weight reduction while maintaining the same detector flux. On the other hand, for the same weight of shield, the scatter shield can be used to decrease the length of the vehicle.

The preceding conclusions show that definite weight savings for a space vehicle are possible through the use of split scatter shields. In order to further analyze this problem, it is recommended that studies be conducted with the aid of computing machines so that the angular distribution and energy degradation of the scattered radiation can be included. Future work in this area should include an investigation of the properties of various shielding materials so that the best material can be selected. Shaping of the shield sections should be analyzed to see if there is any possibility of increasing the advantage of the split shield through this means.

It is hoped that in the near future the problem of the split shield can be applied to an actual situation. If the results of that study continue to show as strong an advantage for the split shield as reported here, experimental facilities should be used to check the accuracy of the theoretical calculations.

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Vita

John Orrin Berga was born [redacted] the son of Oscar Berga and Edith [redacted] Berga. After completing his work in 1947 at [redacted], he entered the United States Naval Academy. He was graduated with the degree of Bachelor of Science and received his commission in the U.S. Air Force in June 1951. Prior to coming to the Institute of Technology (AU), he served as a B-26 navigator in Korea and as an instructor in Navigation in the Air Training Command and at the U.S. Air Force Academy.

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This thesis was typed by Mrs. J.H. Mann

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