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FINAL REPORT FOR UNMANNED SPACECRAFT RTG SHIELD OPTIMIZATION STUDY

For

Goddard Space Flight Center
Greenbelt, Maryland

NASA Contract Number: NAS5-11649

By

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Approved: E. A. Saltarelli

E. A. Saltarelli
Vice President and
Technical Director

TABLE OF CONTENTS

		Page
1.	INTRODUCTION	1
2.	THEORETICAL DESCRIPTION	4
	2.1 Introduction	4
	2.2 Theoretical Discussion	5
3.	CODE SØSC DESCRIPTION	18
	3.1 Introduction	18
	3.2 Code Logic	18
	3.3 Code Operating Information	22
	3.3.1 General	22
	3.3.2 Code Constants	24
	3.3.3 Card Input Details	25
	3.3.4 Code Output	41
	3.3.5 Discussion	47
4.	DESIGN OF EXPERIMENT	50
5.	SUMMARY AND CONCLUSIONS	54
REFERENCES		56
FIGURES		59
APPENDIX I	INTERACTION PHYSICS REVIEW	70
II	SUMMARY DESCRIPTION OF SUBPROGRAM NUGAM1	84
III	CODE SØSC FORTRAN LISTING	93
IV	CODE SØSC SAMPLE INPUT DATA LISTING	131
V	CODE SØSC SAMPLE OUTPUT DATA LISTING	135
VI	SUMMARY OF NUS-600 DETAIL EVALUATIONS	149

LIST OF FIGURES

Figure No.	Title	Page
1	Typical Unmanned Spacecraft	60
2	Schematic Drawing of Spacecraft Showing RTG Source, Shield and Detector Arrangement	61
3	Schematic Definition of Gamma Photon and Neutron Fluxes	62
4	Code SØSC Logic	63
5	Definition of Scattering Structure Coordinate Geometry	64
6	Code SØSC Routing Control Options	65
7	Energy Correspondence Bar Diagram	66
8	Source Term Fluxes at 687 cm From Tandem RTG's	67
9	Weight and Length of LiH + Pb Shield as a Function of LiH to LiH + Pb Length Ratio	68
10	Geometry for Proposed Experiment	69

SUMMARY

This contract final report discusses the development of analytic procedures and computer codes for the prediction of weight optimized radioisotope thermoelectric generator shields for unmanned spacecraft operating 'in vacuo'. An optimization code - - - SØSC, designed to determine shield optimum weights and dimensions with respect to specified criterion fast neutron plus gamma photon fluxes, is described. The code employs a combination of analytic, albedo and Monte Carlo techniques. A theoretical discussion and example predicted shield data are given as well as a proposed verifying experiment design.

1. INTRODUCTION

This final report, prepared for the National Aeronautics and Space Administration, GODDARD SPACE FLIGHT CENTER, by NUS CORPORATION, under Contract NAS5-11649, describes the analytic procedures and computer codes developed for prediction of weight optimized radiation shields for an unmanned spacecraft operating 'in vacuo'. The design of an experiment, to furnish data for comparison with and verification of predicted design, is also presented.

Analytic procedures and computer code logic have been combined to predict optimum weight shields for the protection of scientific experiments from the radiation fields of on-board radioisotope thermoelectric generators, during unmanned spacecraft missions. The optimum weight shield was determined as that exposing the science payload to a specified neutron plus gamma photon integral radiation number flux, when added to the spacecraft scattered radiation contribution. The angular-energy transport of radiation was obtained by an integrated combination of analytic, albedo and Monte Carlo techniques. This approach was considered as the most advantageous compromise for spacecraft engineering design purposes as opposed to the sole use of either a costly Monte Carlo calculation or a less accurate analytic approximation. The spacecraft assumed for the present study is presented schematically in Figure 1.

The work effort was specifically oriented to the radiation field at the energetic particle experiment package indicated in the spacecraft configuration of Figure 1, spacecraft general dimensions, deployment distances and materials were obtained from preliminary design drawings furnished by NASA-GSFC. The radioisotope thermoelectric generators (RTG's) were assumed to be plutonium-oxide fueled, viz. the SNAP-27.

A shield optimization study code --- SØSC was designed and developed to determine the shield material minimum thickness and weight required to limit the spacecraft mission experiment package to a specified radiation flux exposure, eg. ≤ 10 particles/cm^2-sec. The incident criterion flux was taken as the sum of gamma photons and neutrons either transmitted by the shield or scattered by the spacecraft structure. Code SØSC predicts shield requirements for the case of gamma photons, according to a combination of analytic transmission theory, the Monte Carlo transport method, the albedo technique (backscattering theory) and the single scattering approximation method. It employs three component sub-codes for this determination, namely: XEST, NUGAM1 and ALB.

Although code SØSC is provisionally designed to evaluate fast neutron transport in a manner similar to that for gamma photons, photon transport was emphasized in this stage of the NASA program. The code is presently designed to evaluate neutron transport using relaxation theory methods. This course for the case of the SNAP-27 was based on the fact that the RTG total neutron emission rate in the axially perpendicular direction was reported as being 5.7×10^7 n/sec[1]. This is in good agreement with, but less than an earlier NUS estimate of 1.0×10^8 n/sec reported in NUS-600[2]. Taking the gamma photon dose rate as one-tenth of the neutron dose rate and allowing for dose-to-flux conversion as well as spectral distribution gives an integrated RTG emitted photon source of $\sim 1.0 \times 10^9 \gamma$/sec, or approximately ten times that for neutrons. Data obtained late in the work program indicated a γ/n flux ratio of 1.8 and 18.0 for axial and radial emission, respectively. The 1.8 ratio indicates the neutron transport in the shield should be examined by a more exact method such as Monte Carlo.

Section 2 of this report presents the theory and logic on which code SØSC is based. Section 3 presents a description of the code and the necessary users input and output information. Section 4 presents a proposed design for a verifying laboratory experiment. Section 5 consists of a summary and conclusion with respect to the work reported. A brief review of the basic gamma photon and fast neutron physics required, is given in Appendix I while Appendix II recaps the basis of the Monte Carlo technique used.

2. THEORETICAL DESCRIPTION

2.1 Introduction

The radiation field emitted by an encapsulated plutonium oxide radioisotope thermoelectric generator (RTG) assembly consists primarily of an anisotropic polyenergetic distribution of gamma photons and fast neutrons. If RTG assemblies are boom mounted on a spacecraft, as depicted in Figure 1, then boom mounted science experiments packages may be exposed to excessive radiation fields. This radiation interference may be reduced by shielding the RTG's. If the spacecraft scattered radiation is not excessive then shadow shields may be used to reduce RTG radiation fluxes at the experiment to a criterion (acceptable) level. For a given shielding material the shield dimensions and thus weight, are optimized when the criterion flux is obtained. Further optimization may be obtained through judicious selection of materials and their deployment. In the event that the spacecraft scattered flux is excessive then additional RTG side shielding or geometrical redeployments must be considered.

In this report section the theoretical considerations of a method for determining the dimensionally and thus weight, optimized shield, consistent with the criterion flux condition, are presented. The discussion is restricted to the theory underlying the code developed for rapid predictions --- code SØSC; the code is described in Section 3.

The procedures developed use Monte Carlo technique, the albedo technique, single scatter approximation to best advantage to obtain an iterative solution of a basic transport relationship. Since code SØSC uses a modified version of the Monte Carlo code NUALGAM [3], the theory underlying the Monte Carlo code is reproduced in Appendix II, with revisions, from reference (3). This section then is concerned with the components and 'solution' of the basic transport expression. Although the discussion is general, the emphasis is given to photon transport, as stated in Section 1. It is proposed that neutron transport be evaluated in an analogous fashion in the future. In this regard neutrons are considered in the review of the transport relationship.

2.2 Theoretical Discussion

For the purposes of this section the complex spacecraft configuration shown in Figure 1 is redrawn schematically in Figure 2. Only one RTG source is indicated and the mission experiment package is referred to as a detector. In addition, the spacecraft body is replaced by a simpler geometry and the boom-arms omitted.

The radiation number flux at a detector distant r_O from a source $S(E_O)$, of neutrons or gamma photons E_O, as in Figure 2, without a shadow shield, may be defined as

$$\phi_D(E_D) = \phi\alpha(E\alpha) + \phi_O(E_O) \quad , \qquad (1)$$

where

$$\phi\alpha(E\alpha) = \phi\alpha_S(E\alpha_S) + \phi\alpha R(E\alpha_R) \quad ,$$

$\phi\alpha s(E\alpha_S)$ = the primary radiation number scattered to the detector by the area A composed of material j, distant r_1 and r_2 from the source and detector, respectively,

$\phi_{\alpha R}$ ($E_{\alpha R}$) = the 'area A'-originating reaction product flux reaching the detector,

= 0, for gamma photons as the primary radiation, excepting photoneutron interactions (γ,n),

ϕ_o (E_o) = the uncollided primary radiation number reaching the detector.

The energy arguments signify that the detected flux consists of radiation of primary energy E_o, scattered energies E_{α_s} ($<E_o$) and reaction product energies, E_R. The subscript α refers to the spacecraft structure as a secondary source, eg. scattering, i.e. to albedo fluxes.

The number flux reaching the detector <u>with</u> a shadow shield, composed of material i, as indicated in Figure 2, may be defined as

$$\phi_D (E_D) = \phi_\alpha (E_\alpha) + \phi_a (E_o; E_a) , \qquad (2)$$

where

ϕ_a (E_o; E_a) = the shield attenuated flux,

$$= \phi_a (E_o) + \phi_a (E_a) ,$$

ϕ_a (E_o) = the number flux transmitted by the shield without interaction,

$\phi_a\ (E_a) \quad = \phi_{as}\ (E_{as}) + \phi_{ap}\ (E_{ap}) + \phi_{aR}\ (E_{aR})$,

$\phi_{as}\ (E_{as})$ = the shield forward scattered radiation number flux reaching the detector,

$\phi_{ap}(E_{ap})$ = the gamma photon number flux resulting from pair production interactions in the shield,

= 0, for incident photon energies $E_o \leq 1.02$ MeV,

= 0, for incident neutrons,

$\phi_{aR}\ (E_{aR})$ = the shield-originating reaction product number flux reaching the detector, e.g. gamma photons resulting from (n,γ) interactions,

= 0, generally, for gamma photons as the primary radiation, excepting such as photoneutron interactions, i.e. (γ,n).

For fast neutrons as the primary incident radiation, the number flux terms $\phi\alpha_R\ (E\alpha_R)$ and $\phi_{aR}\ (E_{aR})$ in Equation (1) and (2) refers to all product radiations, eg. neutrons, gamma photons, alphas, protons, depending on the reaction probabilities for each.

The number flux terms in Equations (1) and (2) may be estimated either from a combination of analytic relationships and published empirical data or from experiment, either numerical analogue, ie. Monte Carlo method or the conventional laboratory kind. The sole use of the Monte Carlo method is considered as being uneconomical and unjustified. A laboratory experiment is planned for the future by NASA-GSFC as part of the overall program. The present work is thus confined to number flux predictions obtained by analytic methods and by published empirical data and judicious use of Monte Carlo techniques.

Neglecting the reaction product number flux terms for the present, the detector incident number flux may be written as

$$\phi_D\ (E_D) = \phi_a\ (E_o) + \phi_a\ (E_a) + \phi_{\alpha s}\ (E_{\alpha s})\ . \qquad (3)$$

For a normally incident parallel radiation flux $\phi_o(E_o)$, the uncollided number flux transmitted through a shield of thickness L and reaching the detector, is obtained as

$$\phi_a\ (E_o) = \phi_o\ (E_o)\ e^{-\mu(E_o)\cdot L}\ , \qquad (4)$$

where

$\mu\ (E_o)$ = the total linear attenuation coefficient of the shield material for radiation of energy E_o; the notation Σ is generally used for neutrons.

The ratio of the shield total-to-uncollided transmitted flux is referred to as "build-up". The build-up factor may thus be defined as

$$B\ (E_o, L) = \frac{\phi_a\ (E_o) + \phi_a\ (E_a)}{\phi_a\ (E_o)} = \frac{\phi_a\ (E_o, E_a)}{\phi_a\ (E_o)}\ . \qquad (5)$$

The total shield transmitted flux at the detector may be obtained from Equations (4) and (5) as

$$\phi_a\ (E_o; E_a) = B\ (E_o, L)\ \cdot\ \phi_o\ (E_o)\ \cdot\ e^{-\mu(E_o)\cdot L}\ , \qquad (6)$$

if the build-up factor is known.

Although energy and dose build-up factors may be obtained for gamma photons[4,5] and to a lesser degree for fast-neutrons they pertain in almost all cases to semi-infinite single-material-composition shields. For small finite shields, i.e. shadow shields, and number flux requirements as opposed to energy and dose, recourse to either a laboratory experiment or a Monte Carlo study is a prerequisite. In the present work a Monte Carlo evaluation is underway for gamma photons and proposed for fast-neutrons.

For a spectrum of incident source particle energies the shield transmitted flux is obtained by integration as

$$\Phi_a (E_a) = \int_0^\infty \phi_a (E_o, E_a) \, d E_o \quad , \tag{7}$$

$$\simeq \sum_{k=1}^{q} \phi_a (E_{ok}, E_a) \, \Delta E_k \tag{8}$$

For a stratified or homogenous shield composed of m materials, each of thickness ℓ_i, Equation (8) may be rewritten

$$\Phi_a (E_a) \simeq \sum_{k=1}^{q} \phi_o (E_{ok}) \prod_{i=1}^{m} B (E_o, \ell_i) \, e^{-\mu_i (E_{ok}) \ell_i} \quad , \tag{9}$$

$$= \sum_{k=1}^{q} \phi_o (E_{ok}) \cdot B (E_o)_m \prod_{i=1}^{m} e^{-\mu_i (E_{ok}) \cdot \ell_i} \quad , \tag{10}$$

where

$B (E_o)_m$	=	the build-up factor for the composite shield of m materials and incident radiation of energy E_o, and given geometry,
i	=	material identity index,
k	=	energy group index,
q	=	number of energy groups.

The uncollided number flux in the foregoing equations may be determined from a relationship of the kind

$$\phi_o (E_o) = \phi_o (E_o, r_o) = S (E_o) \cdot G (r_o) \quad , \tag{11}$$

where

$S(E_o)$ = source emission rate for radiation of energy E_o,

$G(r_o)$ = the geometry relationship for a source-to-detector distance r_o.

For example, for an isotropically emitting point source and $r_o >>$ detector lateral extent, the geometry factor is

$$G(r_o) = (4\pi r_o^2)^{-1} . \tag{12}$$

Extended source and detector geometries may be evaluated according to the 'Point-Kernel Method'[(4)].

The number flux term, $\phi_{\alpha s}(E_{\alpha s})$ in Equation (3), resulting from primary gamma photons scattered by an area A, as in Figure 2, may be redefined as

$$\phi_{\alpha s}(E_{\alpha s}) = \int_A \phi_{\alpha s}(E_o, \theta, \theta_o, \varphi, r_1, r_2, t; i)\, dA, \tag{13}$$

where

dA = the differential scattering area,

θ_o = the angle between the incident radiation direction and the outward normal of area dA,

θ = the angle between the emergent (scattered) radiation direction and the outward normal of area dA,

φ = the azimuth angle of scattering in the plane of area A,

r_1 = the distance between the source and the area dA,

r_2 = the distance between the area dA and the detector,

t = the thickness of the scattering material at area dA, measured along the inward normal to dA,

i = the identity index of the material of which dA is a part.

For a spectrum of source particle energies the energy integrated flux, $\Phi_{\alpha s}(E_{\alpha s})$, may be obtained by an integration similar to that of Equations (7) and (8), as

$$\Phi_{\alpha s}(E_{\alpha s}) = \int_0^\infty \phi_{\alpha s}(E_{\alpha s})\, dE_o \quad . \tag{14}$$

The flux term in the integrand of Equation (13) may be defined according to albedo theory as[4,6]

$$\phi_{\alpha s}(E_{\alpha s}) = \phi_o(E_o, r_1) \cdot \frac{\cos\theta_o \cdot dA \cdot \alpha(E_o, \theta_o, \theta, \varphi, t; i)}{r_2^2} , \tag{15}$$

where

$\alpha(E_o, \theta_o, \theta, \varphi, t; i)$ = the angular differential number current albedo with respect to the noted arguments (defined for Equation (13)),[4,6]

$\phi_o(E_o, r_1)$ = number flux incident on area dA,

= $S(E_o) \cdot G(r_1)$, c.f. Equation (11).

The assumption underlying the use of the albedo technique for complex geometry analysis is that the scattered radiation particles emerge from the scattering medium surface at a point close to their point of entry. This assumption is generally justified[4], eg. the separation distance between entry and exit for one-half of all escaping gamma photons has been found to be less than one mean-free-path (for incident energy E_o). Photon scattering from very thin or laterally small structures of volume V, may be alternately predicted by the single-scattering approximation method[7], from the relationship

$$\phi_{\alpha ss} = \int_V \phi_0 (E_o, r_1) \cdot \frac{N_e \cdot \sigma_{KN} (E_o, \theta_s)\, dV}{r_2^2} , \qquad (16)$$

where

N_e = the scattering material electron density per cubic centimeter,

$\sigma_{KN} (E_o, \theta_s)$ = the Klein-Nishina angular-energy intensity distribution function[4], for photons of energy E_o and scattering angle θ_s,

θ_s = the angle between the primary and scattered photon directions.

Equation (15) may be solved if values for the number albedo are known. The albedo may be determined by either a laboratory experiment or a Monte Carlo treatment. For gamma photons, recently developed modification of the moments method has been reported as a potential source of albedo data[8]. In the present work, experimental albedo data[9,10], and empirical relationships in accord with both experimental and Monte Carlo results[4,6,11,12], were used for gamma photons. A similar approach is proposed for the case of fast-neutrons.

Since weight is the product of volume and density, the weight optimization of an axially symmetric shadow shield of specified composition may be considered as an optimization of shield thickness, L_{min}, such that

$\phi_D\,(E_D)_{\gamma,n} \le C$, where C is a specified criterion, eg. 10 particles/cm^2-sec. The optimum, or minimum weight of a right-cylindrical shield of radius R_s, may be obtained as

$$W_{min} = \pi R_s^2\, L_{min} \cdot \rho\ , \tag{17}$$

$$= \pi R_s^2 \sum_{i=1}^{m} \ell_{i_{min}} \cdot \rho_i\ , \tag{18}$$

where

ρ_i = the density of shield material i,

ρ = the weighted density of the shield,

= the shield material actual density if $m = 1$.

The total number flux reaching the detector for the case of a polyenergetic source, is obtained from Equation (2) doubly integrated over primary and secondary energies, as

$$\Phi_D = \int_{E_D} \Phi_D\,(E_D)_{\gamma,n} dE_D = \int_{E_o,E\alpha} \phi_\alpha(E\alpha)_{\gamma,n}\, dE_o dE_\alpha + \int_{E_o,E_a} \phi_a(E_o;E_a)_\gamma\, dE_o dE_\alpha +$$

$$+ \int_{E_o,E_a} \phi_a\,(E_o;E_a)_n\, dE_o dE_\alpha\ , \tag{19}$$

where the subscripts γ and n denote gamma photons and fast neutrons. The use of the albedo and build-up factor concepts is tantamount to an integration over E_α and E_a, respectively.

Equation (19) may be further redefined as

$$F = \int_{E_o,E_a} \phi_a\,(E_o;E_a)_\gamma\, dE_o dE_a + \int_{E_o,E_a} \phi_a(E_o;E_a)_n dE_o dE_a\ , \tag{20}$$

where

$$F = \int_{E_D} \phi_D(E_D)_{\gamma,n} dE_D - \int_{E_o, E_\alpha} \phi_\alpha(E_\alpha)_{\gamma,n} dE_o dE_\alpha \quad , \qquad (21)$$

$$= C - \int_{E_o, E_\alpha} \phi_\alpha(E_\alpha)_{\gamma,n} \, dE_o dE_\alpha \quad . \qquad (22)$$

The flux terms in Equation (20) may be obtained from Equations (10) and (13) and L_{min} obtained by an iterative solution. For example, for a single material shield exposed to a monoenergetic source of neutrons and photons, Equation (20) reduces to

$$F = \phi_o(E_o)_\gamma \, B(E_o)_\gamma \, e^{-\mu(E_o)_\gamma L} + \phi_o(E_o)_n \, B(E_o)_n \, e^{-\mu(E_o)_n L} \qquad (23)$$

The foregoing theoretical discussion has presumed a knowledge of gamma photon and fast neutron interaction phenomena. Such phenomena and the relevant interaction physics are summarily reviewed in the Appendix I. In addition, a familiarity with the solution of radiation transport problems by means of the Monte Carlo method is presumed; the reader is referred to the references in this regard[13,14].

The second term in the right-side of Equation (20) is defined by Equation (2). It includes the shield originating neutron-reaction product flux $\phi_{aR}(E_{aR})$, as yet not discussed in any detail. Although the flux $\phi_{aR}(E_{aR})$ reaching the detector, may be predicted by means of either a laboratory experiment or a Monte Carlo code evaluation, it may be estimated for the case of reaction product gamma photons such as result from fast neutron inelastic scatters or absorptions in an axially symmetric shadow shield, as

$$\phi_{aR}(E_{aR}) = \int_0^L g \cdot G(r_\ell) \cdot \Sigma_\gamma(E_o) \cdot \phi_o(E_o)_n \cdot (1-e^{-\lambda\tau}) \cdot e^{-\Sigma_{Tot}(E_o)\ell} \cdot e^{-\mu(E_{aR})(L-\ell)} d\ell , \qquad (24)$$

where

g = the cross-section area of the axially symmetric shadow shield,

	=	πR_s^2, for a cylindrical shield,
ℓ	=	the distance from the shield face at the source to the differential volume $g.d\ell$ (see Figure 3),
$G(r_\ell)$	=	the geometry factor for distance r_ℓ, c.f. Equation (11),
r_ℓ	=	the distance from the differential volume $g.d\ell$ to the detector (see Figure 3),
$\Sigma_\gamma(E_o)$	=	the linear attenuation coefficient of the shield material for fast-neutrons of energy E_o, for production of gamma photons,
$\Sigma_{Tot}(E_o)$	=	the total linear attenuation coefficient of the shield material for fast-neutrons of energy E_o,
$\phi_o(E_o)_n$	=	the shield normally and parallel incident flux of fast neutrons of energy E_o,
	=	$\phi_o(E_o,(r_o-r_\ell))_n$, c.f. Equation (11),
$\mu(E_{aR})$	=	the total linear attenuation coefficient of the shield material for reaction product gamma photons of energy E_{aR},
λ	=	the radioactive decay constant of the reaction-produced or compound nucleus,
τ	=	the duration of exposure to the neutron flux.

For inelastic scattering the decay constant in Equation (24) is relatively large and thus

$$1 - e^{-\lambda\tau} \simeq 1.0 \quad (25)$$

This is also true for activation where the product $\lambda.\tau$ is large.

Considering again the primary radiation emitted by the sources, a modified form of Equation (24), where g, ℓ, r_ℓ and the exponent $\mu(E_{aR})(L-\ell)$ are replaced by dA, t, r_2 and $\mu(E_{\alpha R}).t$ respectively, may be defined as

$$\phi_{\alpha R}(E_{\alpha R}) = \int_0^t dA.G(r_2).\Sigma\gamma(E_O).\phi_O(E_O, r_1)_n(1-e^{-\lambda\tau})e^{-\Sigma_{Tot}(E_O)t}.e^{-\mu(E_{\alpha R})t}dt, \quad (26)$$

to estimate the spacecraft structure reaction product 'albedo', α_R for prediction of fluxes, $\phi_{\alpha R}(E_{\alpha R})$; αR is analogous to α of Equation (15) for $(\theta_O, \theta, \varphi) = (0, 0, 0)$. This albedo, valid for normal incidence and emergence, may be used as in Equation (29) of Section 3.2, to estimate the angular differential albedo. Primary and secondary energy integrations of Equations (24) and (26) are as defined for Equation (20).

The shadow shield as a secondary source of both photons and neutrons, ie. scattered and reaction product radiation, has been discussed. Scattering to the detector may be accounted for either by the use of the build-up factor concept or a Monte Carlo analysis and reaction product radiation intensity may be predicted by the use of Equation (24) or a Monte Carlo analysis.

In addition to being a second order source, the shield may also be considered a third order source, ie. primary radiation interacting in the shield may produce secondary radiation which in turn may interact with the spacecraft structure to yield a third order flux at the detector.

The detected flux resulting from such interactions in the spacecraft structure may be predicted in accord with either Equations (15), (16) or (26) and discussions thereto, providing the shield-originating flux $\phi_0(E_{aR}, r_1 \text{ shield}) = \phi_0(E_{aR}, r_{1s})$, is known and substituted for $\phi_0(E_o, r_1)$. The night-cylindrical shield originating flux in the axially perpendicular direction, may be estimated as

$$\varphi_0 (E_{aR}, r_{1s}) = \int_0^L f(R_s, r_{1s}, E_{aR}) \cdot \Sigma_\gamma(E_o) \cdot \phi_0(E_o)_n (1-e^{-\lambda T}) \cdot e^{-\Sigma_{Tot}(E_o)\ell} d\ell , \quad (27)$$

where the function $f(R_s, r_{1s}, E_{aR})$, valid for $\ell \ll r_{1s}$, takes the shield self-absorption into account. This function is defined for the cylinder as

$$f(R_s, r_{1s}, E_{aR}) = \frac{g}{2\pi} \int_0^{\beta} d\beta \int_{y_1}^{y_2} \frac{e^{-\mu(E_{aR})(y-y_1)}}{y} dy , \quad (28)$$

where

y_1 = $r_{1s} \cos \beta - R_s \cos \psi$,

y_2 = $r_{1s} \cos \beta + R_s \cos \psi$,

ψ = $\pi - \sin^{-1}(\frac{r_{1s} \sin \beta}{R_s})$,

y = integration variable; a distance,

β = integration variable, an angle,

β_1 = the limit, $\sin^{-1} (R_s/r_{1s})$

r_{1s} = the shield-to-spacecraft 'area dA' distance; analogous to r_1 (see Figure 3).

For reasons of clarity the fluxes discussed in this report section are schematically summarized in Figure 3.

3. CODE SØSC DESCRIPTION

3.1 Introduction

This report section describes the general logic, user information and preliminary results obtained using code SØSC, a spacecraft shield optimizing study code, a code written in the FORTRAN-IV language for the IBM-360/91 digital computer. Code SØSC consists of three distinct component code complexes: XEST, NUGAM1 and ALB. Code XEST predicts approximate shield dimensions based on analytic methods. Code NUGAM1 predicts shield buildup factors for final shield dimensions, by the Monte Carlo method. Code ALB determines flux intensities resulting from scattering by the spacecraft structure, based on the albedo technique and/or the single scatter approximation.

The code may be optionally run to evaluate spacecraft scattering only or instead to optimize the shadow shield, neglecting spacecraft scattering. Thus if the scatter contribution is already known then it may be input instead of calculated and the shield optimization carried out.

Code SØSC logic is presented in Section 3.2. Code SØSC consists of a main controlling program --- MAIN, a shield thickness prediction program --- XEST, a complex geometry scatter flux program --- ALB, and a Monte Carlo buildup factor calculating program --- NUGAM1. Development work on these programs focussed on gamma photon transport as noted in Section 1 of this report. Neutron transport was coded according to 'removal' theory[4,15].

3.2 Code Logic

MAIN executes input and final output operation. Details of the input-output are given in Section 3.3.3. The main programs call ALB to determine F for Equation (20). It calls XEST to estimate an approximate thickness value, L_{min_e}, for Equation (20). The Monte Carlo code, NUGAM1, is called to determine buildup factors corresponding to the estimated value of L_{min_e}. Using the thus determined values of F and the buildup factors, the code solves Equation (18) for the optimum thickness L_{min}, by iteration. It will optionally recall NUGAM1 to determine the deviation of the buildup factors for L_{min} from those for L_{min_e}. If this deviation exceeds a tolerance value the code will reiterate. Iteration may be arrested at any loop number specified by the user. Code SØSC logic is summarized in Figure 4.

Code ALB determines the angular-energy integrated flux scattered to the detector by the spacecraft complex structural components illuminated by primary source radiation. Code ALB consists of an albedo package and a generalized geometry package. In its present form the albedo package is only coded for gamma photons because of the lack of fast neutron differential number albedo data. It is proposed to generate fast neutron data according to the Monte Carlo technique, in the future.

The albedo routines in code ALB determine the scattered energy integrated flux $\phi_{\alpha s}(E_{\alpha s})$ defined by Equation (13). The main calling program carries out the integration over primary source energies. The gamma photon number current albedos defined by Equation (15) were obtained from the relationship

$$\alpha(E_o,\theta_o,\theta,\varphi,t;i) = \alpha(E_o,0,0,0,\infty;i)\ .f(\theta_o)\ .\cos\theta\ .g(t)\ , \tag{29}$$

$$= \alpha(E_o;i)\,.f(\theta_o)\,.\cos\theta\ .g(t)\ , \tag{30}$$

where

$\alpha(E_o;i)$ = the angular differential number current albedo for gamma photons perpendicularly incident (θ_o=0) and emergent (θ=0) from scattering material i, ie. 180^o (=θ_s) backscatter,

g(t) = a function to account for reduced backscattering from a material of finite thickness t,

$f(\theta_o)$ = a function to account for the albedo behaviour with change in θ_o .

From reference (16), the azimuthal dependence may be defined in terms of θ, θ_o and the total scattering angle θ_s, as

$$\varphi = \cos^{-1}\left[\frac{\cos\theta_s + \cos\theta_o\cos\theta}{\sin\theta\,\sin\theta_o}\right]$$

where

θ_s = the angle between the incident and emergent photon vectors, i. e., the scattering angle.

The present version of code ALB assumes[9,10,12]

$$f\,(\theta_o) = \text{Cos}\,\theta_o \quad , \tag{31}$$

and[11]

$$g\,(t) = \alpha(E_o, t; i) \;/\; \alpha(E_o; i) \quad , \tag{32}$$

$$= 1 - e^{-ct} \quad , \tag{33}$$

where c is a constant such that g(t) = 0.99, for $t = 2\lambda\,(E_o)_i$; $\lambda\,(E_o)$ is the mean-free-path in material i for photons of energy E_o. Code ALB uses scattering angle θ_s to eliminate the albedo dependence on azimuth φ, in accord with the method of reference (16).

Experimentally measured values for the perpendicular differential number current albedo $\alpha\,(E_o; i)$, obtained from references (9,10), were encoded. For fast neutrons, Monte Carlo data from reference (12) was used for preliminary evaluations.

The code ALB geometry routines require that the spacecraft structure be defined in terms of the spatial coordinates of simple geometrical shapes, e.g. cylinders, tubes, boxes, slabs, etc. These shapes allow the flat-sided cylindrical spacecraft body, boom-arms, antennae, science platforms, etc. to be accounted for. Coordinates are specified with respect to a reference Cartesian coordinate frame as shown in Figure 5. The Cartesian frame may be located arbitrarily but the spacecraft vertical axis is suggested for the Z-axis of the frame. From an engineering standpoint, coordinates may be readily obtained from preliminary or final design drawings. The code determines whether the radiation illuminated surfaces are visible to the detector. It subdivides cylindrical regions radially into planar strips for albedo determinations. The dimensions of the strips are determined as a function of the specific cylinder radius with respect to distance from source and detector. The lateral extent of all plane areas is subdivided into dimensions which are small relative to distance from source and detector. Cylindrical scattering may be optionally carried out according to either the albedo or single scatter methods. Booms are evaluated using the single scatter technique. Wall thickness must be specified for all volume geometries; solids may be specified by taking the wall thickness equal to the radius for a cylinder or the half-breadth in the case of a box.

Code XEST determines the value of L_{min} satisfying equation (20) and thus obtains W_{min} of equation (17), or the ℓi_{min} of equation (18). Although specifically designed for the purpose of shadow shield optimization it is coded for larger shields. Code XEST solves equation (20) by the technique of iteration. For the first iteration the code assumes a build-up factor of unity to determine $L_{min_e}{}^{(1)}$. For the second iteration a Monte Carlo build-up factor based on $L_{min_e}{}^{(1)}$ and calculated by NUGAM1 is used to iterate $L_{min_e}{}^{(2)}$. Iteration is arrested when

$$\left| \left(L_{min_e}{}^{(h)} - L_{min_e}{}^{(h-1)} \right) \right| / L_{min_e}{}^{(h)} \leq \epsilon , \qquad (34)$$

where

ϵ = preassigned tolerance,

h = iteration number.

3.3 CODE OPERATING INFORMATION

3.3.1 General

Code SØSC is written in FORTRAN-IV for the NASA-GSFC IBM-360/91 digital computer. It may be run on any IBM-360 with sufficient core size, ie. the present version requires bytes, (4 bytes/word). There are no Sense Switch or special tape requirements. Input formats are standard FORTRAN-IV, as given in any IBM or CDC Fortran manual; the code has been designed with a view to ease of translation for use on other than IBM computers. Input/output tapes are presently coded as LI and LØ equal to 5 and 6, respectively, at the beginning of MAIN. A code listing is given in Appendix III.

Section 3.3.2 defines the constants appearing in the various subroutines throughout the code. Input card details, order, formats, restrictions and location are given in Section 3.3.3. Card numbers are encircled and defined in the order in which they are read by the code. A sample input listing is presented in Appendix IV. Code output is reviewed in Section 3.3.4. Section 3.3.5 is a discussion of the results obtained with code SØSC. Appendix V is a sample output listing. It corresponds to the sample input of Appendix IV. Debug type output may be obtained by input of card 3. The user is cautioned with respect to profusion of output under this option --- a trial using sample data is recommended first. The code SØSC input data card deck consists of twenty-two (22) types of cards, referred to as Card 1, Card 2, etc. If the type requires more than a single card the reference is made to Card Set ◯.

Code NUGAM1 determines the angular energy transport of gamma photons in a finite cylindrical shield. It was derived from an existing Monte Carlo source self-absorption code --- NUALGAM, developed for NASA-GSFC by NUS Corporation, and described in NUS-536[3]. This code follows photon transport and considers pair-production, Compton scattering and photo-electric interaction phenomena. A description of this code is given in Appendix II. In code NUGAM1, the shield may be composed of a single material of simple or complex composition or stratifications i.e. "discs", of simple or complex composition, including vacuum. The code is presently designed for either an axial point or plane parallel source but may be readily adapted to other distributions. Similarly, the code may be readily modified to allow the study of annular-cylindrical shields, rectangular slabs, etc.

The source spectral distribution may consist of a large number of photon energy groups. In order to reduce costly Monte Carlo evaluation at each energy the code may be restricted to user selected energy groups in the energy domain. Intermediate energy evaluations over the source spectrum are obtained by quadratic interpolation.

Code NUGAM1 may be used to determine angular differential forward build-up for gamma photons. Preliminary studies with this code, which may be either called by code SØSC or used as a separate code, have revealed that the forward buildup factor for the shadow shields is less than that to be expected for a large (semi-infinite) shield, in agreement with qualitative argument.

3.3.2 Code Constants

The constant 0.51097 is required for energy conversion from MeV to the unit of electron rest mass. This value appears in subroutines DCØMP, GENSIG, ØUTPUT, SINGSC SPECTM, and XEST.

The constants PYE, RADAP and CMPI are coded in MAIN and communicated by CØMMØN/CØNST/ and CØMMØN/CØRDS/. They are defined as PYE = π = 3.14159, RADAP = factor for conversion of angles from degrees to radians, CMIP = factor for conversion from cm to inch.

The Avogadro number, 0.6023×10^{24}, is used in subroutines GENSIG and NENSIG.

The constant value 0.28183×10^{-12} cm used in subroutine CIGMA is the classical electron radius, r_o.

The constant value 0.49895×10^{-24} used in subroutine SIGMA is equal to $2\pi r_o{}^2$.

The experimental albedo data used in subroutine ALBEDØ are given in reference (9). The number albedos DAØN, the corresponding energies EE and the atomic number MN of the scattering medium are coded in the DATA statements in ALBEDØ.

The value 0.69314718 in subroutine INDEX is the natural logarithm of 2. Gamma photon and fast neutron cross-sections input data may be taken directly from the references (17, 18, 19, 20, 21, 22).

3.3.3 Card Input Details

NAME	COLUMN	FORMAT	DESCRIPTION, PURPOSE OR USE

Card 1 (single card to define the problem case path; 18I4; MAIN)

(NPATH (I), 18)	1-4, 5-8, etc.	I4	Execution path options (see Figure 6 for specific integer values)

Card 1-1 (single card; 6F10.4; MAIN)

XS	1-10	F10.4	Cartesian coordinates (x,y,z,) of the source geometric center (inches)*.
YS	11-20	F10.4	
ZS	21-30	F10.4	
XD	31-40	F10.4	Cartesian coordinates (x,y,z) of the point detector eg. science package (inches)*.
YD	41-50	F10.4	
ZD	51-60	F10.4	
RADIUS	61-66	F6.3	Radius of shield (inches).
DIST	67-72	F6.3	Source to shield distance (inches).

*The reference Cartesian frame (and its origin) are located by the user as described in Section 3.2.

Card 2 (single card; 3I5, F10.5; MAIN)

NE	1-5	I5	Number of gamma source spectrum energy increment midpoints (≤20).
NG	6-10	I5	Input card option signal: =0, gamma source only, ie. input card sets 3 and 4. =1, neutron source only, ie. input card sets 5 and 6 . =2, gamma and neutron source, ie. input cards sets 3 through 6.

NAME	COLUMN	FORMAT	DESCRIPTION, PURPOSE OR USE
NNE	11-15	I5	Number of fast neutron source spectrum energy increment mid-points (≤20).
INE	16-20	I5	Number of equal energy intervals in escape spectrum from in the range 0 to EE(NE) (≤25).
NØPT	21-25	I5	Option for intermediate output =0, no intermediate output, ±0 intermediate output and NGAMA set equal to 100.
NRAND	26-30	I5	Initial random number (must be odd number and different for each job submitted)
NØES	31-35	I5	Number of indices (and history multipliers) in card set 2 -1 and -2; ≤INE.
ALLØWF	36-42	F7.4	Total number flux allowed at the detector, $(\gamma + n)/cm^2$-sec.
ECT	43-49	F7.4	Low energy cut-off (MeV).
ARREST	50-56	F7.4	The iteration arresting criterion, ϵ, as in Equation (34) and Figure 4; a fraction.
TANDEM	57-63	F7.4	The number of tandem sources, ie. final data is multiplied by TANDEM, eg. = 2 for configuration of Figure 1.
FRG	64-70	F7.4	Gamma photon source axial-to-radial emission ratio; axial is in source-to-detector direction.

NAME	COLUMN	FORMAT	DESCRIPTION, PURPOSE OR USE
FRN	71-77	F7.4	Fast neutron source axial-to-radial emission ratio.

Card Set 2 -1 (single card input only if NE > 4; 20I4; MAIN)

LE(1)	1-4	I4	Index of source spectrum first selected energy mid-point at which a buildup factor is to be determined by code NUGAM1; intermediate index values will be code interpolated (first energy is lowest energy).
LE(2)	5-8	I4	Ditto For second selected energy midpoint
LE(NØES)		I4	Ditto for NØES selected energy midpoint

Card Set 2 -2 (single card; 20F4.0; MAIN)

HGAMA (1)	1-4	F4.0	Multiplier for obtaining the number of Monte Carlo his-tories (in thousands) to be generated at the selected energy index LE(1); eg. HGAMA(1) = 3.0 generates 300 3000 histories.
NGAMA (2)	5-8	F4.0	Ditto for LE(2)
HGAMA (NØES)		F4.0	Ditto for LE(NOES)

NAME	COLUMN	FORMAT	DESCRIPTION, PURPOSE OR USE

Card Set 3 ((NE/12) + 1 cards*; 12F6.2; MAIN)

EE(1)	1-6	F6.2	Gamma photon source spectrum energy at first (lowest energy) increment mid-point (MeV).
EE(2)	1-6	F6.2	Ditto for second energy
.			
.			
EE(12)	7-12	F6.2	Ditto for twelfth energy
EE(NE)	-	F6.2	Ditto for NE energy

*NE/12 = 0 if NE < 12; = 1 if 12 ≤ NE < 24; etc. This iteger meaning applies throughout Section 3.3.

Card Set 4 ((NE/7) + 1 cards; 7F10.3; MAIN)

SS(1)	1-10	F10.3	Gamma photon source isotropic emission rate corresponding to energy EE(1); (photons/second).
SS(2)	11-20	F10.3	Ditto for EE(2)
.			
.			
.			
SS(7)	61-70	F10.3	Ditto for EE(7)
.			
.			
.			
SS(NE)	-	F10.3	Ditto for EE(NE)

NAME	COLUMN	FORMAT	DESCRIPTION, PURPOSE OR USE

Card Set 5 ((NNE/7) + 1 cards; 7F10.3; MAIN)

EN(1)	1-10	F10.3	Fast neutron source spectrum energy at first (lowest energy) increment mid-point (MeV).
EN(2)	11-20	F10.3	Ditto for second energy
.			
.			
EN(7)	61-70	F10.3	Ditto for seventh energy
.			
.			
.			
EN(NNE)	-	F10.3	Ditto for EN(NNE)

Card Set 6 ((NNE/7) + 1 cards; 7F10.3; MAIN)

SN(1)	1-10	F10.3	Fast neutron source isotropic emission rate corresponding to energy EN(1) (n/second).
SN(2)	11-20	F10.3	Ditto for EN(2)
SN(7)	61-70	F10.3	Ditto for EN(7)
.			
.			
.			
SN(NNE)	-	F10.3	Ditto for EN(NNE)

Card 7 (single card; I2; ALB)

NØRF	1-2	I2	Number of spacecraft scattering structural members in the problem model, ie defines the number of times card sets 8 through 15 are to be repeated; card sets

NAME	COLUMN	FORMAT	DESCRIPTION, PURPOSE OR USE
			11 through 13 not input the M value repeated (structual material unchanged).

Card 8 (single card; A22; ALB)

STRUCT	1-8	"A8"	Alphanumeric name of spacecraft scattering member geometry, eg. BOOM, CYLINDER, etc.
PØINT	9-16	"A8"	Alphanumeric name of spacecraft scattering member identi fier or label, e.g. M-F.
RMAT	17-22	"A6"	Alphanumeric name of spacecraft scattering member material, eg. IRON, LEAD, etc.

Card 9 (single card; I1, I4, 2I5, 3F10.5; ALB)

NNNN	1	I1	The number of spacecraft scattering member material elements, eg. = 2 for Al_2O_3. (assumed =1 if input omitted)
M	2-5	I4	Atomic number of spacecraft scattering material.
IP	6-10	I5	Number of Cartesian coordinate points required to describe spacecraft scattering member, eg. = 2 for cylinder. (see Figure 5).
IK	11-15	I5	Spacecraft scattering member geometry identifier: = 0 , plane = 1 , boom arm or cylinder = 2 , rectangular box structure

NAME	COLUMN	FORMAT	DESCRIPTION, PURPOSE OR USE
T2	16-25	F10.5	Spacecraft scattering member thickness for plane or outer radius for cylinder or boom (inches).
T1	26-35	F10.5	Spacecraft scattering member inner radius for cylinder or boom; not required for plane (inches).
Tb	36-45	F10.5	Photon scattering method option: $\mp$ 0 , albedo method = 0 , single scattering method if IK = 0 or1.
NT	46-50	I5	Single to signify the direction of the outward normal for plane (see Figure 5) = + 1 , if origin (0,0,0) of Cartesian frame is within material defined by surface = - 1 , if origin outside (and thus "viewing") the plane = 0 or blank, if IK = 0 (i.e. not a plane).

Card Set 10 ((IP/3) + 1 cards; 9F8.5; ALB)

NAME	COLUMN	FORMAT	DESCRIPTION, PURPOSE OR USE
X(1)	1-8	F8.5	Cartesian coordinates (x,y,z,) of first point required to describe location of spacecraft scattering member (inches)*. (See IP of Card Set 9 and Figure 5).
Y(1)	9-16	F8.5	
Z(1)	17-24	F8.5	
.			
.			
.			

*The order of input of the coordinates must be clockwise "viewing" each surfact from "outside" the volume; the input order for surfaces may be arbitrary.

NAME	COLUMN	FORMAT	DESCRIPTION, PURPOSE OR USE
X(IP)	-	F8.5	Cartesian coordinates (x,y,z) of IP^{th} coordinate point required to describe location of spacecraft scattering member (inches). (see IP of Card Set 9 and Figure 5).
Y(IP)	-	F8.5	
Z(IP)	-	F8.5	

Card 11 (single card; 3I5; GENSIG) (See Figure 7)

NAME	COLUMN	FORMAT	DESCRIPTION, PURPOSE OR USE
NINT	1-5	I5	Gamma photon cross-section table parameter; $_2$NINT energy intervals/group.
ILØW	6-10	I5	Cross-section table parameter; $2^{IL\emptyset W}$ is lowest energy bound of table (m_oc^2 units).
IHIGH	11-15	I5	Cross-section table parameter; 2^{IHIGH} is highest energy bound of table (m_oc^2 units).

Card 12 (single card; I5,3F10.5; GENSIG)

NAME	COLUMN	FORMAT	DESCRIPTION, PURPOSE OR USE
ME	1-5	I5	The number of energies for which cross-section data to be input.
DENSTY	11-20	F10.5	The density of the medium element for which cross-section data to be input (gm/cc).
ATØMNØ	21-30	F10.5	The atomic number of the medium element for which cross-section data to be input.
ANDAW	31-40	F10.5	The atomic weight of the medium element for which cross-section data to be input.

NAME	COLUMN	FORMAT	DESCRIPTION, PURPOSE OR USE
Card Type 13 ((ME/3) + 1 cards; 9E8.3; GENSIG)			
E(1)	1-8	E8.3	First (lowest) energy for input of cross-section data (MeV).
SIGPE(1)	9-16	E8.3	Photoelectric cross-section for energy E(1), (barns/atom).
SIGPP(1)	17-24	E8.3	Pair-production cross-section for energy E(1), (barns/atom).
E(2)	25-32	E8.3	Similar to E(1)
SIGPE(2)	33-40	E8.3	Similar to SIGPE(1)
SIGPP(2)	41-48	E8.3	Similar to SIGPP(1)
E(3)	49-56	E8.3	Similar to E(1)
SIGPE(3)	57-64	E8.3	Similar to SIGPE(1)
SIGPP(3)	65-72	E8.3	Similar to SIGPP(1)
E(4)	1-8	E8.3	Similar to E(1)
.			
.			
.			
E(ME)	-	E8.3	Highest energy for input of cross-section data (MeV).
SIGPE(ME)	-	E8.3	Photoelectric cross-section for energy E(ME) (barn/atom).
SIGPP(ME)	-	E8.3	Pair-production cross-section for energy E(ME) (barn/atom).

NAME	COLUMN	FORMAT	DESCRIPTION, PURPOSE OR USE

Card 14 and Card Set 15 are not input in the present code version. They will be input in a future version for neutron scattering calculations. Although they are not input (and the code does not expect them) they are detailed.

Card 14 (single card; I2, 3F10.5; NENSIG)

NN	1-2	I2	Number of energies for which fast neutron cross-sections are input.
DENSTY	3-12	F10.5	Density as in Card 12.
ATØMNØ	13-22	F10.5	Atomic number as in Card 12.
ANDAN	23-32	F10.5	Atomic weight as in Card 12.

Card Set 15 ((NN/3) + 1 cards; 9F7.2; NENSIG)

ENN(1)	1-7	F7.2	First (lowest) energy for input of fast neutron cross-section (MeV).
XSN(1)	8-14	F7.2	Fast neutron total cross-section for energy ENN(1) (barn/atom).
XAN(1)	15-21	F7.2	Fast neutron scattering cross-section for energy ENN(1) (barn/atom).
.			
.			
.			
.			
XAN(3)	57-63	F7.2	Fast neutron scattering cross-section for energy ENN(3) (barn/atom).
.			
.			
.			
.			

NAME	COLUMN	FORMAT	DESCRIPTION, PURPOSE OR USE
ENN(NN)	-	F7.2	Highest fast neutron scattering cross-section for energy ENN(NN) (barn/atom).
XSN(NN)	-	F7.2	Fast neutron total cross-section for energy ENN(NN) (barn/atom).
XAN(NN)	-	F7.2	Fast neutron scattering cross-section for energy ENN(NN) (barn/atom).

Card 16 (single card; 'A80'; MAIN)

TITLE	1-80	'A80'	Alphanumeric description of shield for user identity.

Card 17 (single card; I5; MAIN)

NØM	1-5	I5	Number of shield material layers, i.e. >1 for a laminar shield (≤9).

Card 18 (single card; 9(F5.2,I2); MAIN)

RA(1)	1-5	F5.2	Shield layer thickness fraction with respect to shield total thickness; for first (1 at source end of shield) layer.
NELE(1)	6-7	I2	Number of elements in first shield layer.
.			
.			
.			
RA(NØM)	57-61	F5.2	Shield layer thickness fraction with respect to shield total thickness; for last (NØM) shield layer.
NELE(NØM)	62-63	I2	Number of elements in shield layer NØM.

NAME	COLUMN	FORMAT	DESCRIPTION, PURPOSE OR USE

Card Set 19 $\left[\left(\left(\sum_{I=1}^{N\emptyset M} \text{NELE}(I)\right)/7\right) + 1;\ 7(\text{F4.0, F6.4});\ \text{MAIN}\right]$

ZZ(1,1)			Atomic number of first shield layer, first elemental component.
DENSY(1,1)			Density in first shield layer of material ZZ(1,1) elemental component.
.			
.			
.			
ZZ(NØM, NELE(NØM))			Density in NØM shield layer of material ZZ(NØM, NELE(NØM)) elemental component.

Card Set 20 (GENSIG)

Consists of Card Set 11 repeated once to define energy variables for the shield.

Card Set 21 (NENSIG)

Consists of Card 12 and Card Set 13 to define shield photon cross-sections, repeated for each shield element and each layer, i.e., Cards 12 and 13, input as a pair, N times, where

$$N = \sum_{I=1}^{N\emptyset M} \text{NELE}(I)$$

Card Set 22 (NENSIG)

Similar to Card 14 and Card Set 15 to define shield fast neutron cross-sections, repeated for each shield and each layer, i.e., Cards 14 and 15, both input, N times, where

$$N = \sum_{I=1}^{N\emptyset M} \text{NELE}(I) .$$

The remainder of this section consists of comments and additional explanation of the input just described. Only those items which it is felt require special treatment will be discussed.

NPATH (I): The option values input on Card (1) route the code as shown in Figure 6. New values must be input for each shield case being studied. At present only the first seven (7) options are used by the code; the remainder NPATH (8) to NPATH (18) are spare for future use.

XS, YS, ZS, XD, YD, ZD, RADIUS, DIST:

The first six items input on Card (1)-1 define the geometric center of the source on tandem source pair and the point detector. The input values are relative to the location of the Cartesion axes and origin chosen by the user. All coordinates unput are similarly referenced. The items RADIUS and DIST correspond to R_s and r_{os} defined in Figures 2 and 3, respectively.

INE, NØRP, NRAND, ALLØWF, ECT, ARREST, FRG, FRN: The shield escape distribution is catergorized into an energy spectrum of INE groups. NØPT allows the user to obtain a profusion of code intermediate output, if $\neq 0$, however only 100 Monte Carlo histories are traced in this event. Repeated use of the same input value of NRAND will result in identical results, hence the instruction that arbitrary but differing values be input for a sequence of runs and run sets. The NASA-GSFC IBM-360 random number generating code requires that NRAND be an odd number. ALLØWF is equivalent to the specified criterion flux, C, defined preceeding Equation (17). C = 10.0 in the present report examples. Monte Carlo histories are terminated for photons whose energy is degraded below ECT. ECT should be input such that it is $\geq 2^{IL\emptyset W}$ (see Figure 7). In the present work examples ECT was taken as 0.1 MeV. Monte Carlo computer time is generally increased by decreasing ECT. Buildup factor iteration, as in Figure 4 is arrested according to un ut value of the fraction, ARREST, which corresponds to ϵ in Figure 4 and Equation (34). Taking Figure 8 as an example the axial-to-radial emission, ratios FRG and FRN are obtained as 0.0833 and 0.804, respectively.

NE, LE(I), NØES, HGAMA(I): if the source spectrum contains a large number of energy groups, e.g. NE = 18, the Monte Carlo evaluation is carried out at the user selected group indices (LI(I), I = 1, NØES) and intermediate values quadratically interpolated, e.g. evaluation may be requested at LE(I) = 1,5,7,9,15 and 18 where NØES + 6 (the number of indices). Since transport intensity is a function of energy for a given material, the number of Monte Carlo histories per energy index may be varied through i input of HGAMA(I), e.g. for the above HGAMA(I) might be = 5,4,3, 2,2, and 1 which corresponds to 5000, 4000, 2000 and 1000 histories.

NØRF, M: card sets (8) through (15) are input NØRF times after input of card (7) (NØRF). Since card sets (11) , (12) and (13) are cross sections for scattering items defined by cards (8) , (9) and (10) and thus may be the same for many sequentially input items, their (11) - (13) input is emitted for repeating value of M. For example, if three aluminum and two iron structural members defined by five repeats of cards (8) , (9) and (10) then in turn, M = 13, 13, 13, 26, 26, and (11) through (13) input twice (for the underlined M).

X(I), Y(I), Z(I), IP, IK, T2, T1, TB, NT: References to Figure 5 is recommended. The coordinates of the corners of each geometry defining the scatter structure model are specified by X(I), Y(I), and Z(I). For a triangular or quadrilateral plane area, the number of corners IP = 3 and 4, respectively. IP = 24 for a box structure; 4 corners/face for six faces. For a box or quadrilateral plane the angles subtended by the sides are arbitrary. For a cylinder (or boom tube) only the co-ordinates of the axial ends are specified, and thus IP = 2; the inner and outer radii are specified per T1 and T2 respectively. T2 specifies wall thickness for a plane or box. Since a cylinder and a plane may be optionally analyzed by either the albedo or single scatter technique, the decision is specified through the value of TB. In order to define the "exterior" side of planar media the direction of the outward normal is specified (+) or (-) per NT = ± 1. The user must determine whether the origin (0,0,0) is "inside or outside" of the planar medium. If the origin is inside the medium then NT=+1, else = -1. It is pointed out that the code automatically subdivides cylinders radially and axially into elemental areas which are small relative to the distance from either source or detector; this is necessary to maintain validity of inverse square relationships. The shapes allowed by the code may be combined to generate other geometries, e.g. a cone may be represented as isosceles plane area triangles in contact on each side.

NINT, ILØW, IHIGH: the cross-section table generated by subroutine GENSIG consists of (IHIGH - ILØW) energy groups, each containing 2^{NINT} sub-intervals. The total number of subintervals, over all groups, is equal to 1+ (IHIGH - ILØW) 2^{NINT}. The energy width of each sub-interval within any given group is the same and equal to $2^{N-1}\,(2^{\mathrm{IL\O W}} / 2^{\mathrm{NINT}})$, where N is the group interval number, beginning at N = 1, the lowest group. The energy bounds of group 1 are $2^{\mathrm{IL\O W}}$ and $2^{\mathrm{IL\O W}+1}$. The energy bounds of group N are $2^{\mathrm{IHIGH}-1}$ and 2^{IHIGH}. The energy unit pertinent to this entire explanatory comment is m_0c^2 (=.51097 MeV). An illustration of this comment is given in Figure 7. The relationship of the cross-sections generated with respect to ECT are also indicated. It should be noted that ECT $\geq 2^{\mathrm{IL\O W}}$.

NELE, DENSTY, ATØMNØ, ANDAW: where the source medium consists of only a single element, e.g. Fe, the earlier descriptions are considered adequate. Where the source consists of such as a compound then further clarification is now given:

Card types 12 and 13 (or 14 and 15) for spacecraft (read as 19 through 22 for shield) must be repeated for each element in the compound, e.g. for Sm_2O_3, input data for Sm and for O. Continuing with Sm_2O_3 as the example, NELE = 2, to indicate two elements (Sm and O); ATØMNØ, ANDAW are input as 62.0, 150.35 and 8.0, 16.0, respectively. Only the input values of DENSTY need reflect the number of atoms of Sm and O in Sm_2O_3. DENSTY is determined as

$$\mathrm{DENSTY}\Big|_{Sm} = \frac{2 * \mathrm{ANDAW}/_{Sm}}{\mathrm{ANDAW}/_{Sm_2O_3}} * \mathrm{DENSTY}/_{Sm_2O_3}$$

$$= \frac{2 * 150.35}{348.7} * 1.51 = 1.302$$

and

$$\mathrm{DENSTY}/_{O} = \frac{3 * 16}{348.7} * 1.51 = 0.208$$

ME, SIGPE, SIGPP, E: the cross-section data required for input on card type 13 may be obtained from the references (17-21). The number of value-sets input from energy E (1) to E (ME), need only encompass the energy range $2^{\mathrm{ILØW}}$ to 2^{IHIGH}, with spacing as per the references. The code generates its own cross-section table using logarithmic interpolation. A table of E, SIGPE, SIGPP is given in Appendix VI of reference (3).

RA(I), NELE(I): the shield may be defined as having laminar layers (R(I), I=1, NØM) and each lamination may have NELE(I) elemental components. RA(I) is a fractional length, e.g. if the shield length = L and RA(1), RA(2) and RA(3) are = 0·1, 0·2 and 0·7, then the lamination lengths, in the source to detector direction are lengths 0·1L, 0·2L and 0·7L. The code determines the optimum value of L. Each lamination I, may have elemental composition NELE(I) e.g. NELE(1), NELE(2) and NELE(3) = 2, 1 and 1, for a three layer LiH + Fe + Pb shield.

3.3.4 Code Output

Throughout the discussion in this section, reference to the Sample Code Output listing of Appendix V is necessary and understood. Output which is adequately defined by headings is either not discussed or mentioned only briefly. Output pages are referred to by means of the encircled letters A, B, C, etc.

A This page consists of the input gamma spectrum and/or neutron spectrum data and the flux at the detector for each energy interval.

B This page consists of the albedo and single scatter information for each input scattering item (e.g. spacecraft structural member or component).

The total (integrated) scattered flux at detector is also given.

C This page consists of shield information: source energy groups, shield material composition, buildup factors, direct and attenuated fluxes as well as the estimated thickness and weight. Initial output of this page for each shield is for buildup factors of unity.

(D) The values on this page are as input according to Section 3.3.3, with a number of exceptions, namely:

1. ESCAPE SPECTRUM ENERGIES (MC**2) —— photons escaping from the source cylinder are terminally categorized within these energy bounds.

2. ESCAPE SPECTRUM ANGLES (RADIANS) —— photons escaping from the source cylinder are terminally categorized within solid angles defined by the escape angles. Zero angle is defined along the + Z-axis in the direction "source to detector".

(E) These page(s) consist of the terminal results of unscattered photon escapes categorized as a function of source energy. The source photon energies are identified obviously for each table, as are the escape angles and solid angles (both in radians). The other columns are identified as follows:

1. NUMBER —— the number of photons escaping between angle A_i and A_{i+1}, ie. in the noted solid angle; based on 4π space.

2. NUMBER/STER —— the number of photons escaping between angle A_i and A_{i+1}, per steradian.

3. FRACT/STER —— the number of photons escaping between angle A_i and A_{i+1}, per steradian per total number of source photon histories initiated.

4. PAIR PHOTØNS —— the number of pair photons escaping between angle A_i and A_{i+1}.

5. UNSCATTERED ESCAPES —— the total number of source photons escaping without a single collision, ie. the sum of item 1 above is given at the bottom of each table.

6. NUMBER AV/STER —— the average number of escaping photons per steradian, ie. the sum of item 1 divided by 4π.

7. PAIR PHOTON ESCAPES —— the total number of unscattered pair photons escapes, ie. the sum of item 4.

8. NO PP IN FWD CONE —— the total number of unscattered pair photon escape in the forward 10 degree cone. Note: in this discussion 'forward' 10 degree cone excludes shield side escapes ie. forward face escapes only.

(F) These page(s) consist of the terminal results of scattered photon escapes categorized according to escape energy interval tables. The escape interval energies, angles and solid angles are identified obviously. The remaining columns are analogous to E above, except for the following:

1. SCATTERED ESCAPES——the total number of source photons escaping after one or more scatterings is given at the bottom of each table, analogous to C4, above.

2. P. E. ABSORPTIONS——the total number of source photons "lost" to photoelectric abosrption.

3. NO.IN FWD CONE/STER——the scattered photon escapes in the the forward 10 degree cone; number per steradian.

(G) The output on this page consists largely of summarization of the data in E and F above. Initial and Cut-off energies are in MeV units. The TOTAL NO. OF COLLISIONS does not refer to a terminal classification and is thus only of either statistical or incidental interest. The termination table consists of the following:

1. ENERGY —— the number of histories terminated through scatter reducing the photon energy below the input cut-off energy (ECT) threshold. Such terminations are considered as absorptions.

2. WEIGHT —— the number of histories terminated through the weight being reduced to less than the termination threshold value (coded as 10^{-5}). Such terminations are regarded as absorptions.

3. ESCAPE —— the number of histories terminated through TOTAL UNSCATTERED ESCAPE plus TOTAL SCATTERED ESCAPE, ie. the sum of items 5 and 6 listed below.

3A. TOTAL ESCAPING FRACTION —— excaping fraction per history, ie. item 3 divided by the total number of histories.

4. ABSORBED (1. + 2. + 7.) —— the number of histories terminated through ENERGY plus WEIGHT plus PHOTOELECTRIC ABSORPTION, ie., the sum of items 1, 2 and 7.

5. TOTAL UNSCATTERED ESCAPES —— this is item E4 repeated.

5A. TOTAL UNSCATTERED FRACTION —— item G5 per history.

6. TOTAL SCATTER ESCAPES —— the number of scattered escaping photons summed over all escape energies.

6A. TOTAL SCATTERED ESCAPE FRACTION —— item G6 per history.

7. PHOTOELECTRIC ABSORPTION —— the number of photoelectrically absorbed photons summed over all energies.

8. PAIR PRODUCTION PHOTONS —— the total number of 0.51 annihilation photons originating in pair production interactions.

9. TOTAL ESCAPES IN FWD 10 - DEG CONE —— total escapes through forward 10 degree cone and summed over all energies.

10. TOTAL IN FWD CONE/STER —— item G9 per steradian.

11. TERMINATION PAIR PHOTONS——this termination table categorizes the fate of the shield pair produced photons.

12. TALLY CHECK——this item should equate to the total number of photon histories.

Page sets D, E, F and G are output for each input index LE(I) and iteration, i.e. NØES times for each iteration, e.g. if 3 iterations then D, E, F and G are output 3* NØES times. At the end of each iteration i.e. every NØES set of D, E, f and G, page C is repeated. The last page C output is the final result for each shield problem and is thus noted. The final results on page C consist the gamma photon and fast neutron source spectra as well as the corresponding iterated buildup factors and detectable attenuated fluxes. The note of change of flux as a function of shield length is tabulated for four shield lengths in the "length-vicinity" of the criterion flux. The first length value: the table is the predicted optimum obtained by quadratic interpolation remaining three values. The optimum shield length L, weighted density ρ and total weight, W, are given. The total structural scattered and shield attenuated fluxes calculated by the code are also output, as are the same values corrected for the number of spacecraft symmetric sources or cource tandems, eg. in the example in Appendices IV and V, TANDEM = 2.0, corresponding to the two Fondem sets shown in Figure 1. Thus although the code calculated scattered and attenuated fluxes of 0.608 and by TANDEM = 2 to equate to ALLØWF = 10.0 when summed, ie. the values become 1.216 and 8.784 particles/cm^2 second.

3.3.5. Discussion

Sample results obtained with the SØSC code are reviewed in this report section. They assume the typical unmanned spacecraft as in Figure 1. The dimensions of this craft were obtained either directly or by scaling NASA-GSFC preliminary design drawings.

The sample calculations assumed four (4) SNAP-27 RTG's, each five (5) years aged and of 1575 thermal watt capacity. The RTG's were taken as being in tandem pairs as in Figure 1. The science experiment package was located 6.87 meters from the RTG's. The unshielded direct and energy integrated number fluxes at the experiment package were taken as 25.2 γ/cm^2-sec and 13.5 neutrons/cm^2-sec per tandem pair of RTG's; these values were obtained from NASA source data. Fluxes in the axially perpendicular direction (radial) were taken as 12.0 and 1.25 times those in the axial direction. The fluxes assumed at a distance of 6.87 meters from RTG tandem pair are shown in Figure 8.

The spacecraft structure scattered flux at the science package was predicted by the code as being 1.22 particles/cm^2-sec, for the four RTG's. The Code SØSC predictions for 8.04 cm diameter optimum weight shields, per RTG tandem pair and the noted materials, were:

LiH	Al	Fe	Pb	
1651	1932	2451	2617	grams
(3.64	4.26	5.40	5.75	lbs)

A two lamination shield of total length 10.56 cm, made up of 1.056 cm Pb (nearest source) and 9.504 cm Al requires a shield weighing 1900 gm. This is 32 gm less than an Al shield and 3.4 cm shorter in length. A laminar shield of Pb and LiH, in the same length fractions, 0.1 and 0.9, reduced the optimum weight to 1580 gm for a length of 16.59 cm compared with 39.5 cm for a LiH shield. A reversal of the shield material order from 0.1 Pb + 0.9 LiH to 0.9 LiH + 0.1 Pb, in the direction: source to detector, led to a weight reduction from 1580 to 1550 gms. Although two laminations of the same materials (e.g. Pb-Al-Pb-Al) generally did not.

Figure 9 shows the weight of a LiH + Pb shield as a function of the ratio of LiH length to total shield length. The optimum weight shield is seen to be given for a ratio of 0.92 (i.e. 0.92 LiH + 0.08 Pb). The optimum is obtained for a slope of zero. The dashed curve in Figure 8 indicates the change in total length of the LiH + Pb shield. At a length ratio of 0.92 the total length is < 50% of the 'all' LiH shield; at a weight ratio of 0.83 (weight ≈ 1600 gm) the total length is reduced by a factor of ~ 3. Thus this curve, obtained by running code SØSC, allows a best compromise between optimum weight and shield length to be chosen; this may be important in a spaceflight mission launching where volume is a prime consideration.

When only gamma photons were considered high atomic numbered material gave the most favorable results. For the sample case, ignoring neutrons i.e. photons only, tungsten and tin shields weights were predicted as 1567 and 1903 gm.

The sample problem output given in Appendix V indicates, on page type C, the range of the buildup factors for the case of the 0.9 LiH + 0.1 Pb shield. They can be seen to range from 1.0 to 1.08, as compared with 1.0 to 1.15 for 0.1 Pb + 0.9 LiH; for Pb only, the factor ranged from 1.0 to 1.33. The build-up factor behaviour in the shadow shield is quite different from the expected for a semi-infinite or bulk, shield. Photons and even neutrons, have a high probability of escaping after one or more scatters. This coupled with the low probability of being scattered to the distant detector accounts for the values being only some 10 or 20% above unity. Only radiation escaping through the shield face closest to the detector were considered as possible contributors to the buildup factor

From the sample problems run and reported herein and as substantiated by earlier determinations reported in NUS-600[2], the assumed spacecraft-payload design yields an energy and particle integrated flux at the payload which is $\sim$ 10% scatter and $\sim$ 90% shield attenuated. This supports the approximated approach to the scatter problem which is designed into Code SØSC.

Code SØSC determinations of the scattered flux at the science experiment, i.e. at the detector, although based on albedo and single-scatter techniques which are, of course, approximate, allow the inclusion of all structural detail. The direct and complete Monte Carlo approach to the scatter problem would be prohibitively complex and costly and would still only provide a good approximation. The Monte Carlo approximation may be inferred from the fact that even in simple geometries Monte Carlo predictions frequently deviate 10% to 50% from good experimental data.

Calculations reported in NUS-600[2] indicated relatively good agreement between single scatter and albedo predictions for geometries where material was either relatively thin or where such as tube members were being considered. Sample evaluations from NUS-600 are reproduced in Appendix VI of this present report.

4. DESIGN OF EXPERIMENT

The design of an experiment to verify the predictions of code SØSC, is outlined in this report section. The experiment is required to verify both the spacecraft scattered and shield transmitted radiation fluxes as well as the optimum shield weight and configuration. Although the experiment must necessarily be carried out in a terrestrial laboratory and thus be influenced by such as air and laboratory structural material interactions as opposed to the ideal in-vacuo environment of deep space, these effects can generally be corrected for.

Referring to Figure 3, the experiment must provide data to substantiate predictions of flux: $\phi_{\alpha}(E_{\alpha}) + \phi_{a}(E_{o}; E_{a})$ as well as give optimum shield length, L. The experiment should be carried out for both gamma photons and neutrons. In order to carry out the experiment for an actual spacecraft with PuO_2 fuelled RTG sources, the spacecraft, RTG's and a suitable detection system are required to be located in a suitable laboratory. Assuming the availability of these items the experiment becomes very straight forward. Such an experiment requires an efficient detector for fast neutrons in the presence of a relatively high gamma photon field, e.g. a liquid organic scintillator such as NE-213 or -218* which allow pulse shape discrimination for detected photon rejection to be accomplished. The gamma photons will be most efficiently detected by a thallium-activated sodium-iodide scintillation detector. The detection capabilities and necessary subsequent analysis for both of these detector types with respect to the proposed experiment, have been adequately described in NUS-486[32].

In the likely event that an actual spacecraft is unavailable for an experiment, a mock-up may be fabricated using "everyday" materials of composition, dimension and mass closely similar to that of a spacecraft. Again laboratory neutron and gamma sources may be judiciously substituted for an actual RTG assembly.

* NE-213 and NE-218 are organic liquid scintillators manufactured by: Nuclear Enterprises, Inc., San Carlos, California.

However, accepting the fact that a mock-up experiment will verify code SØSC data, leads to the obvious idea of simplifying the mock-up. For example, the use of a small number of typical structural component mock-ups will suffice for comparison of experimental data with code predictions for the same configuration. Shield transmission may be studied experimentally by the use of axially located and adjacent thin discs in various quantities and material combinations. This approach to the experiment allows its economical implementation in a conventional laboratory. It requires the availability of the necessary detectors and an associated multichannel pulse-height analyzer as well as neutron and gamma photon sources of known emission strength.

Figure 10 (a) shows a source, detector, shield and scatterer located in the geometry of a proposed experiment. Although the distances r_o, r_1 and r_2 should be chosen such as to model the experiment after the actual spacecraft configuration, dependence on source strength and detection statistics will generally dictate their actual dimensions. For example, since shield attenuation factors will generally be studied in the range 0·2 to 0·02 a source strength, $S_o \sim 1.0$ mC, is desirable to yield a statistically good detector count rate for $r_o = 1$ meter; inverse-square law considerations allow strength to be determined for other values of r_o. Removal of the shield will yield detector count rates larger in accord with the noted attenuation factors. The flux scattered to the detector by the spacecraft mock-up member, of area A, will be less than that along path r_o, in the ratio $r_o^2/(r_1^2 \cdot r_2^2)$ for geometrical reasons, assuming total reflection at A. Since reflection will be far from total, being instead expressed by the differential albedo (see Section 3.2.) and since the actual value of the area A is also a factor, it will be necessary to use a source strength, $S_\alpha >> S_o$, for this experiment phase. Actual source strengths S_o and S_α may be varied to some extent by choice of counting duration.

Referring to Figure 10 (a), and assuming sources S_o and S_α, the experiment may be carried out as follows:

I using source S_α, detect radiation transmitted by a shield of length L and scattering from an area A. Increasing L incrementally the detector will eventually detect only radiation scattered by area A. In this manner ϕ_α (E_α) is experimentally obtained after background subtraction and spectral unfolding analysis. The choice of shield material for this phase is not critical since only elimination of direct radiation is a requirement. Background is determined by repeating the experimental counting for the "infinitely thick" shield with the scattering area A removed. It is recommended that the area A be located away from laboratory structure throughout the experiment. The methods noted here are very similar to those successfully employed in the research of reference (10) excepting that radiation beam collimation will be as indicated in Figure 10 (a).

II using a source S_o which is identical to S_α in all respects except emission strength, scattered flux may be taken as = $(S_o/S_\alpha) \cdot \phi_\alpha (E_\alpha)$, for the shield phase of the experiment; this assumes the presence of area A. Since area A is not necessary for this phase of the experiment, the geometry of Figure 10 (b) is proposed. In Figure 10 (b), the detector is shielded from radiation other than that transmitted by the shield. The detector response function is obtained by counting source radiation with the shield removed; this takes detector shielding and collimation effects into account. For a given shield composition and length the transmitted radiation flux ϕ_a (E_o ; E_a) is obtained. If code SØSC is run for S_o, r_o and this flux as the criterion flux and ALB is omitted then comparison of the computed shield with the experiment shield may be carried out. Laminated shield verifications may be studied in the same manner.

Although the above experiment description calls for reduction of radiation counts to particle fluxes, approximate results may be obtained without reduction if the researcher is cognizant of detector response as a function of energy.

5. SUMMARY AND CONCLUSIONS

Analytic procedures and computer codes have been developed for the prediction of weight optimized radioisotope thermoelectric generator shields to protect science experiments for unmanned spacecraft operating in deep space. The analytic procedures, presented in Section 2.2, consist of iteratively solving the basic transport relationship after first determining the spacecraft scattered flux component. The transport relationship is solved through the use of the Monte Carlo technique and analytic approximation. The scattered flux is obtained through the use of albedo, single scatter and analytic techniques.

A FORTRAN IV IBM-360/91 digital computer code package --- SØSC was designed and developed to carry out the prediction of optimum shield weights and dimensions. This code uses all of the developed procedures to best advantage. In addition to its designed application of shield design for protection of science experiments it may be used to either design shadow shields or to map radiation scattering for general application.

In addition to the technique and code development, an experiment to evaluate predicted data has been presented. This experiment, outlined in section 4, is proposed for future effort. The anticipated spectrometry data to be obtained from the experiment may be readily analyzed with the aid of the spectral analysis codes CUPED[33], CUNED[34] and SØSC developed by NUS for NASA-Goddard Space Flight Center.

It is proposed that a future work program consider the incorporation into code SØSC, of a Monte Carlo neutron transport routine. It is also proposed that code SØSC be modified to take neutron scattering from the spacecraft structure into account. Consideration should also be given to the production of secondary radiation in the shield as a result of neutron interactions, e.g. activation gamma photons. It is proposed that gamma photon transport results - - - albedos, single scattering and buildup factors - - - obtained in the work scope being developed by NUS for NASA-GSFC under contract NAS5-11781, be incorporated into SØSC to the extent necessary and appropriate.

It is concluded that code SØSC and its encoded techniques provide a useful addition to the field of spacecraft radiation transport. The code makes a valuable engineering tool available for both preliminary and final craft engineering design.

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FIGURES

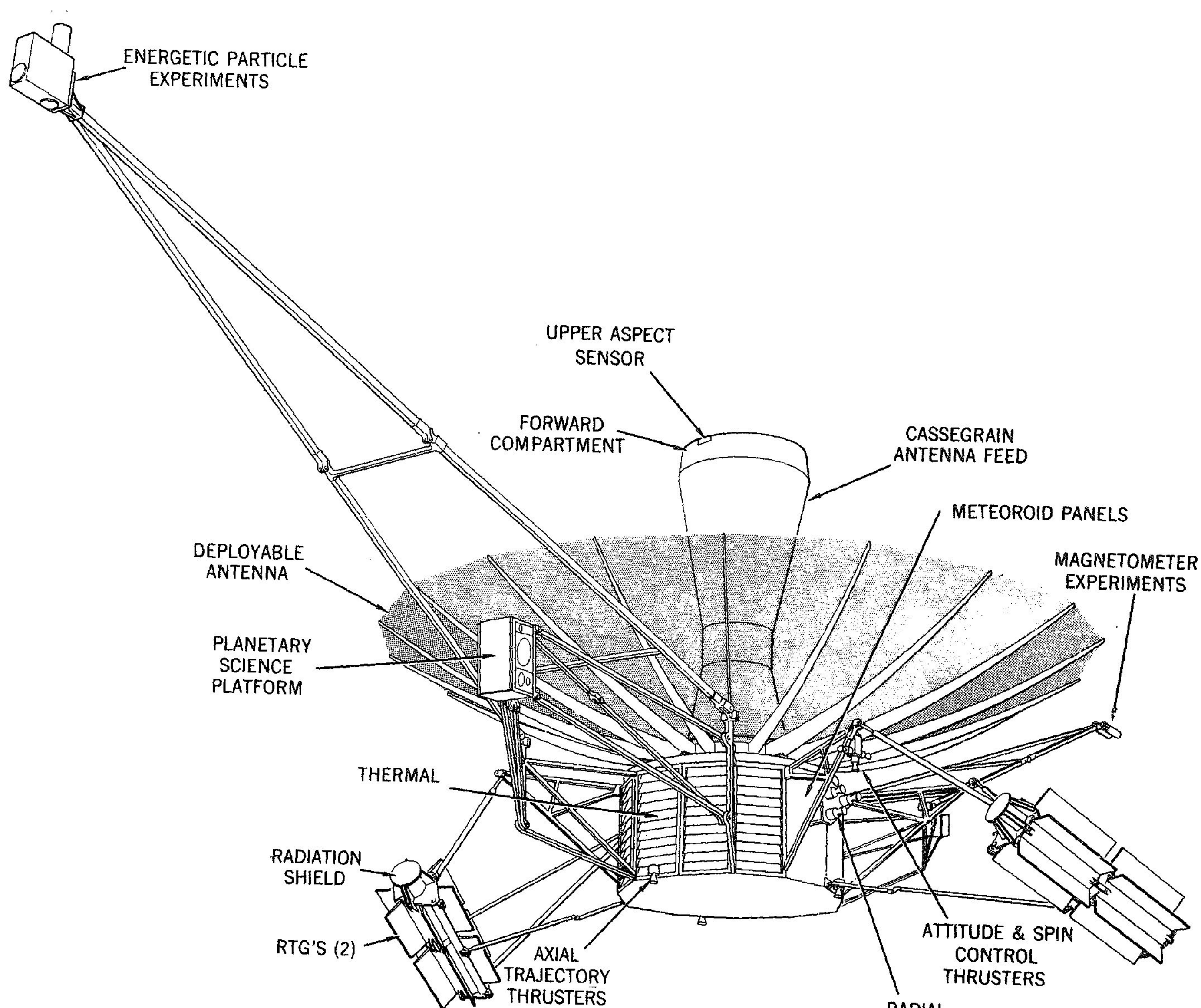

FIGURE 1

TYPICAL UNMANNED SPACECRAFT

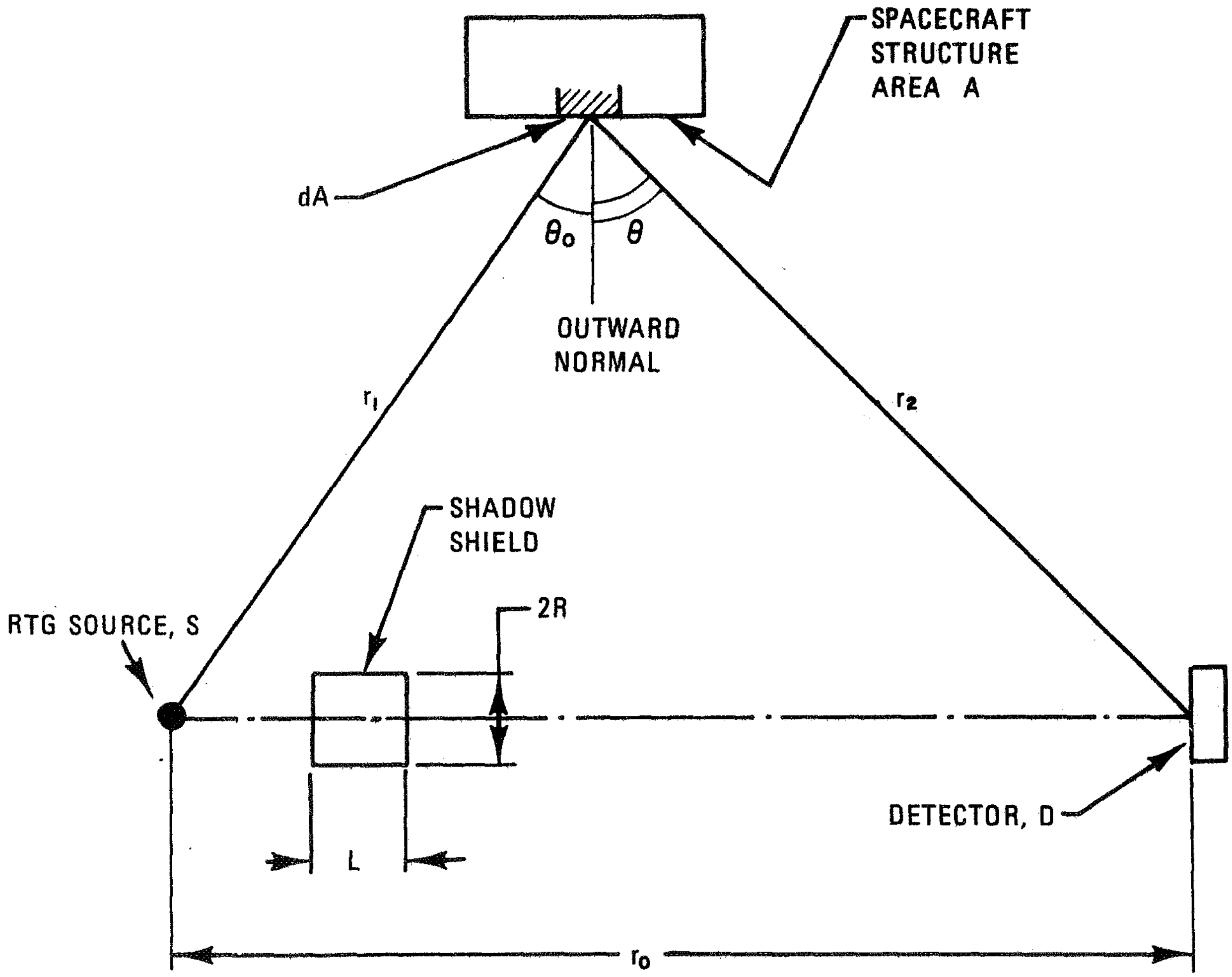

FIGURE 2

SCHEMATIC DRAWING OF SPACECRAFT SHOWING RTG SOURCE, SHIELD AND DETECTOR ARRANGEMENT

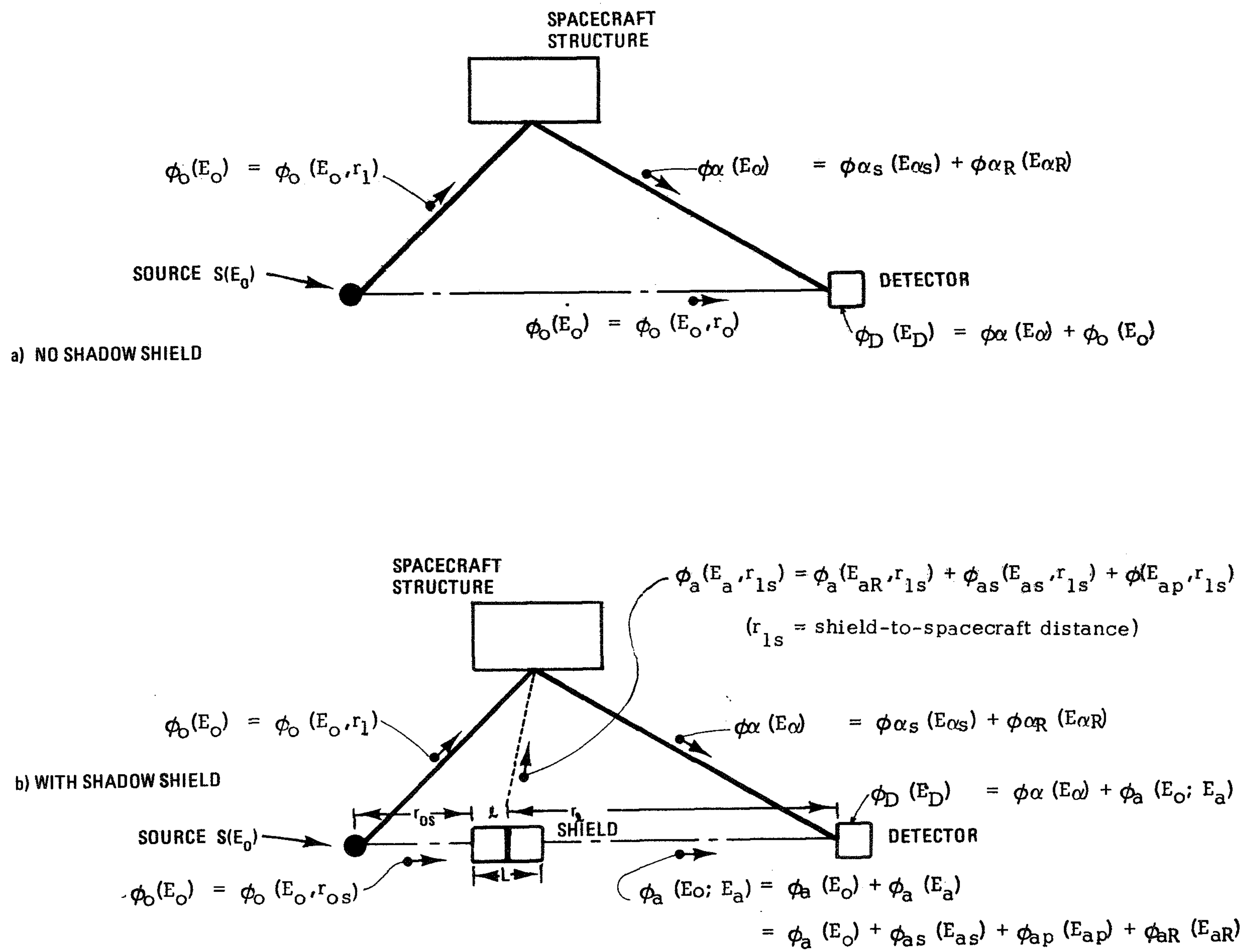

FIGURE 3

SCHEMATIC DEFINITION OF GAMMA PHOTON AND NEUTRON FLUXES

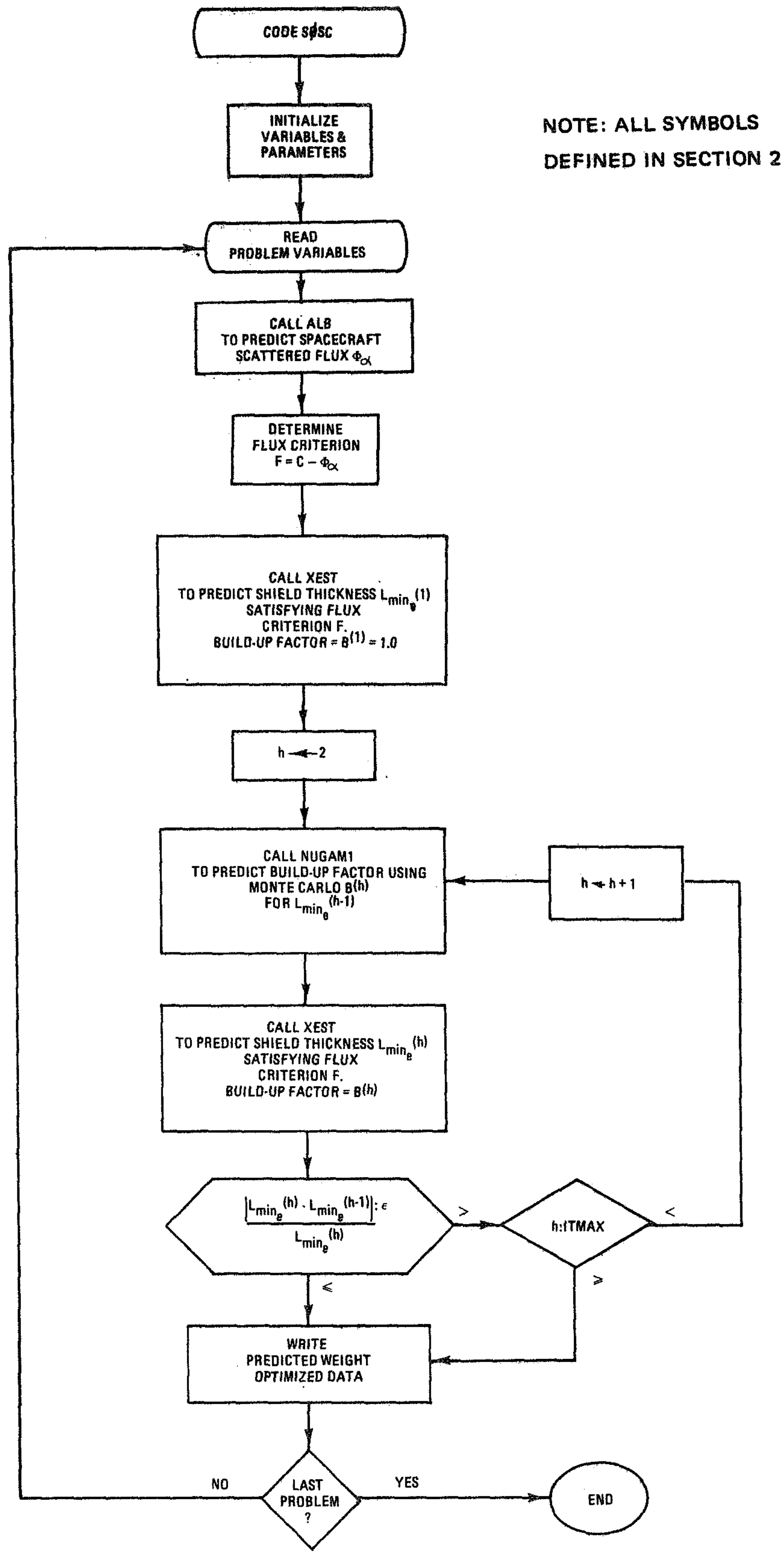

FIGURE 4

CODE SØSC LOGIC

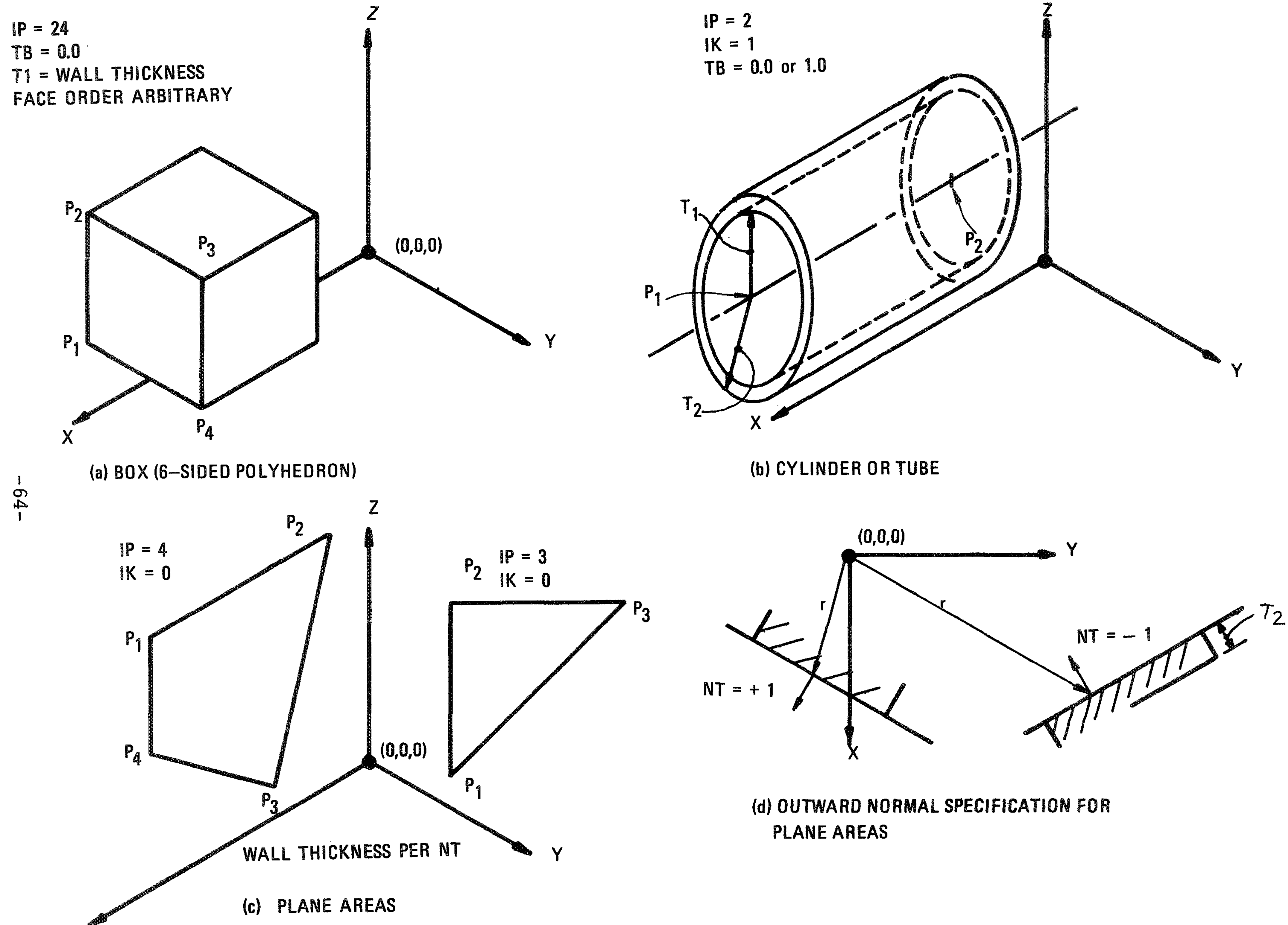

FIGURE 5

DEFINITION OF SCATTERING STRUCTURE COORDINATE GEOMETRY

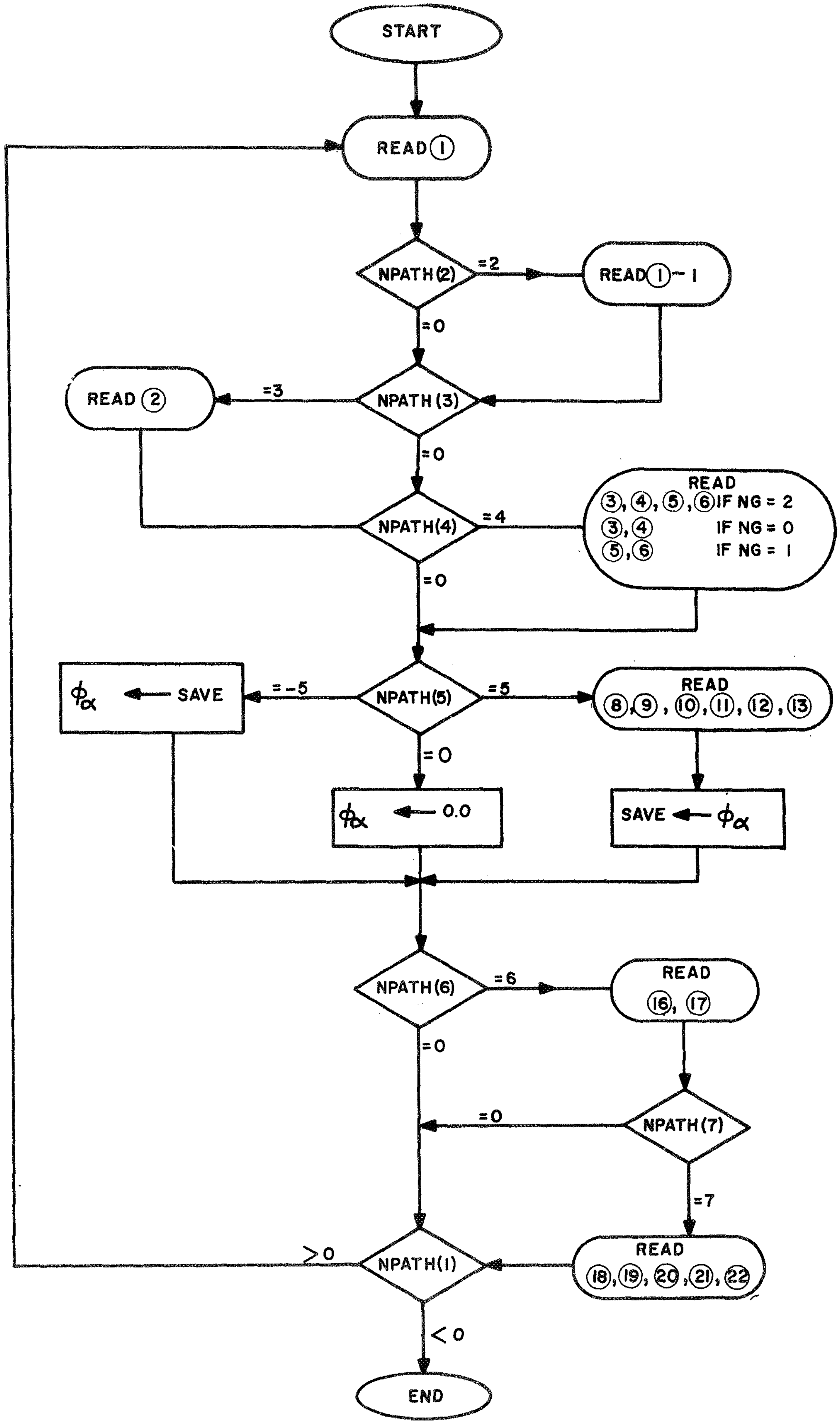

FIGURE 6

CODE SØSC ROUTING CONTROL OPTIONS

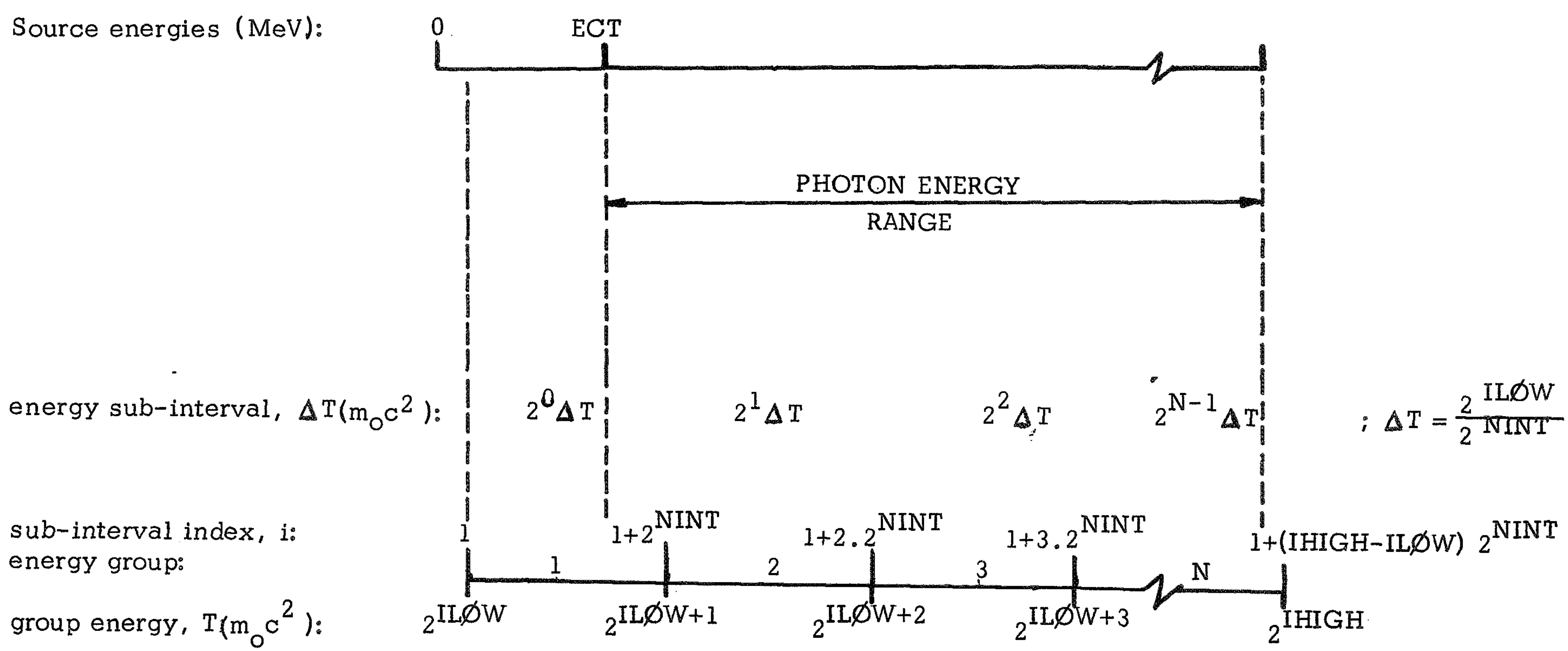

FIGURE 7

Energy Correspondence Bar Diagram

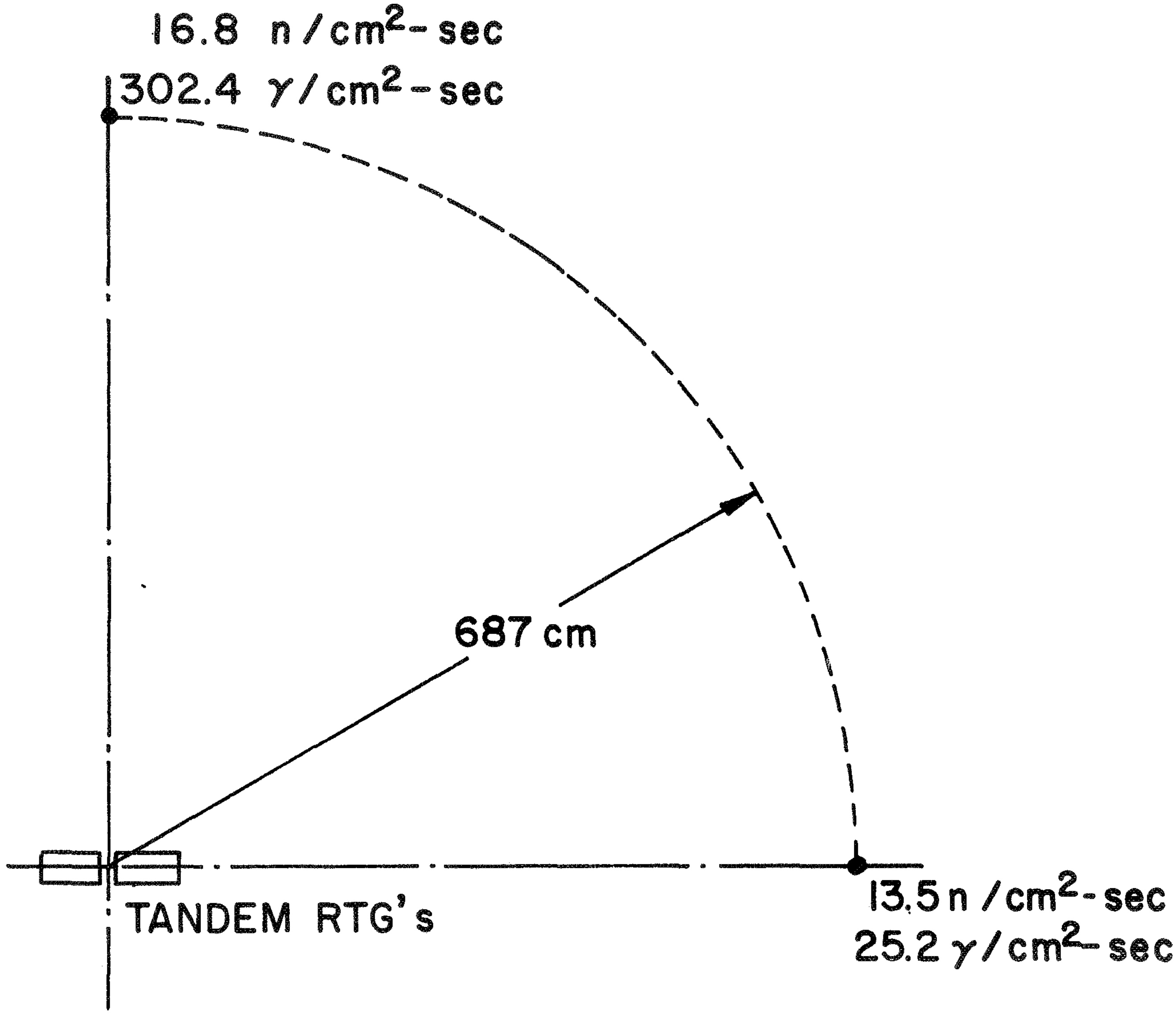

FIGURE 8

SOURCE TERM FLUXES AT 687 cm FROM TANDEM RTG's

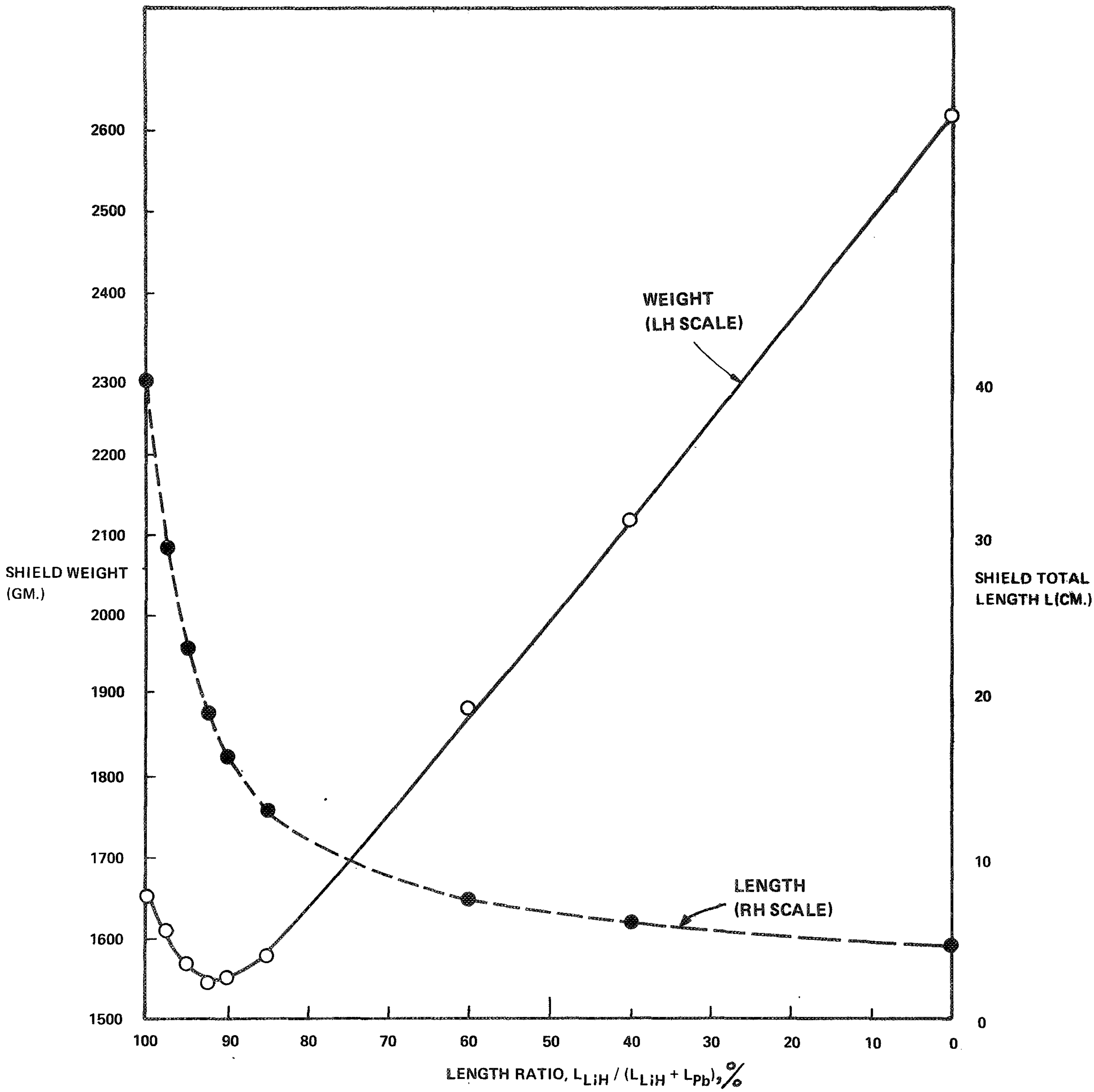

FIGURE 9

WEIGHT AND LENGTH OF LiH + Pb SHIELD
AS A FUNCTION OF LiH TO LiH + Pb LENGTH RATIO

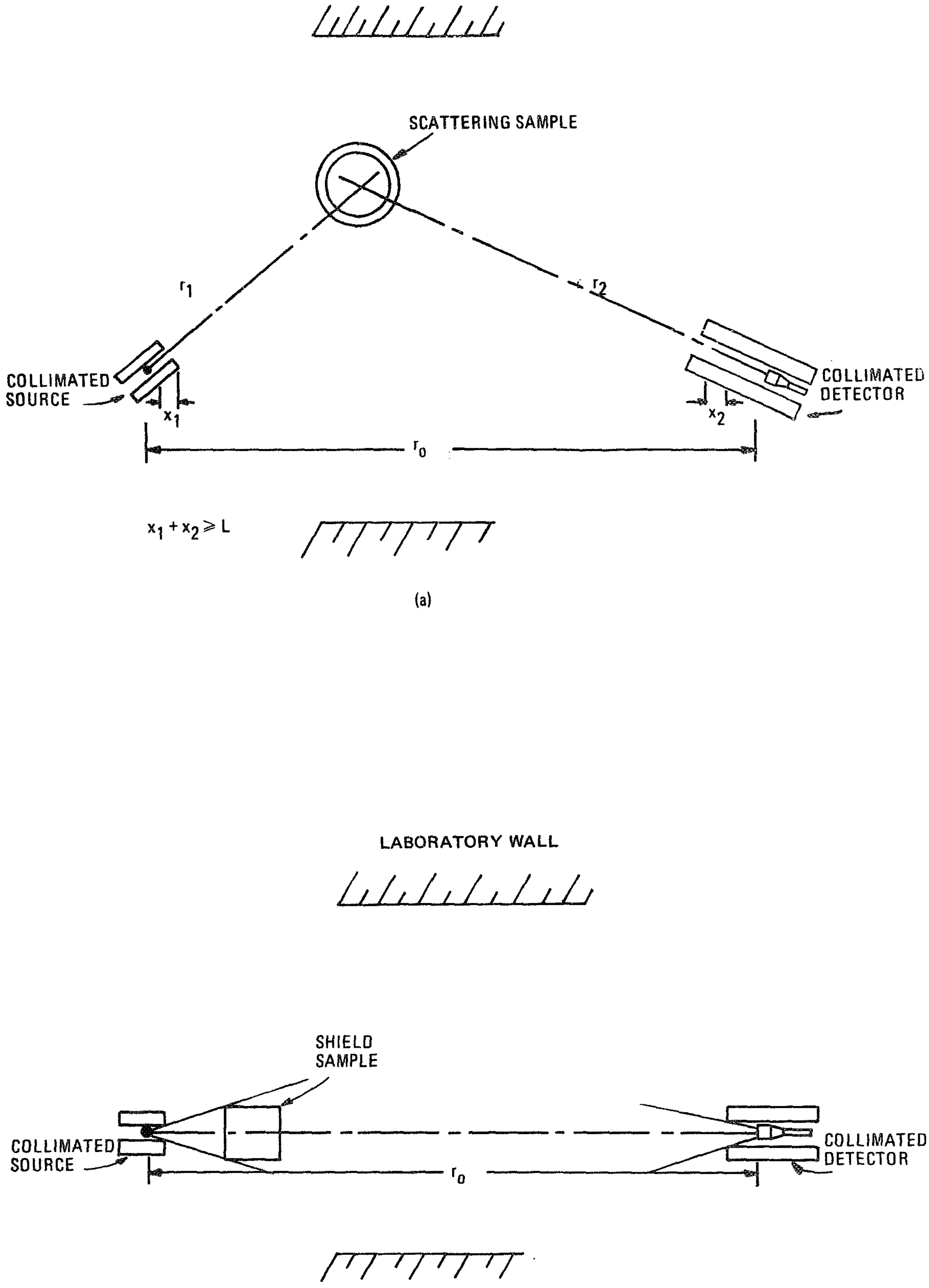

FIGURE 10

GEOMETRY FOR PROPOSED EXPERIMENT

APPENDIX I

INTERACTION PHYSICS REVIEW

APPENDIX I

INTERACTION PHYSICS REVIEW

I GAMMA PHOTON INTERACTION PHENOMENA

In their passage through a medium, photons interact with the electrons and nuclei of atoms in their path. These phenomena form the basis both for their detection and for the deposition of their energy. A discussion of the kind and effect of these interactions as they pertain to the present work is given in this report section [23-27].

There are four kinds of basic gamma photon interaction processes [27], of which only two are relevant in the present work, namely:

a) interaction with atomic electrons,
b) interaction with the electric field surrounding nuclei or electrons.

The effect of (a) may be either scattering or absorption; the latter is the Photoelectric Effect. The scattering may be either one of the two types:

1. Compton inelastic scattering (incoherent), or
2. Rayleigh elastic scattering (coherent).

The effect of (b) is the disappearance of the photon and the creation of an electron-pair; this phenomenon is referred to as the Pair Production Effect.

A brief discussion of these four microscopic phenomena, and their macroscopic attenuating effect on a beam of photons, follows under the headings:

A) Photoelectric Effect
B) Compton Scattering
C) Rayleigh Scattering
D) Pair Production
E) Attenuation

A. Photoelectric Effect

At relatively low photon energies the most probable effect of an interaction is absorption of the incident photon by an electron of the traversed medium followed by ejection of that electron and emission of either characteristic X-rays or "Auger electrons" as explained below. This phenomenon, called the Photoelectric Effect, results in the complete disappearance of the incident photon.

In order that total absorption may take place, and momentum be conserved, the interacting electron must be initially bound, in which case the residual atom recoils. The most tightly-bound electron, with respect to the incident photon energy, has the greatest probability of absorbing the photon. The interaction cross-section is a maximum when the photon energy $E\gamma$, is just equal to the electron binding energy; it decreases gradually as $E\gamma$ increases, and decreases sharply as $E\gamma$ decreases. The most tightly-bound electron in an atom is in the K-shell; it accounts for in excess of 80% of the photoelectric absorptions, with the L-shell accounting for most of the remainder.

The energy of the ejected electron, or photoelectron as it is usually called, is given by:

$$E_e = h\nu_o - E_{eb}, \text{ (MeV)} \tag{1}$$

where

$h\nu_o$ = incident photon energy (MeV).

E_{eb} = electron binding energy (MeV).

The energy E_{eb} is carried away from the atom by radiation emitted as the inner shell vacancy is filled by an outer shell electron, such radiation is referred to as Characteristic X-rays. If the X-rays interact with an outer shell electron as they leave the atom, they will be absorbed and the absorbing electron emitted instead -- an Auger electron. The nuclear decay processes of internal conversion and electron capture may also lead to the emission of characteristic X-rays; so also will the absorption of beta particles.

The photoelectric effect does not lend itself easily to explicit theoretical calculation. Determinations of its cross-sections are usually based on a combination of empirical treatments which vary according to the energy range under consideration. It is the practice of most researchers to make use of tabulations for σ_{PE}, the photoelectric cross-section.

B. Compton Scattering Effect

As the wavelength of gamma photons decrease and their photon energy increases, their behaviour tends towards that of a particle and their identity with a wave diminishes. The region of this transition corresponds to the Compton scattering "threshold." This threshold, not sharply-defined, is entered upon gradually as $h\upsilon_o \rightarrow m_o c^2$, (= 0.51 MeV), where m_o equals the rest mass of the electron. Viewed as solid bodies, the photon and the electron have comparable "masses." As the Compton effect becomes significant, the photoelectric effect significance diminishes.

Compton scattering may be considered as an inelastic collision between an incident photon and a "free" electron of the medium; the collision is analogous to that of billiard ball mechanics. The electron may be thought of as free to recoil on the basis of $h\upsilon_o >> E_{eb}$, as a result of which the incident photon may transfer a portion of its momentum and energy. The consequence of the collision is a scattered photon of energy $h\upsilon_1$, travelling in a new direction and at an angle θ with the original photon direction, and a recoiling electron of energy E_e making an angle ψ with the incident photon direction. θ max = 180°; ψmax = 90°.

The angular and energy relationships of these statements may be expressed as:

$$E_{\gamma_1} = \frac{E_{\gamma_o}}{1 + \frac{E_{\gamma_o}}{m_o c^2}(1 - \cos\theta)}, \text{ MeV.} \tag{2}$$

$$E_e = E_{\gamma_o} - E_{\gamma_1} \tag{3}$$

$$E_\gamma = h\upsilon, \text{ MeV.} \tag{4}$$

$$\cot\psi = (1 + \alpha'_o) \tan\frac{\theta}{2} \tag{5}$$

where

E_{γ_o} = incident photon energy, MeV.

E_{γ_1} = scattered photon energy, MeV.

θ = angle between incident and scattered photon directions.

ψ = angle between incident photon and recoil electron directions.

For convenience in the remainder of this section the following conventional short form is used:

$$\alpha'_o = \frac{E_{\gamma_o}}{m_o c^2}, \quad \alpha'_1 = \frac{E_{\gamma_1}}{m_o c^2} \tag{6}$$

The differential "collision" cross-section for the scattering of photons into a given solid angle $d\Omega$ at a particular angle θ is given by the Klein-Nishina formula, as

$$d\sigma = \frac{r_e^2}{2} \, d\Omega \left\{ \frac{(1 + \cos^2\theta)}{\left[1 + \alpha'_o(1 - \cos\theta)\right]^2} \right\} \times \left\{ 1 + \frac{\alpha_o'^2 (1 - \cos\theta)^2}{(1 + \cos^2\theta)\left[1 + \alpha'_o(1 - \cos\theta)\right]} \right\} \tag{7}$$

where

$d\sigma$ = differential cross-section, cm^2/electron

$d\Omega$ = $2\pi \operatorname{Sin}\theta \, d\theta$, the differential solid angle

r_e = "classical electron radius, $\frac{e^2}{m_o c^2}$

= 2.818×10^{-13} cm.

Equation (7) assumes the incident photons to be unpolarized. It indicates that for large α'_o, scattering is predominantly in the forward cone. As $\alpha'_o \rightarrow 0$, and $\cos\theta \rightarrow 1$, we see

$$d\sigma \rightarrow \frac{r_e^2}{2} (1 + \cos^2\theta) \, d\Omega \tag{8}$$

From Equation (2) equation (7) may be rewritten in terms of energy

$$\frac{d\sigma}{d\alpha'_1} = \frac{\pi r_e^2}{\alpha_o'^2} \left\{ \frac{2}{\alpha'_o} - \frac{2}{\alpha'_1} + \frac{1}{\alpha_o'^2} + \frac{1}{\alpha_1'^2} - \frac{2}{\alpha'_o \alpha'_1} + \frac{\alpha'_o}{\alpha'_1} + \frac{\alpha'_1}{\alpha'_o} \right\} \tag{9}$$

for

$$\alpha'_o \geqslant \alpha'_1 \geqslant \frac{\alpha'_o}{(1 + 2\alpha'_o)}$$

The integration of Equation (9) over all scattered energies yields the total Compton scattering cross-section per electron, σ_{cs}, :

$$\sigma_{cs} = 2\pi r_e^2 \left\{ \frac{1+\alpha'_o}{\alpha'^3_o} \left[\frac{2\alpha'_o(1+\alpha'_o)}{1+2\alpha'_o} - \ln(1+2\alpha'_o) \right] + \right.$$
$$\left. + \frac{\ln(1+2\alpha'_o)}{2\alpha'_o} - \frac{1+3\alpha'_o}{(1+2\alpha'_o)^2} \right\} \tag{10}$$

The total Compton scattering cross-section per atom is given by $Z \cdot \sigma_{cs}$, where Z is atomic number.

C. Rayleigh Scattering Effect

In Compton scattering the atomic electrons are assumed to be unbound. This assumption is only valid at photon energies which are large with respect to the electron binding energy. A low energy photon may be elastically scattered by a tightly bound atomic electron, with the atom as a whole absorbing the recoil momentum. A bound electron has a "mass" which is equivalent to that of its atom. The energy transferred to the atom is small, and so the scattered photon proceeds with a relatively unaltered energy and only a slightly altered direction. This effect is known as the Rayleigh or small-angle scattering effect.

Since all the electrons in a given atom behave similarly, Rayleigh scattering is coherent. Because all the atoms of a given solid may be packed regularly, the effect may extend to the electrons of different atoms. When the scattering angle, $\theta_R \simeq 0$, the scattering will be in phase, i.e. constructive interference. As θ_R increases the tendency is towards destructive interference and so the scattered photons will be found concentrated mainly in a narrow forward cone, and to a lesser extent in other discrete directions. This may be realized from consideration of the photon wavelength, and the atomic radius, analogous to Bragg reflection. This behaviour differs from Compton scattering, where the independence of the electrons precludes the liklihood of interference.

The transition from Rayleigh scattering to Compton scattering is smooth with increasing energy, E_{γ_o}. The Rayleigh scattered photon does not have a unique energy as a function of scattering angle, having instead an energy distribution peaked at a value close to that given by Equation (2).

D. Pair Production Effect

At photon energies of approximately 1.0 MeV the predominant interaction phenomenon is Compton scattering. As E_{γ_o} is increased considerably above this energy the photon may interact with the electric field surrounding either a nucleus or an electron. The photon will be absorbed and replaced by a pair of electrons, a positron and a negative electron. This effect is called Pair Production.

The cross-section for pair production in the field of an orbital electron is negligible until $E_{\gamma_o} \geqslant 4\, m_o c^2$, (= 2.04 MeV). Nuclear pair production, however, has a cross-section which begins at the photon threshold energy $2\, m_o c^2$, (= 1.02 MeV), and increases rapidly thereafter.

The electron pair share and carry away the energy in excess of that required for their creation, as kinetic energy; this may be expressed as

$$(E_{e^-} + E_{e^+}) = E_{\gamma_o} - 2 m_o c^2 \quad (11)$$

The free positron is quickly annihilated by a negative electron after its kinetic energy has been dissipated. The annihilation yields a randomly oriented pair of back-to-back photons, each with an energy of $m_o c^2$.

The electron pair are distributed mainly in the forward direction with the average angle of "deflection" being expressed by $m_o c^2/E_e$.
For $2 m_o c^2 < E_{\gamma_o} < 4 m_o c^2$, $\sigma_{pp} \propto Z^2$.

E. Attenuation

The passage of a beam of photons through a medium is characterized by their interactions with the atoms of that medium. This leads to a reduction in the number of uncollided primary photons at a depth. The reduction is referred to as the attenuation of the incident photon number.

The discussion on interactions has shown that the total microscopic energy dependent cross-section for a particular interaction process occurring, is given by either σ_{PE}, $Z.\sigma_{CS}$, σ_{RS} or σ_{PP}. The total cross-section $\sigma_{TOT}(E_{\gamma_o})$, for "some" process occurring, is then given by the sum of the partial cross-sections as

$$\sigma_{TOT}(E_{\gamma_o}) = \sigma_{TOT} = \sigma_{PE} + Z.\sigma_{CS} + \sigma_{RS} + \sigma_{PP}\,, \ (\mathrm{cm}^2/\mathrm{atom}) \quad (12)$$

from which a total macroscopic cross-section per cm of path may be defined as

$$\mu_{TOT}(E_{\gamma_o}) = \mu_{TOT} = N\sigma_{TOT}, \ (\mathrm{cm}^{-1}) \quad (13)$$

and similarly

$$\mu_{PE} = N\sigma_{PE} ; \mu_{CS} = NZ\sigma_{CS} ; \mu_{RS} = N\sigma_{RS} ; \mu_{PF} = N\sigma_{PP} \tag{14}$$

where

$$N = \frac{\rho \times A_V}{M} ; \quad \text{(atoms present/cc)} \tag{15}$$

assuming one type of atom only.

ρ = density of medium, (gm/cc).

A_V = Avogadro number, (atoms/mole); 6.023×10^{-23}

M = atomic or molecular weight.

The inverse of Equation (13) is defined as the mean free path, ℓ_{TOT}, for a photon prior to interaction, i.e.

$$\ell_{TOT} = \frac{1}{\mu_{TOT}} , \text{ (cm)} \tag{16}$$

Similarly ℓ_{RE}, ℓ_{CS}, ℓ_{RS}, and ℓ_{PP} may be defined from Equation (14). The total macroscopic cross-section is generally referred to as the total linear atteñuation coefficient.

The number of normally incident photons per cm^2-sec in a parallel beam which penetrate a thickness x of a homogeneous medium without interaction, is given by the exponential law as

$$\phi(x) = \phi(0)e^{-\mu x} \ (\gamma/cm^2\text{-sec}) \tag{17}$$

where

$\phi(0)$ = number of photons/cm^2-sec incident at x = 0.

$\phi(x)$ = number of photons/cm^2-sec emerging at x.

μ = cross-section appropriate to the interaction effect under consideration; energy dependent.

Thus, it follows that the probability of uncollided photon transmission through a thickness x is given by p , where

$$p = \frac{\phi(x)}{\phi(0)} = e^{-\mu_{TOT} x} \tag{18}$$

Equation (18) is in agreement with Equation (4) of Report-Section (2.2).

Similarly the probability of some kind of interaction occurring in path length x is given by

$$\epsilon_{TOT}(x) = (1 - p) = (1 - e^{\mu_{TOT} x}) \tag{19}$$

Equations , and assume a normally incident parallel or collimated, photon beam. In practice this can only be nearly achieved by narrow-geometry restrictions. For the case of a poorly collimated or uncollimated photon beam it is necessary to introduce a factor to express the increase of the photon number flux at x over the valued predicted by Equation (3.4.17). This factor, known as a number Build-Up Factor, B(x), may be defined as.

$$B(x) = \frac{\text{Total Number Flux at x}}{\text{Uncollided Flux at x}} \geq 1.0 \tag{20}$$

which is in agreement with Equation (5) of Report-Section (2.2)

Energy and dose build-up factors may be similarly defined.

That μ is a function of both incident photon energy, E_{γ_o}, and the properties of the traversed medium is apparent from the discussions of sub sections (A-D) and equations (12) to (15) . It follows then, that any property, including B (x) which is dependent on μ, is similarly dependent on E_{γ_o}.

II FAST NEUTRON INTERACTION PHENOMENA

Neutrons interact with the nuclei of traversed matter through the mechanism of nuclear force. An interaction is generally referred to as either having scattered or absorbed the incident neutron. The probability of either scattering or absorption varies as a function of the incident neutron energy and the atomic number of the target nuclide, the dependence on atomic number being general and such that for each isotope there is a unique probability, or cross-section [2,28,29].

Perhaps the most convenient and systematic manner of describing neutron interactions consists of invoking the "compound nucleus" concept. According to this concept all interaction modes result in the formation of an intermediate reaction product - a compound nucleus - formed by an absorption of the incident neutron. Symbolically this may be represented as

$$ {}_1n^0 + {}_ZX^A \longrightarrow ({}_ZY^{A+1})^* $$

where, ${}_1n^0$ is the incident neutron, ${}_ZX^A$ the target nucleus before interaction and ${}_ZY^{A+1}$ the compound nucleus formed by the interaction. The asterisk denotes that the compound nucleus will, in general, be left in an excited state for a finite period of time. The energy of the compound nucleus includes both the binding energy and/or part of the kinetic energy of the incident neutron. This energy excess over that of ${}_ZX^A$, distributed in a complex fashion among the nucleons, will cause the compound nucleus system to seek its state of lowest permissible energy in a characteristic "relaxation time", typically about 10^{-20} to 10^{-12} seconds.

The laws of quantum mechanics allow only those reactions to take place which obey certain rigid energy and momentum relationships. This obedience is observed with respect to the available excitation energy of the incident neutron and the distribution of energy levels in the target nucleus, as well as with respect to the symmetry requirements of the interaction,

e. g. parity, baryon number, charge conservation, statistics.

In accord with the compound nucleus concept, scattering and absorption of an incident neutron may be defined in terms of whether or not the compound nucleus emits a neutron during de-excitation. Further and more important, scattering may be separated into two kinds - elastic and inelastic. In elastic scattering the compound nucleus emits a kinetic energy degraded neutron in a very short relaxation time $<10^{-20}$ seconds, and is itself left in exactly the same internal energy state as before the interaction. In inelastic scattering the compound nucleus emits a neutron of partially or totally degraded kinetic energy and is itself left in an internal energy state above that of ${}_{Z}X^{A}$; the excess energy is evolved by emission of one or more gamma photons. The degradation of the neutron kinetic energy by scattering is referred to as thermalization. The compound nucleus may be de-excited by emission of particles other than neutrons, such as alphas and betas accompanied by gamma photons in which case neutron absorption is said to have resulted.

The interaction processes reviewed above are summarized:

(i) Elastic Scattering, (n,n)——A neutron of reduced kinetic energy is emitted by the short-lived compound nucleus which is left in an unexcited state. Kinetic energy is transferred to recoil the target nucleus. In the case of hydrogen target nuclei, for which energy transfer is a maximum, recoil protons result.

(ii) Inelastic Scattering, (n,n')——A neutron of reduced kinetic energy is emitted by the compound nucleus. The compound nucleus is de-excited by gamma photon emission.

(iii) Radiative Capture, (n,γ)——The compound nucleus formed by absorption of an incident neutron is de-excited by relatively high energy gamma photon emission.

(iv) Charged Particle Emission, (n,p), (n,d), (n,α)——The compound nucleus formed by absorption of an incident neutron is de-excited by emission of a charged particle such as a proton, deuteron or alpha, accompanied by gamma photons.

(v) Fission, (n,f)——The compound nucleus formed by absorption of an incident neutron breaks into two ionizing fission fragments, and one or more energetic neutrons, accompanied by gamma photon emission. Fission is most probable in heavy nuclei of odd mass number and less so in heavy nuclei of even mass number. It can occur either as the result of an externally incident neutron or as a consequence of quantum mechanical leakage through the Coulomb barrier, ie., spontaneous fission.

(vi) Other Reactions, (α,n), (γ,n)——Two interaction processes which give rise to neutron emission and thus which must be identified are (α,n) and (γ,n) phenomena in the plutonium-oxide source and its immediate environment. The first reaction proceeds when the energy of an alpha particle exceeds the energetic threshold and Coulomb repulsion barrier for the reaction, and is thus significant only for plutonium alphas (~5.5 meV) incident on light-target nuclei such as beryllium. The second reaction, photo-neutron formation, results from the interaction of high energy gamma photons with light nuclei such as are present in plutonium-oxide as impurities. High energy photons are present in the PuO_2 source through (n,f) reactions and the decay of the $T\ell^{208}$ daughter of the Pu^{236} isotope present in plutonium oxide.

APPENDIX II

SUMMARY DESCRIPTION OF SUBPROGRAM NUGAM1

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Code NUGAM1 derived from NUALGAM[3], is programmed to predict differential and integral energy-angular fractional gamma photon number transport in cylindrical media geometries. It employs the Monte Carlo technique of following and catagorizing a large number of photons from "birth to death". It uses random number and probability theory combined with known interaction distributions to determine such as source and collision site spatial location, as well as trajectory energy and direction throughout each history.

After n interaction events in the source medium, photon number state may be characterized as

$$N_n = N(E_n, \theta_n, \Phi_n, x_n, y_n, z_n; E_m, \theta_m, \Phi_m, x_m, y_m, z_m), \quad (1)$$

where

E = photon energy

θ = polar angle

$\Phi \doteq$ azimuth angle

x, y, z = Cartesian co-ordinates

n = subscript to denote n^{th} event

m = $n-1$, a subscript; $0, 1, \ldots, m, n, \ldots$

o = subscript to denote photon history origin, i.e. "zero interaction,

which describes the spectrum at the arbitrary point $P_n(x_n, y_n, z_n)$. If interaction site P_n is outside the boundaries of the cylinder of height h and radius ρ, and P_m is within, then the fate of the photon is deemed as escape, and so tallied by the code. If an escape is recorded at P_n where $P_m = P_o$, then the photon escape energy is unaltered and identical with the initial or birth energy. A typical escape history is indicated in Figure II-1, where escape is shown between P_2 and P_3. The code employs Cartesian co-ordinates and direction cosines to determine trajectory between interactions.

Although Equation (1) and Figure II-1 characterize photon history state, terminal escape classification is computed with respect to space co-ordinates $(0, 0, \frac{h}{2})$. If a detection band about the Z-axis is assumed at a great distance from the source cylinder then all photons escaping from any point on the source boundary and striking the band may be considered as having the same Z-axis directional cosine. If the detection band subtends the solid angle $d\Omega$ at $\Omega(0, 0, \frac{h}{2})$ then, the photon escape state may be characterized as

$$N = N(E, \Omega) \quad , \tag{2}$$

where

$$E = \text{photon escape energy} \quad .$$

In Equation (2) the understood arguments and subscripts are omitted. Multiplying by differentials in energy and solid angle, the differential angular-energy photon number escape spectrum is given by

$$dN(E, \Omega) = N(E, \Omega)\, dE d\Omega \,, \tag{3}$$

keeping in mind that

$$d\Omega = \text{Sin}\,\theta\, d\,\theta\, d\,\Phi, \tag{4}$$

where

θ = polar angle between escape vector and Z-axis; $0 \leq \theta \leq \pi$

Φ = azimuth angle of escape vector; $0 \leq \Phi \leq 2\pi$.

Substitution of Equation (4) into Equation (3) and integration over energy and angle between desired limits gives the total photon number escaping from the source. The geometry for photon history escape classification is illustrated in Figure II-2.

The co-ordinates of the source point P_o, within the source cylinder are chosen by random number selection as[13]

$$\begin{aligned} z_o &= R_i \cdot h \\ d_o &= \rho \sqrt{R_{i+1}} \\ \Phi_o &= (2 R_{i+2} - 1)\,\pi \end{aligned} \tag{5}$$

where

$d_o = (x_o^2 + y_o^2)^{1/2}$

R_i = denotes a sequence of pseudo random numbers.

The initial direction cosines of the source history are determined similarly by random number selection as[13]

$$\begin{aligned} w &= 2 R_{i+3} - 1, \\ u &= \cos\left[(2 R_{i+4} - 1)\,\pi\right] \; (1-W^2)^{1/2}, \\ v &= \cos\left[(2 R_{i+4} - 1)\,\pi\right] \; (1-W^2)^{1/2}. \end{aligned} \tag{6}$$

The direction cosines u, v, w, correspond to co-ordinates (x_o, y_o, z_o) of Equations (5).

Source photons are initiated with a probability of existence or weight W, equal to 1.0. This weight is reduced after each interaction by the ratio of the scattering to total cross-section. Thus photons are not lost to absorption unless their reducing weight drops below an assigned value, 10^{-5} in NUGAM1. Photons may be lost to absorption if their degraded energy drops below an input threshold value.

The path length between interactions, ℓ, is a function of energy and material composition. It may be determined according to the Monte Carlo technique[14] as

$$\ell = \ell_1 + \ell_2 + \cdots + \ell_{j-1} + \lambda_j^{-1} \left(-\log_e R_i - (\lambda_1 \ell_1 + \lambda_2 \ell_2 + \cdots + \lambda_{jr} \ell_{j-1})\right) \quad (7)$$

where

ℓ_j = actual path length of photon in medium region j

λ = total mean free path for a photon of given energy in a given medium j.

Energy deposition within the source cylinder at the n^{th} interaction site is determined as

$$I_n = \frac{W_m}{\sigma_t} \left(E_m \left(\mu_{pp} + \mu_{pe} \right) + \mu_s \left(E_m - E_n \right) \right), \quad (8)$$

where

W_m = weight after m^{th} interaction

E = photon energy

μ = macroscopic interaction cross-section

pp, pe, s, t = subscripts to identify pair production, photoelectric scattering and total cross-sections

$$\mu_t = \mu_{pp} + \mu_{pe} + \mu_s .$$

The macroscopic cross-sections μ_{pp} and μ_{pe} are determined from the microscopic cross-sections σ_{pp} and σ_{pe} input to code NUGAM1, in accord with the well known relationship

$$\mu = Ao \sum_{i=1}^{i=k} \frac{\rho i \, \sigma i}{A_i} , \tag{9}$$

where

A_o = Avogadro number; 0.6023×10^{24}

ρ = material or element density

A = material or element atomic weight

i = subscript to denote summation for elements, kinds 1 to k

The total macroscopic Compton scattering cross-section per atom is obtained from Equation (9) and

$$\sigma s_i = Z_i \cdot \sigma_{es} , \tag{10}$$

where

Z_i = material or element atomic number

σ_{es} = total microscopic Compton scattering cross-section per electron.

The scattering cross-section σ_{es} is obtained from the Klein-Nishina relationship as[13]

$$\sigma_{es} = 2\pi r_o^2 \left[\frac{2}{E^2} + \frac{1 + E}{(1 + 2E)} 2 + \ln (1 + 2E) (\frac{E^2 - 2E - 2}{2E^3}) \right] , \tag{11}$$

where

r_o = 0.28183×10^{-12} cm

E = photon energy in m_oc^2 (= .51097 MeV) units .

Direction and energy after a scattering are governed by the angular differential form of the Klein-Nishina distribution, with energy related to direction by the Compton scattering relationship(13). Code NUGAM1 selects scattering angle and energy in accord with the method outlined by Kahn in reference (30).

At photon energies greater than 2 m_oc^2 (= 1.02 MeV) pair production results. The code temporarily stores the parent photon characteristics and initiates a daughter photon with isotropically selected direction and energy m_oc^2 (= 0.51097 MeV). The daughter is attributed twice the parent weight in order to simulate an actual photon pair. Upon termination of the daughter history, the parent history is recontinued.

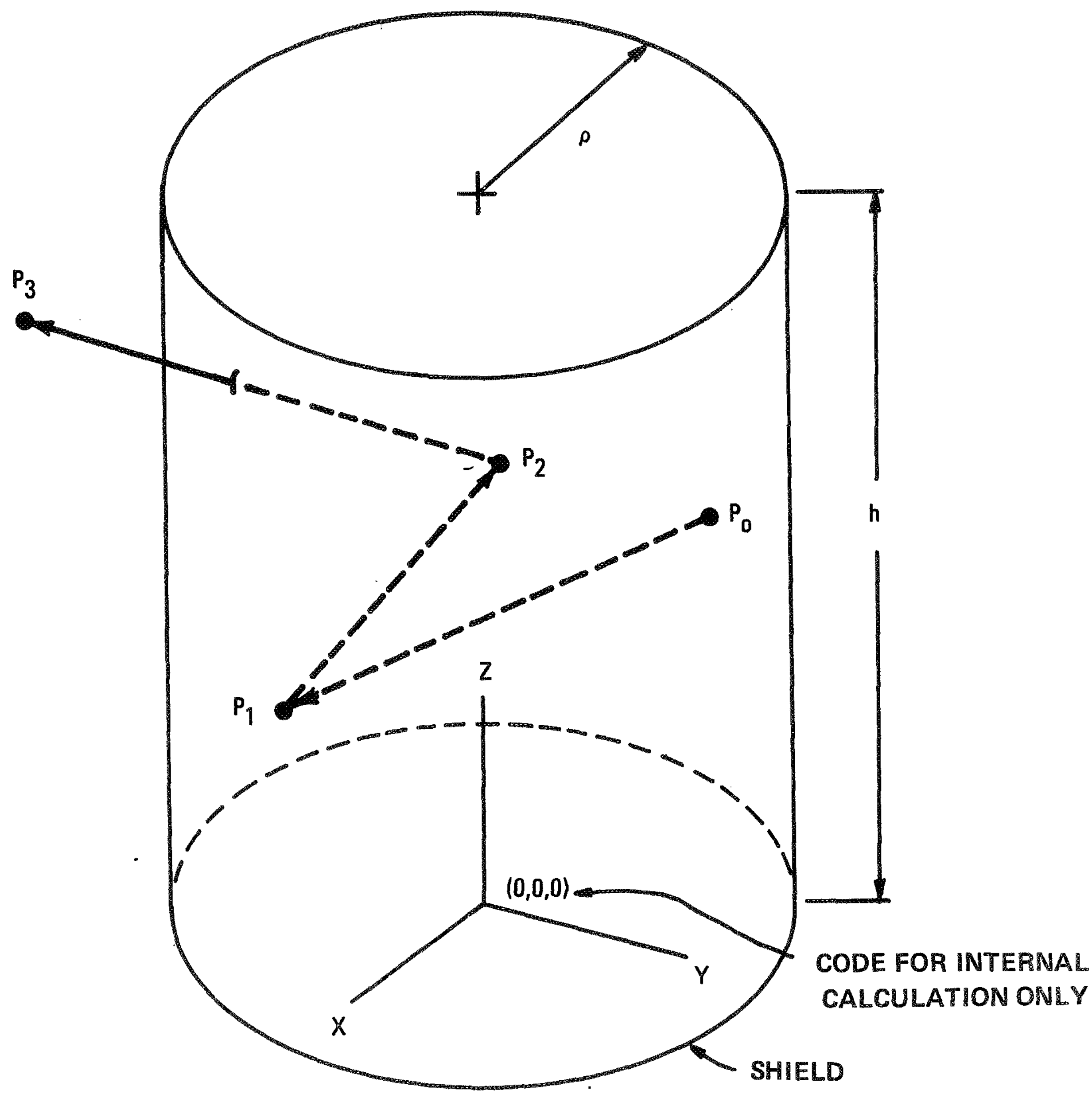

Figure II - 1

Typical Photon Escape History

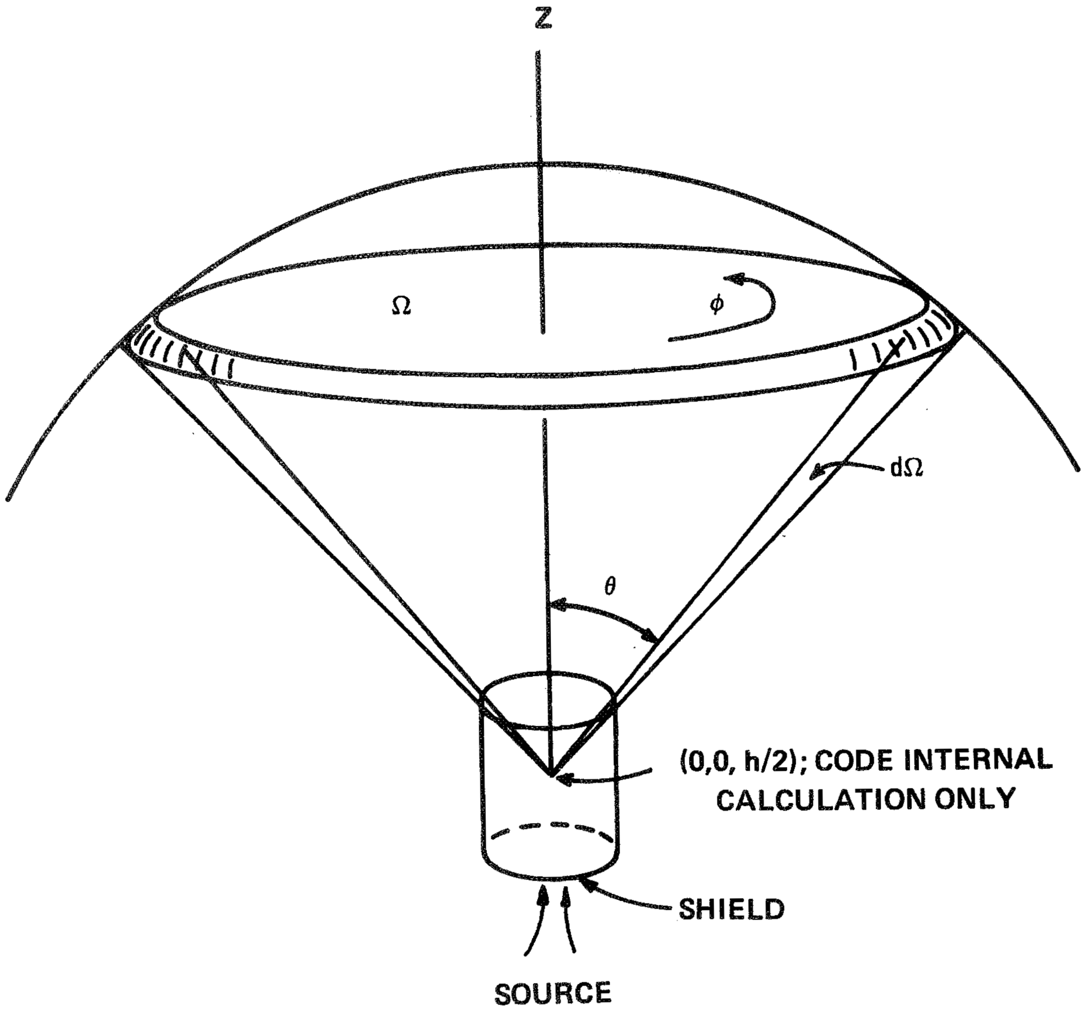

Figure II - 2

Photon History Escape Classification Geometry

APPENDIX III

CODE SØSC FORTRAN LISTING

```
//ZLJUSOSC JOB (NU00311120A,1,H00017,003001),0A5,MSGLEVEL=1
// EXEC FORTRAN,PARM=BCD
//SOURCE.SYSLIN DD UNIT=2314,SPACE=(CYL,(10,5))
//SOURCE.SYSPRINT DD SPACE=(CYL,(2,1))
//SOURCE.SYSIN DD *
C
C
C   PROGRAM SOSC - THE SHIELD OPTIMIZATION STUDY CODE   (MCS CORP.  DEC.,1969)
C                       LAMINATED SHIELD
C
C        SOSC-MAIN PROGRAM
C
      DIMENSION FF(20),MAT(9),AZ(9),RA(9),SS(20), SN(20),FN(20),DENS(5)
      DIMENSION TITLE(80),SAFX(20),SAFNX(20)
      COMMON/PARAM/DUUM(2),ECT,DDUM(5),NOM
      COMMON/RATIO/RA,NE,NME,MN,MG
      COMMON/CONST/PYE,RADAR
      COMMON/PHLUX/FX,SEX(20),SENX(20),BMU(20),ATT(20),BU(20),ATTN(20)
      COMMON/SOURSE/SS,SN,FF,FN,SSA(20),SSNA(20)
      COMMON/CORDS/XS,XD,YS,YD,ZS,ZD,CMPI
      COMMON/TAL/DUM4(1045),INE,IMA,DUM5(1051)
      COMMON/OI/IDENT(19),HEIGHT,RADIUS,HOL,ROR,DIST
      COMMON/RAND/NRAND,NRNDOM
      COMMON/LENG/HT(9),RADSQ,HGAMA(20)
      COMMON/NST/NOP
      COMMON/DENT/DENSY(9,5),NELE(9),ZZ(9,5),WTDEN,ELDENT
      COMMON/LIO/NOPT
      COMMON/STOD/RCM
      COMMON/NLP/NOES,LE(20),NPATH(18)
      CMPI=2.54
      PYE=4.*ATAN(1.0)
      RADAR=180.0/PYE
      NME=20
      NE=20
      MN=0
      MG=0
C FACTORS TO CONVERT RADIAL TO AXIAL SPECTRUM
C     FATPG=0.08333
C     FATPN=0.80
      DO 10 K=1,20
      SS(K)=0.0
      SN(K)=0.0
      FF(K)=0.0
      FN(K)=0.0
      SEX(K)=0.0
      SENX(K)=0.0
   10 CONTINUE
      KUNTER=0
      WRITE(6,300)
  300 FORMAT(1H1,//40X,12H SOURCE DATA )
    9 READ(5,350)(NPATH(K),K=1,18)
  350 FORMAT(18I4)
      KUNTER=KUNTER+1
      IF (NPATH(2)-2) 7,5,7
    5 READ(5,100)XS,YS,ZS,XD,YD,ZD ,RADIUS,DIST
  100 FORMAT(6F10.4,2F6.3)
      RSD=SQRT((XD-XS)**2+(YD-YS)**2+(ZD-ZS)**2)
      RCM=RSD*CMPI
      P4=4.*PYE*RCM*RCM
      RADIUS=RADIUS*CMPI
```

```
      DIST=DIST*CMPI
    7 IF(NPATH(3)-3) 6,8,6
    8 READ(5,120)NF,NG,NNF,INF,NOPI,NRAND,NOES,ALLOWF,FCT,ARREST,TANDEM,
     1 ERG,ERN
  120 FORMAT(7I5,6F7.4)
      IF(NF.LE.4) GO TO 11
      READ(5,121)(LE(K),K=1,NOES)
  121 FORMAT(20I4)
   11 READ(5,122)(HGAMA(K),K=1,NOES)
  122 FORMAT(20F4.0)
    6 IF (NPATH(4)-4) 15,12,15
   12 IF (NG-1) 3,2,3
    3 NG=NG+1
      MG=1
      READ(5,101)(FE(II),II=1,NF)
  101 FORMAT(12F6.2)
      READ(5,130)(SS(I),I=1,NF)
  130 FORMAT(7F10.3)
      IF(NG.EQ.1) GO TO 1
    2 MN=1
      READ(5,140)     (EN(II),II=1,NNF)
  140 FORMAT( 7F10.5    )
      READ(5,130) (SN(I),I=1,NNF)
    1 S=0.0
      SA=0.0
      WRITE(6,301)
  301 FORMAT( // 2X,15HGAMMA SPECTRUM ,16X,74H ENERGY(MEV)       NO.OF GA
     1MMA/SEC       NO.OF GAMMA/SEC     FLUX AT DETECTOR ,4X,16HFLUX AT DE
     2TECTOR /55X,8H(RADIAL),13X,7H(AXIAL),12X,8H(RADIAL),12X,7H(AXIAL)
     3 /)
      DO 1000 I=1,NF
      SSA(I)=SS(I)*ERG
      S=S+SS(I)
      SA=SA+SSA(I)
      SAFX(I)=SS(I)/P4
      SFX(I)=SSA(I)/P4
      WRITE(6,302)I,FE(I),SS(I),SSA(I),SAFX(I),SFX(I)
  302 FORMAT(20X,I5,5F20.7)
 1000 CONTINUE
      TSFX=S/P4
      TSFAX=SA/P4
      WRITE(6,303) S,SA,TSFX,TSFAX
  303 FORMAT( /35X,10H    TOTAL=    ,4F20.7)
      IF(NG.EQ.1) GO TO 4
      WRITE(6,304)
  304 FORMAT(//2X,17HNEUTRON SPECTRUM, 14X,74H ENERGY(MEV)       NO.OF NE
     1UT./SEC       NO.OF NEUT./SEC     FLUX AT DETECTOR ,4X,16HFLUX AT DE
     2TECTOR /55X,8H(RADIAL),13X,7H(AXIAL),12X,8H(RADIAL),12X,7H(AXIAL)
     3 /)
      SSNAX=0.0
      SSN=0.0
      DO 2000 I=1,NNF
      SSNA(I)=SN(I)*ERN
      SSNAX= SSNAX+SSNA(I)
      SSN=SSN+SN(I)
      SAFNX(I)=SN(I)/P4
      SFNX(I)=SSNA(I)/P4
      WRITE(6,302)I,EN(I),SN(I),SSNA(I),SAFNX(I),SFNX(I)
 2000 CONTINUE
      TSFNX=SSN/P4
```

```
      TSENAX=SSNAX/P4
      WRITE(6,303)SSM,SSMAX,TSENX,TSENAX
    4 WRITE(6,200) PCM,ALLOWE
  200 FORMAT( //,38H DIST. BET. SOURCE AND DETECTOR (CM)= ,F12.4,9X,
     125HALLOWED FLUX AT DETECTOR=,F12.4)
   15 IF(NPATH(5)-5) 17,16,18
   16 TOTSAA=0.0
      GO TO 19
   17 TOTSAA=SAVE
      GO TO 19
   18 CONTINUE
C BECAUSE NO NEUTRON ALBEDO CALCULATION  SET MN=0
      MN=0
      CALL ALB(TOTSAA)
      SAVE=TOTSAA
      MN=1
   19 FX=ALLOWE-TOTSAA
      WRITE(6,110)TOTSAA,FX
  110 FORMAT(22H TOTAL SCATTERED FLUX= ,F12.4,5X,25H ALLOWED ATTENUATED
     1FLUX= ,F12.4)
   20 IF(NPATH(6)-6) 30,21,30
   21 READ(5,113)(TITLE(I),I=1,80)
  113 FORMAT(80A1)
      WRITE(6,114)(TITLE(I),I=1,80)
  114 FORMAT(1H1,80A1,//)
      READ(5,111)NOM
  111 FORMAT(I5)
      READ(5,109) (RA(I),NELE(I),I=1,NOM)
  109 FORMAT(10(F5.2,I2))
      IF (NPATH(7)-7)25,23,25
   23 DO 250 I=1,NOM
      NELEN=NELE(I)
      DENS(I)=0.0
      READ(5,112)(ZZ(I,J),DENSY(I,J),J=1,NELEN)
  112 FORMAT(7(F4.0,F6.4))
      DO 149 J=1,NELEN
  149 DENS(I)=DENS(I)+DENSY(I,J)
  250 CONTINUE
      NOR=0
      CALL GTSIGM(1,1,NOM,A,B)
   25 WTDEN=0.0
      DO 160 I=1,NOM
  160 WTDEN=WTDEN+DENS(I)*RA(I)
      IT=0
      NOR=1
      CALL BLDUP(1.0 ,BU,BNU,IT)
      CALL XEST (NOM,X, IT)
   55 IT=IT+1
      CALL BLDUP(X,    BU,BNU,IT)
      CALL XEST (NOM,X1,IT)
      ENDURE=ABS(X1-X)/X1
      WRITE(6,115) ENDURE,ARREST
  115 FORMAT(/20H ACCURACY FRACTION =,F8.5,7X,21HARRESTING CRITERION =,
     1        F8.5)
      X=X1
      WRITE(6,116)(TITLE(I),I=1,80)
  116 FORMAT(//1X,80A1)
      IF(IT.GE.3)GO TO 29
      IF(ENDURE.GT.ARREST) GO TO 55
   29 WRITE(6,117) KUNTER
```

```
117 FORMAT(///5X,39HEND OF CALCULATION FOR SHIELD NUMBER *,I2,1H*)
 30 IF (NPATH(1).GE.0) GO TO 9
    STOP
    END
    SUBROUTINE BLDUP(X,    BU,BNU,IT)
    DIMENSION EN(20),FACTS(20),FACTMS(20),F(20),Y(6),Z(6),FWNOPS(20)
    DIMENSION BU(20),BNU(20),AT(20),B(20),BEX(20)
    COMMON/STOP/FCM
    COMMON/TAL/DUM4(1045),INE,INA,DUY5(1051)
    COMMON/SOURSE/DUMS(40),EE(20),EM,     DUMSS(40)
    COMMON/RATIO/RA(9),NE,NNE,MN,MG
    COMMON/CONST/PYE,RADAR
    COMMON/RAND/NRAND,NRNDOM
    COMMON/PARAM/NGAMA,EZERO,ECT,DUM(5),NOM
    COMMON/OUTP/NCOLL(151),DUM1(604),BVOL(151),DUM7(604)
    COMMON/OI/NB,IDENT(18),HEIGHT,RADIUS,HOL,ROR,DIST
    COMMON/SPE/ESPECT(30),SPECT(30),NREAD,LOOPN,DUM6(20)
    COMMON/PHLUX/EX,SEX(20),DUMPH(40),ATT(20),DUMPH1(20),ATTN(20)
    COMMON/LIO/NOPT
    COMMON/DENT/DENSY(9,5),NELE(9),ZZ(9,5),WTDEN,ELDENT
    COMMON/EWNO/TEW,TEWPS
    COMMON/NLP/NOES,LE(20),NPATH(18)
    COMMON/LENG/HT(9),RADSQ,HGAMA(20)
    SPECT(1)=1.0
    NREAD=1
    NDISTN=1
    NNGAMA=1000
    RADSQ=RADIUS*RADIUS
    OMEGA0=2.*PYE*(1.-DIST/SQRT(DIST*DIST+RADSQ))
    IF(IT.NE.0)GO TO 50
    DO 20 I=1,20
    BU(I)=1.0
    BNU(I)=1.0
 20 CONTINUE
    RETURN
 50 HEIGHT=X
    BVOL(1)=PYE*HEIGHT*RADSQ*WTDEN
    RC=RCM-X-DIST
    FACK=1.0/(RC*RC)
    DO 51 J=1,NOM
 51 HT(J)=RA(J)*HEIGHT
    IF(NE.LE.4) GO TO 41
    IF(NOES.EQ.NE) GO TO 41
    DO 60 J=1,NOES
    JJ=LE(J)
    E(J)=EE(JJ)
    ESPECT(1)=E(J)
    NGAMA=NNGAMA*HGAMA(J)
    CALL NUGAM1
    FWNOPS(J)=TEWPS/NGAMA
    AT(J)=ATT(JJ)
    B(J)=1.+FWNOPS(J)*OMEGA0/AT(J)
 60 CONTINUE
C     WRITE(6,100) OMEGA0,BVOL(1),X,(J,LE(J),E(J),FWNOPS(J),B(J),
C    1                 J=1,NOES)
100 FORMAT(9H OMEGA0= ,F12.4,9H    BVOL= ,F12.4/
   165H NUGAM1 IS CALLED AT       ENERGY(MEV)      NO IN FW-CONE/STER    B-
   2UP,9X,16H    FOR SHIELD = ,F10.5,5H (CM) /
   3(1X,2I8,2X,3E17.7))
 55 DO 40 J=1,NE
```

```
      EO=EE(J)
      CALL TA(EO ,E,4,1,MOX,MUN,Z,Y,B,2,L,0)
      BU(J)=TE(3,Z,Y,EO)
   40 CONTINUE
      GO TO 43
   41 NOES=NE
      DO 42 J=1,NOES
      ESPECT(1)=EE(J)
      NGAMA=NNGAMA*HGAMA(J)
      CALL NUGAM1
      EWNOPS(J)=TEWPS/NGAMA
   42 BU(J)=1.+EWNOPS(J)*OMEGA0/ATT(J)
   43 CONTINUE
C  43 WRITE(6,110)(J,EE(J),          BU(J),J=1,NE)
  110 FORMAT(//31H GAMMA     NO        ENERGY(MEV)                 6X,     18H
     1    CALCULATED B-UP      /(9X,I3,2E20.5))
      IF(MN.EQ.0) GO TO 31
C     WRITE(6,120)(K,EN(K),          BNU(K),K=1,NNE)
  120 FORMAT(//31H NEUTRON   NO        ENERGY(MEV)                 6X,     18H
     1    CALCULATED B-UP      /(9X,I3,2E20.5))
   31 RETURN
      END
      SUBROUTINE XEST(NOM,XXST,IT)
      DIMENSION MZ(9),EE(20),B(20), PA(9),Z(6),Y(6),UMU(9,20),CUMU(20),
     1XSECT(3),EPG(20),XMU(20),EN(20),EG(20),
     2XNU(20),EGN(20),CUMU(20),UMU(9,20),ENY(30),XS(30),XNCT(5,30)
      COMMON/CONST/PYE,RADAP
      COMMON/SOURSE/DUMSS(40),EE,EN,SS(20),SN(20)
      COMMON/DENT/DUM(9,5),NDUM(9),ZDUM(9,5),WTDEN,ELDENT
      COMMON/RATIO/PA,NE,NNE,MN,MG
      COMMON/PHLUX/FX,SEX(20),SENX(20),BNU(20),ATT(20),B,ATTN(20)
      COMMON/LENG/HT(9),RADSO,HGAMA(20)
      COMMON/NLP/NOES,LE(20),NPATH(18)
      IF(IT.NE.0) GO TO 42
      IF(MG-1)43,53,43
   53 DO 26 J=1,NE
      EO=EE(J)/.51097
      UM=0.0
   11 DO 25 N=1,NOM
      CALL GTSIGW(3,1,N,EO,XSECT)
      UMU(N,J)=XSECT(1)
      UM=UM+PA(N)*UMU(N,J)
   25 CONTINUE
      CUMU(J)=UM
   26 CONTINUE
   43 IF(MN-1)42,52,42
   52 IF(NPATH(7)-7) 46,45,46
   45 DO 39 N=1,NOM
      NRATS=NDUM(N)
      CALL NENSIG(NOM,ENY,XS,NRATS)
      DO 30 LN=1,NOM
   30 XNCT(N,LN)=XS(LN)
   39 CONTINUE
   46 DO 226 J=1,NNE
      EOO=EN(J)
      UM=0.0
      DO 225 NN=1,NOM
      CALL TA(EOO,ENY,NOM,1,MOX,MUN,Z,Y,XS,2,L,0)
      Y(1)=XNCT(NN,L+1)
      Y(2)=XNCT(NN,L+2)
```

```
      Y(3)=XNCT(NN,I+3)
C     WRITE(6,9999) NON,MOX,MUN,L,(Z(KA),Y(KA),KA=1,3),EOO
      UNU(NN,J)=TE(3,7,Y,EOO)
      UN=UN+RA(NN)*UNU(NN,J)
  225 CONTINUE
      CUMU(J)=UN
  226 CONTINUE
   42 CONTINUE
      X=1.0
      KAY=0
   31 FLU=0.0
      FLN=0.0
      IF(MG-1)41,51,41
   51 DO 27 J=1,NF
      XMU(J)=X*CUMU(J)
      FG(J)=B(J)*EXP(-XMU(J))*SEX(J)
   27 FLU=FLU+FG(J)
   41 IF(MN-1)40,50,40
   50 DO 72 J=1,NNF
      XNU(J)=X*CUMU(J)
      BNU(J)=1.0
      FGN(J)=BNU(J)*EXP(-XNU(J)*0.67)*SENX(J)
   72 FLN=FLN+FGN(J)
   40 FLUS=FLU+FLN
      IF(FLUS-FX)28,28,29
   29 X=X+1.0
      FLUU=FLUS
      GO TO 31
   28 IF(KAY-0)33,32,33
   32 FLO=FLUS
      KAY=1
      X=X+1.0
      GO TO 31
   33 CONTINUE
      Z(1)=FLUU
      Z(2)=FLO
      Z(3)=FLUS
      Y(1)=X-2.0
      Y(2)=X-1.0
      Y(3)=X
      XXST=TE(3,7,Y,FX)
      DO 60 J=1,NF
      ATT(J)=      EXP(-CUMU(J)*XXST)
   60 CONTINUE
      WRITE(6,99)
   99 FORMAT(1H0/,125H     J     ENERGY(MEV)    WTD-MU(CM-1)        WTD-MU*X
     1    NO.AT SOURCE BARE FLUX AT D  BUILDUP FACT.   ATT.FLUX AT D   ATT.
     2FAC(XEST)   )
      WRITE(6,100)(J,EE(J),CUMU(J),XMU(J),SS(J),SEX(J),B(J),FG(J),ATT(J)
     1 ,J=1,NF)
  100 FORMAT(12H GAMMA-DATA /(2X,I3,8E15.4))
      IF(MN-1)90,80,90
   80 DO 70 I=1,NNF
   70 ATTN(I)=        EXP(-CUMU(I)*XXST)
      WRITE(6,200)(J,EN(J),CUMU(J),XNU(J),SN(J),SENX(J),BNU(J),FGN(J),
     1ATTN(J),J=1,NNF)
  200 FORMAT(14H NEUTRON-DATA /(2X,I3,8E15.4))
   90 WRITE(6,101)XXST,FX,(Y(I),Z(I),I=1,3)
  101 FORMAT(1H1,2X,47HDETECTED FLUX AS A FUNCTION OF SHIELD THICKNESS
     1          //8X,34H X-EST. (CM)    FLUX(NO/CM*CM*SEC)   /(2(6X,E14.5)))
```

```
      WPL=XXST*WTDEN
      WT=WPL*PYE*RADSQ
      WRITE(6,102) IT,XXST,WTDEN,WT
  102 FORMAT(///15H ITERATION NO.=,I3,/21H  SHIELD LENGTH(CM) =,F10.4,
     1    5X,20H  WEIGHTED DENSITY= , F8.4,5X,12H WT.(GRAMS)=,F12.4)
      RETURN
      END
      SUBROUTINE NENSIG(NON,ENY,XS,NELE)
      DIMENSION ENY(30),XS(30),ENN(30),XSN(30) ,Z(6),Y(6)
      COMMON/DENT/DUM(100),FLDENT
      FLDENT=0.0
      DO 5 L=1,30
    5 XS(L)=0.0
      IDENS=0.0
      DO 49 KM=1,NELE
      FINT=0.1
      EN=0.0
      N=0
      READ(5,1000)NN,DENSTY,ATOMNO,ANDAW,(ENN(I),XSN(I),I=1,NN)
 1000 FORMAT(I2,3F10.5/(10F7.2))
      ADEN=0.6023*DENSTY/ANDAW
      FLDEN=ADEN*ATOMNO
    7 EN=EN+FINT
      CALL TA(EN,ENN,NN,1,MOX,MUN,Z,Y,XSN,2,L,0)
      XNN=TF(3,Z,Y,EN)
      N=N+1
      ENY(N)=EN
      XS(N)=XS(N)+XNN*ADEN
      IF(EN.GE.0.99)FINT=0.5
      IF(EN.GE.4.9) FINT=1.0
      IF(EN-12.0) 7,9,9
    9 NON=N
      FLDENT=FLDENT+FLDEN
   49 CONTINUE
C     WRITE(6,501)(ENY(LL),XS(LL),LL=1,NON)
  501 FORMAT(16H NEUTRON X-SECT.,4(2X,2E12.4))
      RETURN
      END
      SUBROUTINE GENSIG(K1,FLOW,NINT,NERAN,ERG,NRANGE,XSECT,NMED)
      SUB GENERATES CROSS-SECTIONS
      COMMON/LIO/NOPT
      COMMON/NST/NOR
      COMMON/DENT/DENS(9,5),NELL(9),ZZ(9,5),WTDEN,FLDENT
      COMMON/EROR/I
      DIMENSION E(40),SIGPE(40),SIGPP(40),XSECT(8330),ERG(20)
     1   ,ENERGY(1000)
      READ(5,1)NINT,ILOW,IHIGH
    1 FORMAT(3I5)
      LEMNO=1
      KP=K1+1
      MNINT=2**NINT
      NERAN=MNINT*(IHIGH-ILOW)+1
      GO TO (2,3),KP
    2 MRANGE=2*NERAN
      GO TO 4
    3 MRANGE=3*NERAN
    4 ELOW=2.**ILOW
      XNINT=2.**NINT
      NRANGE=MRANGE*NMED
      DO 37 J=1,NMED
```

```
      JENC=MRANGE*(J-1)
      J1=JENC+1
      J2=JENC+MRANGE
      NELE=NELL(J)
      ELDENT=0.0
      DO 5 K=J1,J2
    5 XSECT(K)=0.
      IF(NOPT.EQ.0) GO TO 401
      WRITE(6,201)NINT,ILOW,IHIGH,NELE,NOR
  201 FORMAT(1H1, ///40X,30H GENERATED CROSS-SECTION DATA    //
     1         8H NINT = ,I5,6X,7HILOW = ,I5,6X,8HIHIGH = ,I5,6X,14HNO.ELE
     2MENTS = ,I5,6X,6HNOR = ,I5)
  401 DO 31 LL=1,NELE
      READ(5,7)NE,DENSTY,ATOMNO,ANDAW
    7 FORMAT(I5,5X,3F10.5)
      IF(NOPT.EQ.0) GO TO 402
      WRITE(6,999)NE,NERAN,ATOMNO,DENSTY,MNINT,ANDAW
  999 FORMAT(30H NO.CROSS-SECTION ENERGIES      ,I5,6X,26HNO.ENERGY SUBIN
     1TERVALS       ,I5,12X,13HATOMIC NUMBER,11X,F12.5/1X,15HDENSITY (GM/C
     2C) ,7X,F12.5,6X,26HINTERVALS/ENERGY GROUP      ,I5,12X,13HATOMIC WE
     3IGHT ,11X,F12.5)
  402 DO 50 JK=1,LEMNO
      READ(5,6)(E(K),SIGPE(K),SIGPP(K),K=1,NE)
      IF(NOPT.EQ.0) GO TO 50
      WRITE(6,206)(E(K),SIGPE(K),SIGPP(K),K=1,NE)
   50 CONTINUE
    6 FORMAT(9F8.3)
  206 FORMAT(42H MICROSCOPIC CROSS-SECTION TABLE (INPUT)    /(1X,6E18.7))
      ADEN=(0.6023/ANDAW)*DENSTY
      ELDEN=ADEN*ATOMNO
      ELDENT=ELDENT+ELDEN
      IF(NOPT.EQ.0) GO TO 403
      WRITE(6,8)ADEN,ELDEN
    8 FORMAT(/8H  ADEN= ,E14.7,10H    ELDEN=  ,E14.7//
     112X,8HSIGMA-TL,7X,8HSIGMA-PE,7X,8HSIGMA-PP,7X,8HSIGMA-SC,7X,6HENER
     2GY /)
  403 DO 3000 K=1,NE
      IF(SIGPE(K)) 3001,3001,3000
 3001 KAY=K
      CAY=(SIGPE(K-2)*E(K-2)**3+SIGPE(K-1)*E(K-1)**3)/2.0
      IF(NOPT.EQ.0) GO TO 3003
      WRITE(6,2999)KAY,CAY
 2999 FORMAT(6H  KAY=,I5,7H  CAY= ,E14.7)
      GO TO 3003
 3000 CONTINUE
      GO TO 3005
 3003 DO 3004 K=KAY,NE
 3004 SIGPE(K)=CAY/E(K)**3
 3005 CONTINUE
      DO 9 K=1,NE
      SIGPP(K)=ADEN*SIGPP(K)
      E(K)=E(K)/.51097
      ASIG=SIGMAS(E(K))*ELDEN
      SIGPE(K)=SIGPE(K)*ADEN
      ATOTAL=SIGPE(K)+SIGPP(K)+ASIG
      IF(NOPT.EQ.0) GO TO 9
      WRITE(6,88)ATOTAL,    SIGPE(K),SIGPP(K),ASIG,E(K),K
   88 FORMAT(8X,5E15.7,I10)
    9 CONTINUE
      DEL=ELOW/XNINT
```

```
      FN=FLOW
      I=1
      L=1
      M=1
   10 IF(F(I+1)-FLOW)11,11,100
   11 I=I+1
      GO TO 10
  100 GO TO (12,101),KP
  101 IPP=I
  102 IF(SIGPP(IPP))103,104,105
  103 CALL ERROR(SIGPP(IPP))
  104 IPP=IPP+1
      GO TO 102
  105 SPP=ALOG(SIGPP(IPP+1)/SIGPP(IPP))/ALOG(F(IPP+1)/F(IPP))
C     WRITE(3,915)IPP,SPP
C 915 FORMAT(10H GENSIG-6  /1X,I10,10X,F14.7)
   12 S=ALOG(SIGPE(I+1)/SIGPE(I))/ALOG(F(I+1)/F(I))
C     WRITE(3,916)I,KP,S
C 916 FORMAT(10H GENSIG-7  /1X,2I10,10X,F14.7)
   13 GO TO (19,14),KP
   14 IF(IPP-I)17,19,19
   17 IPP=I
      SPP=ALOG(SIGPP(IPP+1)/SIGPP(IPP))/ALOG(F(IPP+1)/F(IPP))
   19 O=FN-F(I+1)
      IF(O)23,20,20
   20 I=I+1
      FYE=I
      IF(I-NF)12,22,21
   21 CALL ERROR(FYE)
   22 I=I-1
   23 MT=M+JENC
      MS=MT+NERAN
      AS=SIGMAS(FN)*FLDEN
      XSECT(MS)=XSECT(MS)+AS
      FEE=F(I+1)
C     WRITE(3,950)I,MS,M,MT,NERAN,NF,IPP,JENC,KP,O,FN,FEE,FLDEN,SPP,
C    1XSECT(MS),XSECT(MT)
C 950 FORMAT(10H GENSIG-8  /1X,9I10/1X,7F14.7)
      AP=0.0
      GO TO (26,24),KP
   24 IF(FN-2.)26,26,25
   25 MP=MS+NERAN
      AP=SIGPP(IPP+1)*EXP(SPP*ALOG(FN/F(IPP+1)))
      XSECT(MP)=XSECT(MP)+AP
   26 ENERGY(M)=FN*0.51097
      AE=SIGPE(I+1)*EXP(S*ALOG(FN/F(I+1)))
      AT=AE+AP+AS
      XSECT(MT)=XSECT(MT)+AT
      IF(M-NERAN)27,31,28
   27 M=M+1
      FN=FN+DEL
      FL=L
C     WRITE(3,960)L,M,NERAN,MP,MS,IPP,MNINT,FL,FN,DEL,XSECT(MP)
      IF(L-MNINT)30,29,28
   28 CALL ERROR(FL)
   29 DEL=2.*DEL
      L=0
   30 L=L+1
      GO TO 19
   31 CONTINUE
```

```
      DO 36 K=1,NERAN
      MT=K+JENC
      MS=MT+NERAN
      XSECT(MS)=XSECT(MS)/XSECT(MT)
C     WRITE(3,980)K,MT,JENC,MS,XSECT(MS)
C 980 FORMAT(10H GENSIG-10  /1X,4I10,5X,F14.7)
      IF(XSECT(MS)-1.)33,33,32
   32 XSECT(MS)=1.
   33 GO TO (36,34),KP
   34 MP=MS+NERAN
      XSECT(MP)=XSECT(MP)/XSECT(MT)
      IF(XSECT(MP)-1.)36,36,35
   35 XSECT(MP)=1.
   36 CONTINUE
   37 CONTINUE
      NGROUP=IHIGH-ILOW
      ERG(1)=ELOW
      DO 60 J=2,NGROUP
   60 ERG(J)=ERG(J-1)*2.
      JO=NERAN
      DO 302 JK=1,NMED
      NER=MRANGE*(JK-1)+1
      NERAM=NER+NERAN-1
      IF(NOPT.EQ.0) GO TO 2001
      WRITE(6,1999)
 1999 FORMAT(1H1,36X,19HCROSS SECTION TABLE  ///18X,5HTOTAL,23X,
     1  10HSCAT/TOTAL,20X,9HP-P/TOTAL ,14X,12HENERGY (MEV)  //)
      DO 302 J=NER,NERAM
      JJ=J+JO
      JJJ=JJ+JO
      K=J-(JK-1)*MRANGE
      WRITE(6,2000)J,XSECT(J),JJ,XSECT(JJ),JJJ,XSECT(JJJ),ENERGY(K)
 2000 FORMAT(1X,3(I10,F20.5),F20.5)
  302 CONTINUE
      IF(NOPT.EQ.0)GO TO 2001
      WRITE(6,920) NGROUP,IHIGH,ILOW,(ERG(J),J=1,NGROUP)
  920 FORMAT(12H GENSIG END   ,3I10/(1X,5F20.5))
 2001 RETURN
      END
      SUBROUTINE NUGAM1
C  NUGAM1 - PROGRAM FOR POINT SOURCE OUTSIDE OF THE CYLINDER
C                    FOR PARALLEL SOURCE IF DIST EQUALS TO ZERO
      COMMON/RAND/NRAND,NRNDOM
      COMMON/PARAM/NGAMA,EZERO,ECT,HE,HRR,HLEAK,HABS,TOTCOL,NMED
      COMMON/OUTP/NCOLL(151),DUM1(1359)
      COMMON/OI/NB,IDENT(18),HEIGHT,RADIUS,HOL,ROR,DIST
      COMMON/GAMMB/DUM(6),EB,WB,DUM3(4),IMED,IREG,DUM4,NAME
      COMMON/STRT/TSECT(5),SPROB(5),PPROB(5)
      COMMON/EROR/III
      COMMON/XINDEX/EOLD
      COMMON/SPE/ESPECT(30),SPECT(30),NLOOP,LOOPN,DUM6(20)
      COMMON/CONST/PYE,RADAP
      COMMON/NST/NOR
      COMMON/LIO/NOPT
      COMMON/PPP/PPUNS(20),PPWC,PPEC,PPPE,PPTOT,HRR1,HE1,HP,PUNTOT,PSTOT
      COMMON/TAL/E(25),A(20),RM(25,20),ROM(25,20),INE,INA,PE(25,20),
     1  P5(25,20),EW(25),PEW(25),P5I
      COMMON/PUT/POMTOT,RMTOT,PPERM
      COMMON/EWNO/TEW,TEWPS
      DIMENSION CSECT(3),B(3)
```

```
      III=0
      FOLD=0.0
      WRITE(6,50)
   50 FORMAT(1H1)
      CALL SPECTM(1)
      CALL DCOMP(1)
      ROMTOT=0.0
      RMTOT=0.0
      NLP=1
      LOOPN=NLP
      IMED=1
      IREG=1
      CALL SPECTM(2)
      HF=0.
      HRP=0.
      HLEAK=0.
      HABS=0.
      TOTCOL=0.
      DO 3 M=1,NMED
      CALL GTSIGW(3,1,M,EZERO,CSECT)
      TSECT(M)=CSECT(1)
      SPROB(M)=CSECT(2)
      PPROB(M)=CSECT(3)
C     WRITE(3,200)M,EZERO,(CSECT(JJ),JJ=1,3)
C 200 FORMAT(8H MAIN-1 /10X,I5,10X,4E14.7)
    3 CONTINUE
      NARG=1
   10 NAME=NAME+1
      SCAT=0.0
      HP=0.0
      HF1=1.0
      HRR1=1.0
      IF(NOPT.EQ.0)GO TO 2001
      WRITE(6,250)NAME
  250 FORMAT(26H CURRENT HISTORY NUMBER =  ,I10)
 2001 IF(NAME-NGAMA)11,11,21
   11 CALL SOURCE
      IM=1
C     WRITE(3,270)NAME
   30 IF(EB-ECT)12,12,13
   12 HF=HF+HF1
      NARG=3
   22 CONTINUE
      IF(NOPT.EQ.0)GO TO 23
      WRITE(6,260)LOW,NAME,NARG,FATE,HLEAK,HRR,HABS,TOTCOL
  260 FORMAT(7H MAIN-2 /1X,3I5,5X,5E14.7)
   23 CALL DCOMP(4)
      GO TO 10
   13 CALL TESTWT(LOW)
C     WRITE(3,270)NAME
      IF(LOW)15,15,16
   15 HRR=HRR+HRR1
      NARG=3
      GO TO 23
   16 CALL COLLIS(FATE,IM)
C     WRITE(3,270)NAME
C 270 FORMAT(22H SOURCE HISTORY NO. =  ,I10)
      IF(FATE)17,18,19
   17 HABS=HABS+1.
      NARG=3
```

```
      GO TO 23
   18 HLEAK=HLEAK+1.
      NARG=3
      WABS=1.0-WB-HP
      CALL TALLY(SCAT,EB,WABS,0,1,0)
      GO TO 23
   19 TOTCOL=TOTCOL+1.
      SCAT=FATE
      CALL DCOMP(3)
      GO TO 30
   21 NAME=NAME-1
      CALL DCOMP(5)
      WRITE(6,50)
      IF(NLP-NLOOP)1010,1000,1000
 1010 NLP=NLP+1
      CALL DCOMP(1)
      GO TO 2000
 1000 CONTINUE
 2000 GO TO 100
  100 RETURN
      END
      SUBROUTINE AZI(PHIC,PHIS)
      COMMON/RAND/N,NM
      COMMON/CONST/PYE,RADAP
      PHI=2.*PYE*RNGEN(N)
      PHIC=COS(PHI)
      PHIS=SIN(PHI)
      RETURN
      END
      SUBROUTINE CKMAT(PATH,I,TX,MM,FL)
      DIMENSION TX(9)
      COMMON/OI/NB,IDENT(18),HEIGHT,RADIUS,HOL,ROR,DIST
      COMMON/LIO/NOPT
      COMMON/GAMMB/XB,YB,ZB,ALPB,BETB,GAMB,DUM(10)
      COMMON/PARAM/NG,F(7),NMED
      COMMON/LENG/HT(9),RADSQ,HGAMA(20)
      THT=0.0
      FLDL=0.
      SL=0.
      TSAVE=HT(I)
      AGAMB=ABS(GAMB)
      IF(ZB) 12,11,12
   11 PPL=0.0
      GO TO 3
   12 DO 1 J=1,I
    1 THT=THT+HT(J)
      PPL=THT-ZB
      IF(GAMB)2,3,3
    2 PPL=HT(I)-PPL
      K=I
      II=1
      GO TO 4
    3 K=NMED
      II=I
    4 IF(ZB) 5,6,5
    5 HT(I)=PPL
    6 DO 10 JK=II,K
      IF(GAMB)20,20,30
   20 J=I-JK+1
      GO TO 40
```

```
   30 J=JK
   40 IF(J.LT.1) GO TO 60
      IF(J-I) 43,47,42
   42 JJ1=J-1
      GO TO 44
   43 JJ1=J+1
   44 SL=SL+HT(JJ1)/AGAMB
      X=XB+SL*ALPB
      Y=YB+SL*BETB
      IF((X*X+Y*Y).GT.RADSQ ) GO TO 60
   47 FLDLM1=FLDL
      FLDL=FLDL+ HT(J)*TX(J)/AGAMB
      IF(FLDL-PATH)10,50,50
   10 CONTINUE
C   IF PASSES THROUGH 10 THEN ESCAPED
   60 MM=0
      GO TO 70
   50 JI=J
   35 FL=SL+(PATH-FLDLM1)/TX(JI)
      MM=JI
   70 IF(NOPT.EQ.0) GO TO 80
      WRITE(6,100)MM,I,K,II,JI, ZB,PPL,PATH,GAMB,AGAMB,FLDL,FLDLM1,SL,
     1FL,X,Y,XB,YB,RADSQ,
     1 (HT(L),TX(L),L=1,NMED)
  100 FORMAT(12H CKMAT   MM= ,5I4/7F12.5,/7F12.5/(1X,6F15.6))
   80 HT(I)=TSAVE
      RETURN
      END
      SUBROUTINE COLLIS(FATE,IM)
      DIMENSION XSECT(3),TX(9),SX(9),PPX(9),PEX(9)
      COMMON/RAND/N,NM
      COMMON/GAMMB/XB,YB,ZB,ALPB,BETB,GAMB,EB,WB,SIGTB,SPROB,PPROB,
     1PHPROB,IMEDB,IREGB,NUM(2)
      COMMON/GAMMA/XA,YA,ZA,DUM1(3),EA,WA,SIGTA,SPROA,PPROA,PHPROA,
     1IMEDA,IREGA,DUM2(2)
      COMMON/PARAM/NG,E(7),NMED
      COMMON/ENGEOM/BEB,NHIST
      COMMON/LIO/NOPT
      COMMON/PPP/PPUNS(20),PPWC,PPEC,PPPE,PPTOT,HRR1,HE1,HP,PUNTOT,PSTOT
      NHIST=NUM(2)
      DO 15 M=1,NMED
      CALL GTSIGW(3,1,M,EB,XSECT)
      BEB=EB
      TX(M)=XSECT(1)
      SX(M)=XSECT(2)
      PPX(M)=XSECT(3)
      PEX(M)=1.-SX(M)-PPX(M)
   15 CONTINUE
      I=IM
      PATH=-ALOG(RNGEN(N))
      CALL CKMAT(PATH,I,TX,MM,TPATH)
      IF(MM) 18,18,19
   19 XA=XB+TPATH*ALPB
      YA=YB+TPATH*BETB
      ZA=ZB+TPATH*GAMB
      CALL GEOM(FATE)
      IF(NOPT.EQ.0)GO TO 2001
      WRITE(6,200)  EB      ,PATH,ZA,YA,XA,GAMB,BETB,ALPB,ZB,YB,XB,FATE,
     1(TX(I),SX(I),PPX(I),PEX(I),I=1,NMED)
  200 FORMAT(10H COLLIS-1    ,8F12.4/1X,8F12.4/(1X,4F12.4))
```

```
      GO TO 2001
   18 FATE=0.0
 2001 IF(FATE.EQ.0.)GO TO 39
      IMEDB=MM
      CALL KLEIN(THETC)
      CALL AZI(PHIC,PHIS)
      CALL ROT(THETC,PHIC,PHIS)
      SIGTB=TX(IMEDB)
      SPROB=SX(IMEDB)
      PPROB=PPX(IMEDB)
      PHPROB=PEX(IMEDB)
      WA=WB*SPROB
      I=IMEDB
      IF(NOPT.EQ.0)GO TO 3000
      WRITE(6,300)FA,THETC,PHIC,PHIS,SIGTB,SPROB,PPROB,WA
  300 FORMAT(10H COLLIS-3   ,F14.7/1X,7F14.7)
 3000 CALL PAIR(I)
      IM=I
   39 RETURN
      END
      SUBROUTINE DCOMP(NARG)
      COMMON/GAMMB/DUM(6),EB,WB,DUM1(4),IMED,NRGB,NDU,NAME
      COMMON/GAMMA/DUM2(6),EA,WA,DUM3(4),IMEDA,NRGA,NDU1,NAMEA
      COMMON/DI/NB,IDENT(18),HEIGHT,RADIUS,HOL,ROB,DIST
      COMMON/OUTP/NCOLL(151),BOXAV(151),BOXSQ(151),BOXVR(151),COEFV(151)
     1   ,BVOL(151),COLL(151),AE(151),Q(151),VARE(151)
      COMMON/PARAM/NG,EZERO,DUM6(6),NMED
      COMMON/DC/OMEV
      COMMON/TAL/E(25),A(20),RM(25,20),ROM(25,20),INE,INA,PE(25,20),
     1  R5(25,20),EW(25),PEW(25),P5
      COMMON/SPE/ESPECT(30),SPECT(30),NREAD,LOOPN,OMGA(20)
      COMMON/OMEGA/ORM(25,20),OROM(25,20),EORM(25,20),EOROM(25,20),
     1  TROM(25),TRM(25),PRM(25),TOTROM,TOTRM,PERM
      COMMON/LIO/NOPT
      COMMON/PPP/PPUNS(20),PPWC,PPEC,PPPE,PPTOT,HPR1,HE1,HP,PUNTOT,PSTOT
      COMMON/EWNO/TOTEW,TEWPS
C     ZEROES FOR NARG=1 (FIRST CALL FROM MAIN)
      AME=NAME
      GO TO (1,2,3,4,5),NARG
    1 DO 6 I=1,151
    6 NCOLL(I)=0
      BLOV=BVOL(1)
      II=0
      DO 7 I=1,1359
    7 BOXAV(I)=0.
      BVOL(1)=BLOV
      DO 40 I=1,6
      DUM(I)=0.
   40 DUM2(I)=0.
      EB=0.
      WB=0.
      EA=0.
      WA=0.
      IMED=0
      NRGB=0
      NDU=0
      NAME=0
      IMEDA=0
      NRGA=0
      NDU1=0
```

```
      NAMEA=0
      DO 41 I=1,4
      DUM1(I)=0.
   41 DUM3(I)=0.
C     WRITE(3,200)NARG,NB
C 200 FORMAT(18H DCOMP. ZERO CALL  ,20X,2I10)
    2 RETURN
    3 DMEV=DEACT(ADDER)
      IF(NOPT.EQ.0)GO TO 3000
      WRITE(6,210)DMEV,ADDER,NB
  210 FORMAT(16H DCOMP. NARG 3-1  ,20X,2F14.7,I10)
 3000 IF(NB-1)2000,2000,2001
 2000 JJ=1
      JS=151
      GO TO 11
 2001 CONTINUE
      IF(JJ.GE.NB)GO TO 120
   11 COLL(JJ)=COLL(JJ)+DMEV
      COLL(JS)=COLL(JS)+DMEV
      NCOLL(JJ)=NCOLL(JJ)+1
      NCOLL(JS)=NCOLL(JS)+1
      DO 13 I=1,12
      DUM(I)=DUM2(I)
   13 DUM2(I)=0.
      NRGB=NRGA
      IF(NOPT.EQ.0)GO TO 120
      WRITE(6,250)JJ,JS,NRGB,COLL(JJ),COLL(JS),NCOLL(JJ),NCOLL(JS)
  250 FORMAT(16H DCOMP. NARG 3-2  ,3I10,2F20.7,2I10)
  120 RETURN
    4 EQ=EZERO*.51097
      IF(NOPT.EQ.0)GO TO 3001
      WRITE(6,265)(COLL(I),BOXAV(I),I=1,NB)
  265 FORMAT(16H DCOMP. NARG 4-1  ,2F20.5/(1X,2F20.5))
 3001 DO 20 I=1,NB
      BOXAV(I)=BOXAV(I)+COLL(I)
      AE(I)=(AE(I)+BOXAV(I)/EQ)/AME
      BOXSQ(I)=BOXSQ(I)+COLL(I)**2
   20 COLL(I)=0.
      NRGB=1
      NRGA=1
      DO 21 I=1,12
      DUM2(I)=0.
   21 DUM(I)=0.
      IF(NOPT.EQ.0)GO TO 3002
      WRITE(6,260)NAME,EQ,(BOXAV(I),AE(I),BOXSQ(I),I=1,NB)
  260 FORMAT(16H DCOMP. NARG 4-2  ,I10,4F20.5/(1X,3F20.5))
 3002 RETURN
    5 DO 30 I=1,NB
      BOXAV(I)=BOXAV(I)/AME
      Q(I)=BOXAV(I)*1.60207E-8
      AME1=NAME-1
      BOXVR(I)=(BOXSQ(I)/AME-BOXAV(I)**2)/AME1
      IF(BOXVR(I))30,30,31
   31 SRVR=SQRT(BOXVR(I))
      COEFV(I)=SRVR/BOXAV(I)
      VARE(I)=2.5666282285E-16*SRVR*SRVR
   30 CONTINUE
      IF(NOPT.EQ.0)GO TO 3003
      WRITE(6,275)NAME,(BOXAV(I),Q(I),BOXVR(I),COEFV(I),VARE(I),I=1,NB)
  275 FORMAT(16H DCOMP. NARG 5    /I10/(1X,5F14.7))
```

```
3003 TOTROM=0.0
     DO 400 I=1,NREAD
     TROM(I)=0.0
     DO 390 J=1,INA
     TROM(I)=ROM(I,J)+TROM(I)
 390 CONTINUE
     TOTROM=TROM(I)+TOTROM
 400 CONTINUE
     TOTRM=0.0
     PERM=0.0
     DO 420 I=1,INF
     TRM(I)=0.0
     PRM(I)=0.0
     DO 410 J=1,INA
     TRM(I)=RM(I,J)+TRM(I)
     PRM(I)=PE(I,J)+PRM(I)
 410 CONTINUE
     TOTRM=TRM(I)+TOTRM
     PERM=PRM(I)+PERM
 420 CONTINUE
     ENG=NG
     SINA=INA
     DO 60 J=1,INA
     DO 50 I=1,INF
     ORM(I,J)=RM(I,J)/ OMGA(J)
  50 FORM(I,J)=ORM(I,J)/ENG
     DO 60 I=1,NREAD
     OROM(I,J)=ROM(I,J)/ OMGA(J)
  60 FOROM(I,J)=OROM(I,J)/ENG
     WRITE(6,24)
     I=LOOPM
     WRITE(6,25)ESPECT(I)
     WRITE(6,27)(J,A(J),A(J+1),OMGA(J),ROM(I,J),OROM(I,J),FOROM(I,J),
    1            PPUNS(J),J=1,INA)
     SUMA=0.0
     PUNTOT=0.0
     DO 6550 J=1,INA
     PUNTOT=PUNTOT+PPUNS(J)
6550 SUMA=SUMA+OROM(I,J)
     SUMA=SUMA/SINA
  65 CONTINUE
     WRITE(6,70)TROM(I),SUMA,PUNTOT,P51
     TOTEW=0.0
     PSTOT=0.0
     WRITE(6,26)
     WRITE(6,25)ESPECT(I)
     DO 66 I=1,INF
     WRITE(6,28)F(I),F(I+1),I
     WRITE(6,72)(J,A(J),A(J+1),OMGA(J),RM(I,J),ORM(I,J),FORM(I,J),
    1            R5(I,J), J=1,INA)
     PPSTOT=0.0
     SUMA=0.0
     DO 6551 J=1,INA
     PPSTOT=PPSTOT+R5(I,J)
6551 SUMA=SUMA+ORM(I,J)
     SUMA=SUMA/SINA
     FWTOT=FW(I)+PEW(I)
     FTPS=FWTOT/OMGA(INA)
     WRITE(6,71)TRM(I),PRM(I),SUMA,PPSTOT,FWTOT,FW(I),PEW(I),FTPS
     PSTOT=PSTOT+PPSTOT
```

```
      TOTEW=TOTEW+EWTOT+RST
      TEWPS=TOTEW/OMGA(INA)
   66 CONTINUE
   24 FORMAT(1H1,30H TALLY      UNSCATTERED ESCAPES   ////)
   25 FORMAT(1H0//46X,18HSOURCE ENERGY =      ,F8.5,4H MEV)
   26 FORMAT(1H1,30H TALLY      SCATTERED ESCAPES     ////)
   27 FORMAT(1H0// 110H      J     ANGLES A(J) TO A(J+1)      SOLID ANGLE
     1 NUMBER          NUMBER/STER      FRACT/STER    PAIR PHOTONS          //
     2  (1X,(I4,2F12.5,5F15.5)))
   28 FORMAT(1H0//31X,24HESCAPE ENERGY INTERVAL     ,F8.5,4H TO   ,F8.5,
     1   8H  INDEX   ,I5)
   70 FORMAT(1H0//25H UNSCATTERED ESCAPES =      ,F12.5//
     1   25H NUMBER AV/STER          =      ,F12.5
     2 //25H PAIR PHOTON ESCAPES =      ,F12.5,
     3 //25H NO. P P IN FWD CONE =     ,F12.5)
   71 FORMAT(1H0//23H SCATTERED ESCAPES =      ,F12.5//
     1   23H P.F.ABSORPTIONS     =      ,F12.5//
     2   23H NUMBER AV/STER      =      ,F12.5
     2 //25H PAIR PHOTON ESCAPES =      ,F12.5
     3//23H NUMBER IN FWD CONE   = ,3F12.5
     4//23H NO.IN FWD CONE/STER =  ,F12.5)
   72 FORMAT(1H0// 110H      J     ANGLES A(J) TO A(J+1)      SOLID ANGLE
     1 NUMBER          NUMBER/STER      FRACT/STER    PAIR PHOTONS          //
     2  (1X,(I4,2F12.5,5F15.5)))
      PAPRO=R5(LOOPN,1)
      CALL OUTPUT(INF,PAPRO)
      RETURN
      END
      FUNCTION DEAC1(X)
      COMMON/GAMMB/DUM(6),FB,WB,SIGTB,SPROB,PPROB,PHPROB,DUM1(4)
      COMMON/GAMMA/DUM2(6),FA,WA,SIGTA,SPROA,PPROA,PHPROA,DUM3(4)
      COMMON/LIO/NOPT
      ADD1=(FB-2.)*PPROB
      ADD2=FB*PHPROB
      ADD3=(FB-FA)*SPROB
      DEACT=WB*.51097*(ADD1+ADD2+ADD3)
      IF(NOPT.EQ.0)GO TO 10
      WRITE(6,3)ADD1,ADD2,ADD3,PPROB,PHPROB,SPROB,WB,FA,FB
    3 FORMAT(7H DEACT /1X,7E14.7/1X,2E14.7)
   10 RETURN
      END
      SUBROUTINE ERROR(X)
      COMMON/EROR/I
      I=I+1
      WRITE(6,1)I,X
    1 FORMAT (17H ERROR NUMBER   = ,I4,10X,19H VARIABLE VALUE   =   ,F14.7)
      CALL EXIT
      RETURN
      END
      SUBROUTINE FOWARD(IFW)
      COMMON/GAMMB/XB,YB,ZB,ALP,BET,GAM,BDUM(10)
      COMMON/DI/DUM(19),HEIGHT,RADIUS,HOL,ROP,DIST
      COMMON/LIO/NOPT
      COMMON/LENG/HT(9),SORAD,HGAMA(20)
      IFW=0
      DZ=HEIGHT-ZB
      DL=DZ/GAM
      X=XB+DL*ALP
      Y=YB+DL*BET
      SQX=X*X
```

```
      SQY=Y*Y
      IF((SQX+SQY).LE.SQRAD)IEW=1
      IF(NOP1.EQ.0) GO TO 10
      WRITE(6,110)IEW,DZ,DL,X,Y,XB,YB,ZB,SQX,SQY,SQRAD,HEIGHT
  110 FORMAT(10H FORWARD    ,I5,6E12.5/15X,5E12.5)
   10 RETURN
      END
      SUBROUTINE GEOM(FATE)
      COMMON/GAMMA/X,Y,Z,DUM(10),NDUM,DUM1(2)
      COMMON/DI/NB,IDENT(18),HEIGHT,RADIUS,HOL,ROR,DIST
      COMMON/ENGEOM/E,N
      COMMON/LENG/HT(9),RADSQ,HGAMA(20)
    1 IF(X*X+Y*Y.GT.RADSQ)GO TO 6
    2 IF(Z.GT.0..AND.Z.LE.HEIGHT)GO TO 3
      GO TO 6
    3 FATE=1.
      NDUM=1
      GO TO 7
    6 FATE=0.
    7 CONTINUE
C     WRITE(3,200)N,KEY,FATE,X,Y,Z,RADSQ,E
C 200 FORMAT(6H GEOM   ,10X,2I10/1X,6E14.7)
      RETURN
      END
      SUBROUTINE GTISO (U,V,W,RHO,PHI)
      COMMON/RAND/N,NM
      COMMON/CONST/PYE,RADAP
      W=RNGEN(N)*2.-1.
      RHO=SQRT (1. -W*W)
      PHI=(RNGEN(N)*2. -1.)*PYE
      U=COS (PHI)*RHO
      V=SIN (PHI)*RHO
C     WRITE(3,3)U,V,W,RHO,PHI
C   3 FORMAT(6H GTISO /1X,5E14.7)
      RETURN
      END
      SUBROUTINE GTSIGW(I,K1,MED,E,SIGMA)
C     SUB RETRIEVES CROSS-SECTIONS
      COMMON/NST/NOR
      DIMENSION XSECT(8330),SIGMA(3),KK(3),ERG(20)
      GO TO (1,3,3),I
    1 IF(NOR.GT.0)GO TO 40
      CALL GENSIG(K1,FLOW,NINT,NERAN,ERG,NRANGE,XSECT,MED)
   40 NOR=NOR-1
      MNINT=2**NINT
      MEDTOT=NERAN*(2+K1)
C     WRITE(3,20)MNINT,MEDTOT,K1,I,(ERG(J),J=1,20)
      CALL INDEX(KK,K1,0.,FLOW,NINT,MED,MEDTOT,MNINT,NERAN,ERG)
      RETURN
    3 CALL INDEX(KK,K1,E,FLOW,NINT,MED,MEDTOT,MNINT,NERAN,ERG)
C     WRITE(3,20)MNINT,MEDTOT,K1,I,(ERG(J),J=1,20)
C  20 FORMAT(9H GTSIGW-1 /1X,4I10/(1X,5E14.7))
      IF(K1)5,5,6
    5 L=2
      GO TO 7
    6 L=3
    7 DO 10 M=1,L
      N=KK(M)
      SIGMA(M)=XSECT(N)
   10 CONTINUE
```

```
C     WRITE(3,30)L,KK(1),KK(2),KK(3),SIGMA(1),SIGMA(2),SIGMA(3)
C  30 FORMAT(9H GTSIGM-2 /1X,4I10/1X,3F14.7)
      RETURN
      END
      SUBROUTINE KLEIN(THETA)
      COMMON/RAND/N,NM
      COMMON/GAMMB/B(16)
      COMMON/GAMMA/BA(16)
      COMMON/LIQ/NOPT
      TEB=B(7)+B(7)
      TEBP1=TEB+1.
C     WRITE(3,200)TEB,TEBP1,B(7)
C 200 FORMAT(9H KLEIN-1   ,10X,3F14.7)
      IF(B(7).GT.7.)GO TO 11
    3 CRI=TEBP1/(TEB+9.)
   10 IF(RNGEN(N).GT.CRI)GO TO 2
    1 R2=RNGEN(N)
      Y=1.+TEB*R2
      IF(NOPT.EQ.0)GO TO 2000
      WRITE(6,210)R2,Y,CRI
  210 FORMAT(9H KLEIN-2   ,3F14.7)
 2000 IF(RNGEN(N).LE.4./Y-4./(Y*Y))GO TO 9
      GO TO 10
    2 R2=RNGEN(N)
      CONST=1.+TEB*R2
      Y=TEBP1/CONST
      CAS=1.+(2.*R2-2.)/CONST
      IF(NOPT.EQ.0)GO TO 2001
      WRITE(6,230)CAS,Y,CONST,R2
  230 FORMAT(9H KLEIN-3   ,4F14.7)
 2001 IF(RNGEN(N).GT..5*(CAS*CAS+1./Y))GO TO 10
    8 BA(7)=B(7)/Y
      THETA=CAS
      RETURN
    9 BA(7)=B(7)/Y
      THETA=1.-2.*R2
      RETURN
   11 R1=RNGEN(N)
      X=TEBP1**R1
      TEMP1=1.-X
      CAS=TEMP1/B(7)+1.
      TEMP2=1./X
      TX=(CAS*CAS-TEMP1+TEMP2)*.5*TEMP2
      IF(NOPT.EQ.0)GO TO 2002
      WRITE(6,220)TX,R1,X,TEMP1,CAS,TEMP2
  220 FORMAT(9H KLEIN-4   ,6F14.7)
 2002 IF(RNGEN(N).GT.TX)GO TO 11
   12 BA(7)=B(7)/X
      THETA=CAS
      RETURN
      END
      SUBROUTINE INDEX(IX,K1,F,FLOW,NINT,MED,MEDTOT,MNINT,NFRAN,FRG)
      COMMON/XINDEX/FOLD
      DIMENSION FRG(20),IX(3)
      FM=MNINT
      NK=2+K1
      IF(F-FLOW)5,5,10
    5 IX(1)=(MED-1)*MEDTOT+1
      GO TO 15
   10 IF(F-FOLD)1,11,1
```

```
    1 EOLD=E
      J=ALOG(E/ELOW)/.6931471 8+1.
      I=EM*E/ERG(J)-EM+1.49
   11 IX(1)=(J-1)*MNINT+I+(MED-1)*MEDTOT
   15 DO 20 K=2,NK
   20 IX(K)=IX(K-1)+NERAN
C     WRITE(3,200)NK,K1,J,I,MEDTOT,NERAN,MNINT,E,ELOW,ERG(J),(IX(K),
C    1K=1,NK)
C 200 FORMAT(7H INDEX   /1X,7I5,3E14.7/(1X,I10))
      RETURN
      END
      SUBROUTINE OUTPUT(INE,PAPRO)
      COMMON/PARAM/NGAMA,EZERO,ECT,HE,HRR,HLEAK,HABS,TOTCOL,NMED
      COMMON/OUTP/NCOLL(151),BOXAV(151),BOXSQ(151),BOXVR(151),COEFV(151)
     1,BVOL(151),COLL(151),AE(151),E(151),VARE(151)
      COMMON/OI/NB,IDENT(18),HEIGHT,RADIUS,HOL,ROR,DIST
      COMMON/SIRT/TSECT(5),SPROB(5),PPROB(5)
      COMMON/PUT/ROMTOT,RMTOT,RPERM
      COMMON/OMEGA/DUMB(2050),PRM(25),TOTROM,TOTRM,PERM
      COMMON/PPP/PPUMS(20),PPWC,PPEC,PPPE,PPTOT,HRR1,HE1,HP,PUNTOT,PSTOT
      COMMON/EWNO/TOTEW,TEWPS
      SUMP=0.0
      DO 65 I=1,INE
   65 SUMP=PRM(I)+SUMP
      ECT=ECT*.51097
      EZERO=EZERO*.51097
      AGAMA=NGAMA
C     WRITE(3,202)(IDENT(I),I=1,12)
C 202 FORMAT(1H1,12A6)
      WRITE(6,200)NGAMA,EZERO,ECT,NCOLL(NB)
  200 FORMAT(1H1,76HNO. OF HISTORIES INITIAL ENERGY     CUT-OFF ENERGY
     1 TOTAL NO. OF COLLISIONS // I10,9X,F10.3,8X,F10.3,11X,I10 //)
C     WRITE(3,9)
C   9 FORMAT(1H0,45H          TOTAL XSECT    SCAT PROB     PAIR PROB  /)
C     WRITE(3,10)(I,TSECT(I),SPROB(I),PPROB(I),I=1,NMED)
C  10 FORMAT(1H ,I5,3(3X,F10.4))
      RPE=PERM-RPERM
      ROMT=TOTROM-ROMTOT
      RMT=TOTRM-RMTOT
      RABS=HE+HPR+RPE
      IF(TOTROM-ROMT)50,50,51
   50 PUMS=0.0
   51 PMUS=SUMP-PUMS
      HABS=HE+HRR+PMUS
      HL=ROMT+RMT
      WRITE(6,2000)
 2000 FORMAT(1H0,30HTERMINATION PRIMARY PHOTONS      //  )
      FHL=HL/AGAMA
      FRO=ROMT/AGAMA
      FRM=RMT/AGAMA
      WRITE(6,203)HE,HRR,HL,FHL,HABS,    ROMT, FRO, RMT,FRM, PMUS,PPTOT
  203 FORMAT(                          15H  1. ENERGY      ,F12.5///
     115H  2. WEIGHT      ,F12.5///15H  3. ESCAPE      ,F12.5,
     A 17X, 24H  (3./NO. OF HISTORIES) ,F12.5,///
     215H  4. ABSORBED    ,F12.5///32H  5. TOTAL UNSCATTERED ESCAPES   .
     3F12.5,24H  (5./NO. OF HISTORIES) F12.5///32H  6. TOTAL SCATTERED E
     4SCAPES       ,F12.5,24H  (6./NO. OF HISTORIES) F12.5///32H  7. PHOT
     5OELECTRIC ABSORPTIONS    ,F12.5,                                 ///
     6  32H  8. PAIR PRODUCTION PHOTONS      ,F12.5///  )
      WRITE(6,100)TOTEW,TEWPS
```

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  100 FORMAT(36H  TOTAL ESCAPES IN FWD 10-DEG. CONE=,F12.5,10X,
     123HTOTAL IN FWD CONE/STEP=,F12.5)
C      WRITE(3,1000)PPE,PABS
C1000 FORMAT(//2F12.5//)
      PPESC=PUNTOT+PSTOT
      PPABS=PPEC+PPWC+PPPE
      CHECK=(PPABS+PPESC)/2.0+HABS+HL
      WRITE(6,3000)
 3000 FORMAT(1H0,26HTERMINATION PAIR PHOTONS  //  )
      WRITE(6,201)PPEC,PPWC,PPESC,PPABS,PUNTOT,PSTOT,PPPE,PPTOT
  201 FORMAT(                         15H  1. ENERGY      ,F12.5///
     115H  2. WEIGHT      ,F12.5///15H  3. ESCAPE      ,F12.5///
     215H  4. ABSORBED    ,F12.5///32H  5. TOTAL UNSCATTERED ESCAPES   ,
     3F12.5                                  ///32H  6. TOTAL SCATTERED E
     4SCAPES       ,F12.5,                              ///32H  7. PHOT
     5OELECTRIC ABSORPTIONS    ,F12.5,                                ///
     6  32H  8. PAIR PRODUCTION PHOTONS      ,F12.5 /// )
      WRITE(6,4000) CHECK
 4000 FORMAT(15H TALLY CHECK = ,F12.5)
      ROMTOT=TOTROM
      RMTOT=TOTRM
      RPERM=PERM
      DO 3 I=1,NB
      RCONV=1.60207E-8/BVOL(I)
      BOXAV(I)=BOXAV(I)*RCONV
      IF(BOXVR(I))4,4,5
    5 BOXVR(I)=SQRT(BOXVR(I))*RCONV
    4 CONTINUE
C      WRITE(6,204)
  204 FORMAT(1H1,108H          AV.DOSE(RADS)  DOSE STD.   COEF. VAR.
     1            MASS       E(G-RADS)     VAR.OF E     ABSD.FRAC. /)
    3 CONTINUE
C    3 WRITE(6,206)  BOXAV(I),BOXVR(I),COEFV(I),          BVOL(I),E(I),
C     1VARE(I),AE(I)
  206 FORMAT(1H ,  10X,2(F10.3,3X),F10.3,  13X,3(F10.3,3X),-1PF10.4)
      PUMS=SUMP
      RETURN
      END
      SUBROUTINE PAIR(IM)
      DIMENSION TB(12),NTB(4),TA(12),NTA(4)
      DIMENSION XSECT(3),TX(9),SX(9),PPX(9),PEX(9)
      COMMON/RAND/N,NM
      COMMON/GAMMB/BEFOR(12),NB(4)
      COMMON/GAMMA/AFTER(12),NA(4)
      COMMON/PARAM/NN,DO,ECT,DI(5),NMED
      COMMON/LIO/NOPT
      COMMON/PPP/PPUNS(20),PPWC,PPEC,PPPE,PPTOT,HRRI,HEI,HP,PUNTOT,PSTOT
      IF(NOPT.EQ.0)GO TO 2000
      WRITE(6,300)BEFOR(7)
  300 FORMAT(8H PAIR-1  ,10X,F14.7)
 2000 IF(BEFOR(7).LE.2.)GO TO 2
      SCAT=0.0
    1 DO 3 I=1,12
      TB(I)=BEFOR(I)
    3 TA(I)=AFTER(I)
      DO 4 I=1,4
      NTB(I)=NB(I)
    4 NTA(I)=NA(I)
      DO 11 I=1,3
   11 BEFOR(I)=AFTER(I)
```

```
      IF(NOPT.EQ.0)GO TO 2001
      WRITE(6,350)(NTB(JJ),NTA(JJ),JJ=1,4),(TB(I),TA(I),I=1,12)
  350 FORMAT(8H PAIR-2  /1X,8I10/(1X,6F14.7))
 2001 CALL GTISO(BEFOR(4),BEFOR(5),BEFOR(6),ROW,FIF)
      BEFOR(7)=1.
      BEFOR(8)=2.*BEFOR(8)*BEFOR(1))
      TOB=BEFOR(8)
      PPTOT=PPTOT+TOB
      HRR1=HRR1-TOB/2.0
      HF1=HF1-TOB/2.0
      HP=HP+TOB/2.0
      J=IM
   10 BEFOR(12)=0.
      DO 15 M=1,NMED
      CALL GTSIGW(3,1,M,BEFOR(7),XSECT)
      TX(M)=XSECT(1)
      SX(M)=XSECT(2)
      PPX(M)=XSECT(3)
      PEX(M)=0.
   15 CONTINUE
      PATH=-ALOG(RNGEN(N))
      CALL CKMAT(PATH,J,TX,MM,TPATH)
      IF(MM) 18,18,19
   19 DO 20 K=1,3
   20 AFTER(K)=BEFOR(K)+TPATH*BEFOR(K+3)
      CALL GEOM(FATE)
      IF(NOPT.EQ.0)GO TO 2002
      WRITE(6,360)MM,     PATH,AFTER(1),AFTER(2),AFTER(3),BEFOR(1),
     1BEFOR(2),BEFOR(3), (TX(I),SX(I),PPX(I),PEX(I),I=1,NMED)
  360 FORMAT(8H PAIR-3  ,10X,I5/1X,7F14.7/(1X,4F14.7))
      GO TO 2002
   18 FATE=0.0
 2002 IF(FATE.EQ.0.)GO TO 6
      MED=MM
      CALL KLEIN(THETC)
      CALL AZI(PHIC,PHIS)
      CALL ROT(THETC,PHIC,PHIS)
      BEFOR(9)=TX(MED)
      BEFOR(10)=SX(MED)
      BEFOR(11)=PPX(MED)
      AFTER(8)=BEFOR(8)*SX(MED)
      SCAT=FATE
      CALL DCOMP(3)
      J=MED
      IF(NOPT.EQ.0)GO TO 2003
      WRITE(6,380)PROB,FATE,THETC,PHIC,PHIS,THETC,(BEFOR(I),I=8,11)
  380 FORMAT(8H PAIR-5  /(1X,5F14.7))
 2003 IF(BEFOR(7).LT.FCT)GO TO 60
    7 CALL TESTWT(LOW)
      IF(LOW)160,160,10
    6 CONTINUE
      ES=BEFOR(7)
      WABS=TOB-BEFOR(8)
      CALL TALLY(SCAT,ES,WABS,1,TOB)
  600 DO 23 I=1,12
      BEFOR(I)=TB(I)
   23 AFTER(I)=TA(I)
      DO 24 I=1,4
      NB(I)=NTB(I)
   24 NA(I)=NTA(I)
```

```
      GO TO 2
   60 PPEC=PPEC+TOB
      GO TO 600
  160 PPWC=PPWC+TOB
      GO TO 600
    2 RETURN
      END
      SUBROUTINE ROT(THETC,PHIC,PHIS)
      COMMON/GAMMB/BUM(3),A,B,C,BUM1(10)
      COMMON/GAMMA/DUM(3),AA,AB,AC,DUM1(10)
      COMMON/LIO/NOPT
      IF(C)1,2,3
    1 IF(C+1.0)6,4,6
    4 THETS=SQRT(1.0-THETC*THETC)
      AA=-PHIC*THETS
      AB=PHIS*THETS
      AC=-THETC
      GO TO 20
    3 IF(C-1.0)6,5,6
    5 THETS=SQRT(1.0-THETC*THETC)
      AA=PHIC*THETS
      AB=PHIS*THETS
      AC=THETC
      GO TO 20
    2 THETS=SQRT(1.0-THETC*THETC)
      A1=A
      AA=-B*PHIS*THETS+A1*THETC
      AB=A1*PHIS*THETS+B*THETC
      AC=-PHIC*THETS
      GO TO 20
    6 THETS=SQRT(1.0-THETC*THETC)
      T=SQRT(1.-C*C)
      A1=A
      AA=A1*C*PHIC*THETS/T-B*PHIS*THETS/T+A1*THETC
      AB=B*C*PHIC*THETS/T+A1*PHIS*THETS/T+B*THETC
      AC=-T*PHIC*THETS+C*THETC
   20 CONTINUE
      IF(NOPT.EQ.0)GO TO 2000
      WRITE(6,300)AA,AB,AC,THETS,C,A,B
  300 FORMAT(5H ROT  /1X,7E14.7)
 2000 RETURN
      END
      FUNCTION RNGEN(IX)
      IY=IX*65539
      IF(IY)5,6,6
    5 IY=IY+2147483647+1
    6 YFL=IY
      YFL=YFL*.4656613E-9
      IX=IY
      RNGEN=YFL
      RETURN
      END
      FUNCTION SIGMAS(A)
      SIGMAS=.49895*(2./(A**2)+(1.+A)/((1.+(2.*A))**2)+ALOG(1.+(2.*A))*
     1(1.-2.*(1.+A)/(A**2))/(2.*A))
      RETURN
      END
      SUBROUTINE SOURCE
      COMMON/RAND/N,NM
      COMMON/GAMMB/X,Y,Z,ALP,BET,GAM,ENER,WGT,DUM(5),NRG,DOM(2)
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```
      COMMON/PARAM/DUM1,EZERO,DUM2(6),NMED
      COMMON/OI/NB,IDENT(18),HEIGHT,RADIUS,HOL,ROR,DIST
      COMMON/LIO/NOPT
      COMMON/LENG/HT(8),SQRAD,HGAMA(20)
      COMMON/CONST/PYE,RADAP
      IF(DIST)21,20,21
   20 CALL SPAR
      RETURN
   21 W2=DIST/(SQRT(DIST*DIST+SQRAD))
      GAM=1.-(1.-W2)*RNGEN(N)
      R1=DIST/GAM
      PHI=(RNGEN(N)*2.-1.)*PYE
      FL=SQRT(R1*R1-DIST*DIST)
      X=FL*COS(PHI)
      Y=FL*SIN(PHI)
      Z=0.0
      ALP=X/R1
      BET=Y/R1
      ENER=EZERO
      WGT=1.
      NRG=1
      IF(NOPT.EQ.0)GO TO 200
      WRITE(6,100)W2,PHI,X,Y,Z,ALP,BET,GAM,ENER,HEIGHT,RADIUS,HOL,ROR
     1  ,FL, R1
  100 FORMAT(8H SOURCE   ,7X,7E14.5/1X,8E14.5)
  200 RETURN
      END
      SUBROUTINE SPAR
      COMMON/RAND/N,NM
      COMMON/GAMMB/X,Y,Z,ALP,BET,GAM,ENER,WGT,DUM(5),NRG,DOM(2)
      COMMON/PARAM/DUM1,EZERO,DUM2(6),NMED
      COMMON/OI/NB,IDENT(18),HEIGHT,RADIUS,HOL,ROR,DIST
      COMMON/LIO/NOPT
      COMMON/CONST/PYE,RADAP
      D=SQRT(RNGEN(N))*RADIUS
      Z=0.0
      PHI=(RNGEN(N)*2.-1.)*PYE
      X=D*COS(PHI)
      Y=D*SIN(PHI)
      GAM=1.0
      ALP=0.0
      BET=0.0
      WGT=1.0
      ENER=EZERO
      NRG=1
      IF(NOPT.EQ.0)GO TO 200
      WRITE(6,100)Z,D,PHI,X,Y,ALP,BET,GAM,ENER,HEIGHT,RADIUS,HOL,ROR,ROW
     1,FIE
  100 FORMAT(18H PARALLEL SOURCE   ,7X,7E14.5/1X,8E14.5)
  200 RETURN
      END
      SUBROUTINE SPECTM(K)
      COMMON/RAND/NRAND,NRNDOM
      COMMON/PARAM/NGAMA,EZERO,ECT,DUM1(5),NMED
      COMMON/SPE/ESPECT(30),SPEC1(30),NREAD,LOOPN,OMGA(20)
      COMMON/OI/NB,IDENT(18),HEIGHT,RADIUS,HOL,ROR,DIST
      COMMON/TAL/E(25),A(20),RM(25,20),ROM(25,20),INE,INA,PE(25,20),
     1  R5(25,20),EW(25),PEW(25),P51
      COMMON/CONST/PYE,RADAP
      COMMON/OUTP/NCOLL(151),DUM5(604),BVOL(151),DUM6(604)
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      COMMON/LIO/NOPT
      COMMON/PPP/PPUNS(20),PPWC,PPEC,PPPE,PPTOT,HPR1,HE1,HP,PUNTOT,PSTOT
      NDISTN=1
      GO TO (1,2),K
    1 IF(NOPT-1)2450,2400,2400
 2400 NGAMA=100
 2450 WRITE(6,2501)NGAMA,NRAND,HEIGHT,NREAD,NDISTN,RADIUS,INE,ECT,
     1 BVOL(1),DIST
 2501 FORMAT(1H0,28HNUMBER OF PHOTON HISTORIES    ,I5,6X,26HINITIAL RANDO
     1M NUMBER       ,I10,7X,24HCYLINDER HEIGHT (CM)      ,F12.5 / 1X,
     228HNO.SOURCE SPECTRUM ENERGIES  ,I5,6X,26HCONTROL PARAMETER-NDISTN
     3   ,I5,12X,24HCYLINDER RADIUS (CM)      ,F12.5 / 1X,28HNO.EQUAL ENE
     4RGY INTERVALS     ,I5,6X,25HLOW ENERGY CUTOFF (MEV)    ,F12.5,6X,
     524HCYLINDER VOLUME (CM**3)   ,F12.5/
     660X,16HPOINT SOURCE IS F12.5,32H  (CM) BELOW THE CYLINDER Z-AXIS)
      INA=18
      AIN=INA
      IN=INA+1
      BIN=IN
      IIN=INE+1
      BEN=INE+1
      NB=1
      NRAD=1
      NLAYER=1
      WRITE(6,3001)(ESPECT(I),I=1,NREAD)
 3001 FORMAT(1H ,25HSOURCE SPECTRUM ENERGIES  / (1X,6E15.5))
      WRITE(6,3002)(SPECT(I),I=1,NREAD)
 3002 FORMAT(1H ,40HSOURCE SPECTRUM INTENSITY DISTRIBUTIONS  /
     1  (1X,6E15.5))
 2850 ECT=ECT/0.51097
      EXT=ECT
      NRNDOM=NRAND
      AD=NRAD
      ROR=RADIUS/AD
      AYER=NLAYER
      HOL=HEIGHT/AYER
      EDIF=((ESPECT(1)/0.51097)-0.0)/(BEN-1.0)
      DO 10 I=1,IN
      XK=IN-I
   10 A(I)=XK*PYE/AIN
      DO 100 I=1,IIN
      XK=IIN-I
  100 E(I)=EDIF*XK
      E(1)=ESPECT(1)/0.51097
      E(IIN)=0.0
      A(IN)=0.0
      NN=IIN
  988 IF(ECT-E(NN))999,909,9999
 9999 NN=NN-1
      GO TO 988
  999 NN=NN+1
      E(NN)=ECT
  909 CONTINUE
      WRITE(6,3005)(E(I),I=1,IIN)
 3005 FORMAT(1H ,32HESCAPE SPECTRUM ENERGIES (MC**2)/ (1X,6E15.5))
      WRITE(6,3006)(A(I),I=1,IN)
 3006 FORMAT(1H ,34HESCAPE SPECTRUM ANGLES (RADIANS)  /(1X,6E15.5))
      DO 20 J=1,INA
      OMGA(J)=2.0*PYE*(COS(A(J+1))-COS(A(J)))
      PPUNS(J)=0.0
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      DO 15 I=1,INF
      FW(I)=0.0
      PFW(I)=0.0
      PF(I,J)=0.0
      R5(I,J)=0.0
      ROM(I,J)=0.0
   15 RM(I,J)=0.0
   20 CONTINUE
      PPFC=0.0
      PPWC=0.0
      PPPF=0.0
      PPTOT=0.0
      P51=0.0
      RETURN
    2 EZERO=ESPECT(LOOPN)/0.51097
      ECT=EXT
      IF(NOPT.EQ.0)GO TO 2000
      WRITE(6,3003)EDIF,INF,INA
 3003 FORMAT(10H SPECTM-4    ,F15.5,2I5)
 2000 RETURN
      END
      SUBROUTINE TALLY(SCAT,ES,WABS,NPP,TOB)
      COMMON/TAL/F(25),A(20),RM(25,20),ROM(25,20),INF,INA,PF(25,20),
     1  R5(25,20),FW(25),PFW(25),P51
      COMMON/GAMMB/DUM(5),GAMB,DUMEB,WB,DUM3(8)
      COMMON/SPE/ESPECT(30),SPECT(30),NREAD,LOOPN,OMGA(20)
      COMMON/CONST/PYE,RADAP
      COMMON/LIO/NOPT
      COMMON/PPP/PPUNS(20),PPWC,PPFC,PPPF,PPTOT,HRR1,HE1,HP,PUNTOT,PSTOT
      IFW=0
      ANGLE=ARCOS(GAMB)
  200 DO 3 J=1,INA
      IF(ANGLE-A(J))11,11,12
   11 IF(ANGLE-A(J+1))12,14,14
   14 IF(SCAT)1,2,1
    2 IF(NPP)23,22,23
   22 ROM(LOOPN,J)=ROM(LOOPN,J)+TOB
      GO TO 24
   23 PPUNS(J)=PPUNS(J)+TOB
      IF(J.EQ.INA)CALL FOWARD(IFW)
      IF(IFW.EQ.1)P51=P51+TOB
   24 IF(NOPT.EQ.0) GO TO 2000
      WRITE(6,21)NPP,J,ANGLE,GAMB,ES,ROM(LOOPN,J),PPUNS(J),SCAT,A(J),FS,
     1WB,WABS
   21 FORMAT(9H TALLY 2  ,2I5,6F15.5/4F15.5)
      GO TO 2000
    1 IF(J.EQ.INA)CALL FOWARD(IFW)
      DO 4 I=1,INF
      IF(ES-F(I))111,111,121
  111 IF(ES-F(I+1))121,121,141
  141 IF(NPP)43,42,43
   42 RM(I,J)=RM(I,J)+WB
      PF(I,J)=PF(I,J)+WABS
      IF(IFW.EQ.1) FW(I)= FW(I)+WB
      GO TO 5
   43 R5(I,J)=R5(I,J)+WB
      PPPF=PPPF+WABS
      IF(IFW.EQ.1)PFW(I)=PFW(I)+WB
      GO TO 5
  121 CONTINUE
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    4 CONTINUE
      I=INF
   12 CONTINUE
    3 CONTINUE
      J=INA
    5 CONTINUE
      IF(NOPT.EQ.0)GO TO 2000
      WRITE(6,20)LOOPN,J,I,ANGLE,GAMB,ES,ROM(LOOPN,J),RM(I,J),SCAT,
     1  A(J),E(I),WB,PE(I,J),R5(LOOPN,J),WABS,NPP,IOB
   20 FORMAT(9H TALLY 1  ,3I5,6E15.5/6E15.5,I10,F15.5)
 2000 RETURN
      END
      SUBROUTINE TA(F,X,M,MM,MOX,MUN,Z,Y,R,NDEGRE,L,LL)
      DIMENSION X(200),Z(6),Y(6),R(200)
      MOX=M
      MUN=MM
    7 KDEL=(MOX-MUN)/2
    8 IF(KDEL)18,14,18
   18 KP=MUN+KDEL
      DIF=X(KP)-F
      IF(X(KP).GT.X(KP+1))DIF=-DIF
      IF(DIF)12,12,11
   11 MOX=KP
      GO TO 7
   12 DIFF=F-X(KP)
      IF(X(KP).GT.X(KP+1))DIFF=-DIFF
      IF(DIFF)24,24,13
   13 MUN=KP
      GO TO 7
   24 MUN=KP
      MOX=KP+1
   14 IF(MOX-M)4,5,4
    5 L=MUN-2
      GO TO 6
    4 L=MUN-1
    6 NN=NDEGRE+1
      IF(LL)15,2,15
    2 DO 3 I=1,NN
      J=I+L
      Z(I)=X(J)
    3 Y(I)=R(J)
   15 RETURN
      END
      FUNCTION TF(N,X,Y,EO)
      DIMENSION X(6),Y(6)
      S=0.0
      I=1
   28 IF(I-N)21,21,22
   21 P=Y(I)
      J=1
   27 IF(J-N)23,23,24
   23 IF(I-J)25,26,25
   25 P=P*(EO-X(J))/(X(I)-X(J))
   26 J=J+1
      GO TO 27
   24 S=S+P
      I=I+1
      GO TO 28
   22 TF=S
      RETURN
```

```
      END
      SUBROUTINE TESTWT(LOW)
      COMMON/RAND/N,NM
      COMMON/GAMMB/DUM(7),WB,DUM1(8)
      COMMON/LID/NOPT
      IF(WB-1.0E-5)1,1,3
    1 IF(WB)4,2,4
    2 LOW=0
      IF(NOPT.EQ.0)GO TO 2000
      WRITE(6,100)WB,LOW
  100 FORMAT(10H TESTWT-1   ,F20.7,I10)
 2000 RETURN
    4 IF(RNGEN(N)-1.0E-5)5,5,2
    5 WB=WB*1.0E5
    3 LOW=1
C     WRITE(3,200)WB,LOW
C 200 FORMAT(10H TESTWT-2  /1X,F14.7,I10)
      RETURN
      END
      SUBROUTINE AGEOM(IP,X,Y,Z,THETA,THETO,THETS,R,RS,AREA,NT)
      COMMON/CORDS/XX(2),YY(2),ZZ(2),CMPI
      COMMON/CXYZ/XC,YC,ZC
      DIMENSION X(4),Y(4),Z(4),                        THA(2)
      SUMX=0.0
      SUMY=0.0
      SUMZ=0.0
      DO 10 K=1,IP
      SUMX=SUMX+X(K)
      SUMY=SUMY+Y(K)
      SUMZ=SUMZ+Z(K)
   10 CONTINUE
      XC=SUMX/IP
      YC=SUMY/IP
      ZC=SUMZ/IP
      CALL UVETOR(IP,X,Y,Z,UX,UY,UZ,AREA,NT)
      DO 20 KK=1,2
      RX     =XX(KK)-XC
      RY     =YY(KK)-YC
      RZ     =ZZ(KK)-ZC
      CALL ANGTHE(RX,RY,RZ,UX,UY,UZ,THE)
      THA(KK)=THE
C     WRITE(6,1001)UX,UY,UZ,XC,YC,ZC,RX,RY,RZ,KK
 1001 FORMAT(10H UX,UY,UZ, 3E15.5/10H XC,YC,ZC=  3E15.5/10H RX,RY,RZ= ,
     13E15.5,5X,2HK=,I3)
      IF(KK.EQ.2) GO TO 15
      R1=RX
      R2=RY
      R3=RZ
   20 CONTINUE
   15 CALL ANGTHE(RX,RY,RZ,R1,R2,R3,THETS)
      AREA=AREA*CMPI*CMPI
      R=SQRT(RX*RX+RY*RY+RZ*RZ)*CMPI
      RS=SQRT(R1*R1+R2*R2+R3*R3)*CMPI
      THETO=THA(1)
      THETA=THA(2)
C     WRITE(6,1000)THA(1),THA(2) ,THETS,R,RS,AREA
 1000 FORMAT(5X,15HINCIDENT ANGLE=,F10.5,5X,17HREFLECTING ANGLE=,F10.5,
     15X,9H THETS = ,F10.5/3X,3HR= ,F10.4,5H  RS=,F10.4,7H  AREA=F12.4)
      RETURN
      END
```

```
      SUBROUTINE ALB(TOTSAA)
      DIMENSION X(40),Y(40),Z(40),PX(40),PY(40),PZ(40)          ,XSC(30)
      DIMENSION P1(40),P2(40),P3(40),EE(20),EN(20),PA(9)
      DIMENSION XSECT(3),EPG(20),YO(6),ZO(6),ENY(30)
      DIMENSION STRUCT(8),POINTS(8),RMAT(6)
      COMMON/SOURSE/SS(20),SN(20),EE,EN,DUMSS(40)
      COMMON/RATIO/PA,NE,NNE,MN,MG
      COMMON/CORDS/XS,XD,YS,YD,ZS,ZD,CMPI
      COMMON/BOOM/IBOOM,DL
      COMMON/CONST/PYE,RADAP
      COMMON/GANXS/ENY,XSC,NON
      COMMON/MUU/UMU,UNU
      COMMON/NST/NOP
      COMMON/DENT/DUM1(45),NELL(9),DUM2(47)
      COMMON/RSTOS/RSCOB,RDTOB
      XSOLD=XS
      YSOLD=YS
      ZSOLD=ZS
      XDOLD=XD
      YDOLD=YD
      ZDOLD=ZD
      TOTSAA=0.0
      MOLD=0
      WRITE(6,97)
   97 FORMAT(1H1,40X,6HALBEDO //131H INPUT STRU.     NAME  MATERIAL   THIC
     1K(CM)    LENGTH(CM)    RADIUS(CM)    AREA(CM**2)  DIST(FR.S)    DIST(F
     2R.D)   NO ABDO FLUX   S-SC FLUX     /)
      READ(5,99)NORE
   99 FORMAT(I2)
      DO 10 NSS=1,NORE
      READ(5,98)(STRUCT(I),I=1,8), (POINTS(I),I=1,8),(RMAT(I),I=1,6)
   98 FORMAT(8A1,2X,8A1,2X,6A1)
      READ(5,100)NNNN,M,IP,IK,T2,T1,TB,MT,(X(I),Y(I),Z(I),I=1,IP)
  100 FORMAT(I1,I4,2I5,3F10.5,I5,/(9F8.3))
      ALBE=0.0
      TLSS=0.0
      XS=XSOLD
      YS=YSOLD
      ZS=ZSOLD
      XD=XDOLD
      YD=YDOLD
      ZD=ZDOLD
      MX=0
      MZ=0
      IC=0
      IBOOM=0
      T=(T2-T1)*CMPI
      IF(TB.NE.0.0)IBOOM=1
      IF(M.EQ.MOLD) GO TO 2
      NELL(1)=1
      IF(NNNN.NE.0)NELL(1)=NNNN
      NOR=0
      CALL GTSIGW(1,1,1,A,B)
      IF(MN-1)82,81,81
   81 NNN=NELL(1)
      CALL NENSIG(NON,ENY,XSC,NNN)
   82 MOLD=M
    2 IF(IP.EQ.4.OR.IP.EQ.3) GO TO 4
    1 CALL CKTRAN(IP,IK,X,Y,Z,IXY,RHO,P1,P2,P3,IPP)
      IF(IP.LE.2) GO TO 12
```

```
      RHO2=0.0
      ROUT=0.0
      PAREA=0.0
      RSOC=RSCOB*CMPI
      ROTB=ROTOB*CMPI
      IROP=4
C     IF(IK.EQ.3)IROP=3
   23 IC=IC+1
      IA=(IC-1)*IROP
      DO 40 K=1,IROP
      X(K)=P1(IA+K)
      Y(K)=P2(IA+K)
   40 Z(K)=P3(IA+K)
      GO TO 7
   12 IF(IXY.NE.0) GO TO 14
    3 CALL ROTATE(X,Y,Z,IXY,RHO)
   14 CALL DIVIDE(IXY,RHO,PX,PY,PZ,N,NA,T2)
      ROUT=T2*CMPI
      RHO2=RHO*2.0*CMPI
      PAREA=0.0
      RSOC=RSCOB*CMPI
      ROTB=ROTOB*CMPI
      NAA=NA-1
      NN=2*N
   20 MX=MX+1
      X(1)=PX(MX)
      X(2)=X(1)
      X(3)=PX(MX+1)
      X(4)=X(3)
      IF(IXY.EQ.1) GO TO 8
      Y(1)=PY(MX)
      Y(2)=Y(1)
      Y(3)=PY(MX+1)
      Y(4)=Y(3)
      IF(IXY.EQ.2) GO TO 8
      Z(1)=PZ(MX)
      Z(2)=Z(1)
      Z(3)=PZ(MX+1)
      Z(4)=Z(3)
    8 MZ=MZ+1
      IF(IXY-2)21,21,22
   21 Z(1)=PZ(MZ)
      Z(2)=PZ(MZ+1)
      Z(3)=Z(2)
      Z(4)=Z(1)
      IF(IXY-2)22,9,22
   22 Y(1)=PY(MZ)
      Y(2)=PY(MZ+1)
      Y(3)=Y(2)
      Y(4)=Y(1)
      IF(IXY-2)7,9,9
    9 X(1)=PX(MZ)
      X(2)=PX(MZ+1)
      X(3)=X(2)
      X(4)=X(1)
    7 IP=4
    4 CALL AGEOM(IP,X,Y,Z,THETA,THETO,THS,R,RS,AREA,NT)
      IF(IK.NE.0) GO TO 60
      ROUT=0.0
      RHO2=0.0
```

```
      PAREA=AREA
      RSOC=RS
      PDTB=R
   60 IF(IBOOM.EQ.1) GO TO 50
      IF(THETA.GT.90..OR.THETO.GT.90.) GO TO 5
      ALBEG=0.0
      DO 25 KF=1,NF
      EO=FF(KF)
      DO=SS(KF)
      EG=EO/0.51097
      CALL GTSIGW(3,1.1,EG,XSECT)
      UMU=XSECT(1)
      CALL ALBEDO(EO,M,THETA,THETO,THS,T,ALBED)
      ALFLUX=DO*COS(THETO/RADAP)*ALBED*AREA/(4.*PYE*RS*RS*R*R)
      ALBEG=ALBEG+ALFLUX
C     WRITE(6,150)EO,UMU,DO,ALFLUX,ALBEG
  150 FORMAT(8H  AT E= ,F7.3,6H  MU= ,F12.5,19H NO. OF GAM.SOURCE F12.4,
     110H  ALFLUX= ,F12.4,14H  ACC.ALFLUX= ,F12.4)
   25 CONTINUE
      ALBXN=0.0
      IF(MN.EQ.0)GO TO 16
      DO 30 KEN=1,NNF
      EOO=EN(KEN)
      DO=SN(KEN)
      CALL TA(EOO,ENY,NON,1,MOX,MUN,ZO,YO,XSC,2,L,0)
      UNU=TF(3,ZO,YO,EOO)
C  ASSUME NO ALBEDO DUE TO NEUTRON REFLECTION
      ALBEN=0.0
      ANFLUX=DO*COS(THETO/RADAP)*ALBEN*AREA/(4.*PYE*RS*RS*R*R)
      ALBXN=ALBXN+ANFLUX
   30 CONTINUE
      GO TO 16
    5 ALBEG=0.0
      ALBXN=0.0
   16 ALBE=ALBE+ALBEG+ALBXN
C     WRITE(6,200)ALBEG,ALBXN,ALBE,IC,MZ,MX,(X(I),Y(I),Z(I),I=1,IP)
  200 FORMAT(15H FLUX(G.,N.,T.),3E12.4,11H  IC,MX,MZ ,3I5,/(3F10.4))
      GO TO 15
   50 CALL SINGSC (IK,T2,T1,THS,R,RS,PHLUSS,PHLUSN,AREA)
      TLSS=TLSS+PHLUSS+PHLUSN
C     WRITE(6,250)IC,MX,MZ,PHLUSS,PHLUSN,TLSS
  250 FORMAT(18H SINGLE SCATTERING,3I5,3E12.4)
   15 IF(MZ.EQ.0) GO TO 11
      IF(MZ.LT.NAA) GO TO 8
      MZ=0
      IF(MX.LT.NN) GO TO 20
   11 CONTINUE
      IF(IC.EQ.0) GO TO 6
      IF(IA.LT.(IPP-4))GO TO 23
    6 WRITE(6,600)NSS,(STRUCT(I),I=1,8),(POINTS(I),I=1,8),(RMAT(I),I=1,6
     1),T,RHO2,ROUT,PAREA,RSOC,RDTB,ALBE,TLSS
  600 FORMAT(/1X,I2,2X,8A1,1X,8A1,1X,6A1,8(F13.4))
C   6 WRITE(6,300)ALBE
C 300 FORMAT(9H  ALBEDO=,F15.6)
C     IF(IBOOM.NE.1) GO TO 19
C     WRITE(6,400)TLSS
C 400 FORMAT(23H  TOTAL SINGLE SCATT.= ,F15.6)
   19 TOTSAA=ALBE+TLSS+TOTSAA
   10 CONTINUE
      WRITE(6,500)TOTSAA
```

```
500 FORMAT(   ///
   1  70X, 35H TOTAL CALCULATED SCATTERED FLUX = ,E13.5// )
      RETURN
      END
      SUBROUTINE ALBEDO(EO,M,TH,THO,THS,T,ALBED)
      DIMENSION EE(3),DAON(3,10),MN(10),D(3),Z(3),Y(3)
      COMMON/CORDS/DUM(6),CMPI
      COMMON/MUU/UMU,UNU
      COMMON/CONST/PYE,RADAP
      DATA EE/0.412,0.662,1.25/
      DATA DAON/0.095,0.125,0.111,    0.082,0.117,0.102,                    C AL
     1          0.056,0.091,0.100,    0.044,0.072,0.095,                    TI FF
     2          0.00975,0.016,0.053,  0.00976,0.011,0.044/                  SN  (
      DATA MN/6,13,22,26,50,92/
      KOO=1
      TT=T
      GF=THICK(EO,UMU,TT)
      DO 30 I=1,6
      IF(M.EQ.MN(I)) GO TO 1
      IF(M.LT.MN(I+1).AND.M.GT.MN(I)) GO TO 2
   30 CONTINUE
      WRITE(6,222)
  222 FORMAT(44H CHARGE NO.OF THE MATERIAL IS GT 92 OR LT 6 )
      RETURN
    1 KOO=0
    2 N=I
      DO 3 J=1,3
      D(J)=DAON(J,N)
    3 CONTINUE
      IF(EO.GT.EE(2)) GO TO 4
      L=0
      GO TO 5
    4 L=1
    5 Z(1)=EE(L+1)
      Z(2)=EE(L+2)
      Y(1)=D(L+1)
      Y(2)=D(L+2)
C     WRITE(6,220)EO,L,(Z(J),Y(J),J=1,2)
  220 FORMAT(8H TA-DATA,F12.3, I5,4F12.3)
      DALPHO=TE(2,Z,Y,EO)
C     WRITE(6,111)DALPHO ,M,N
  111 FORMAT(10H DALPHO-1 ,E15.5,5H  M= ,I3,5H  N= ,I3)
      IF(KOO.EQ.0) GO TO 50
      DO 20 K=1,3
      D(K)=DAON(K,N+1)
   20 CONTINUE
      Y(1)=D(L+1)
      Y(2)=D(L+2)
      DALP=TE(2,Z,Y,EO)
      ZM=M
      Z(1)=MN(N)
      Z(2)=MN(N+1)
      Y(1)=DALPHO
      Y(2)=DALP
      DALPHO=TE(2,Z,Y,ZM)
   50 ALBED=DALPHO*COS(TH/RADAP)*COS(THO/RADAP)*GF
C     WRITE(6,112)EO,DALPHO,GF,ALBED
  112 FORMAT(7H ALBED ,4E15.5)
      RETURN
      END
```

```
      SUBROUTINE ANGTHE(X1,Y1,Z1,X2,Y2,Z2,THE)
      COMMON/CONST/PYE,RADAP
      VECT1=SQRT(X1*X1+Y1*Y1+Z1*Z1)
      VECT2=SQRT(X2*X2+Y2*Y2+Z2*Z2)
      THE=ARCOS((X1*X2+Y1*Y2+Z1*Z2)/(VECT1*VECT2))
C     WRITE(6,1)VECT1,VECT2,THE
    1 FORMAT(31H ANGTHE-V1,V2,ANGLE(IN RADIAN) ,3F14.5)
      THE=THE*RADAP
      RETURN
      END
      FUNCTION CIGMA(E,THE)
C ENERGY IS IN THE UNIT OF M*C*C
      COMMON/CONST/PYE,RADAP
      AT=COS(THE/RADAP)
      A=1.-AT
      B=1.+AT*AT
      EA=E*A
      CIGMA=(2.8183E-13)**2/2.*B/(1.+EA)**2*(1.+EA*EA/(B*(1.+EA)))
C     WRITE(6,111)AT,A,B,E,EA,CIGMA
  111 FORMAT(8H CIGAM   ,6E15.5)
      RETURN
      END
      SUBROUTINE CKTRAN(IP,IK,X,Y,Z,IXY,RHO,PX,PY,PZ,IPP)
      DIMENSION X(24),Y(24),Z(24),PX(40),PY(40),PZ(40)
      COMMON/CORDS/XX(2),YY(2),ZZ(2),CMPI
      COMMON/RSTOS/RS,RD
      OX=0.0
      OY=0.0
      OZ=0.0
      DO 1 I=1,IP
      PX(I)=0.0
      PY(I)=0.0
    1 PZ(I)=0.0
      DELX=X(2)-X(1)
      DELY=Y(2)-Y(1)
      DELZ=Z(2)-Z(1)
      IPP=0
      IF(IP-2) 5,5,10
    5 IXY=0
      IF(DELX.EQ.0.0.AND.DELY.EQ.0.0)IXY=3
      IF(DELZ.EQ.0.0.AND.DELX.EQ.0.0)IXY=2
      IF(DELZ.EQ.0.0.AND.DELY.EQ.0.0)IXY=1
      OX=(X(1)+X(2))/2.0
      OY=(Y(1)+Y(2))/2.0
      OZ=(Z(1)+Z(2))/2.0
      RHO=SQRT((X(1)-OX)**2+(Y(1)-OY)**2+(Z(1)-OZ)**2)
      IF(IXY)2,2,4
   10 IPP=IP
      XSUM=0.0
      YSUM=0.0
      ZSUM=0.0
      DO9 I=1,IPP
      XSUM=XSUM+X(I)
      YSUM=YSUM+Y(I)
      ZSUM=ZSUM+Z(I)
    9 CONTINUE
      OX=XSUM/IPP
      OY=YSUM/IPP
      OZ=ZSUM/IPP
      DO 19 I=1,IPP
```

```
      PX(I)=X(I)-DX
      PY(I)=Y(I)-DY
      PZ(I)=Z(I)-DZ
   19 CONTINUE
    4 DO 20 K=1,2
      XX(K)=XX(K)-DX
      YY(K)=YY(K)-DY
      ZZ(K)=ZZ(K)-DZ
   20 CONTINUE
 1000 FORMAT(7H IXY=  ,I2,9H    RHO=   ,F10.4/(6X,6F12.4))
      RS=SQRT(XX(1)*XX(1)+YY(1)*YY(1)+ZZ(1)*ZZ(1))
      RD=SQRT(XX(2)*XX(2)+YY(2)*YY(2)+ZZ(2)*ZZ(2))
C   2 WRITE(6,1000)IXY,RHO,DELX,DELY,DELZ,DX,DY,DZ,(XX(L),YY(L),ZZ(L),L=
C    11,2)
    2 CONTINUE
      RETURN
      END
      SUBROUTINE DIVIDE(IXY,RHO,PX,PY,PZ,N,NA,T2)
      DIMENSION PX(40),PY(40),PZ(40)
      COMMON/CONST/PYE,RADAP
      COMMON/BOOM/IB,DL
      COMMON/CORDS/XS,XD,YS,YD,ZS,ZD,CMPI
      RADOB=T2
C  CYLINDER IS DIVIDED INTO NL SECTIONS OF DL LENGTH
      RD=SQRT(XD*XD+YD*YD+ZD*ZD)
      RS=SQRT(XS*XS+YS*YS+ZS*ZS)
      SN=2.0
    1 DL=RHO/SN
      SS=(RS-DL  )/5.0
      DD=(RD-DL  )/5.0
      IF(DL.LE.SS.AND.DL.LE.DD) GO TO 2
      SN=SN+1.
      GO TO 1
    2 N=RHO/DL
      NL=2*N+1
C    ANGLE IS DIVIDED INTO DA-DEGREES INTERVALS
C     WRITE(6,3000) IB
 3000 FORMAT(5X,4HIB= ,I2)
      IF(IB)4,4,3
    3 NA=2
      AINT=PYE
      GO TO 8
    4 DA=45.0
    5 AINT=DA/RADAP
      A=AINT*RADOB
      IF(A.LE.SS.AND.A.LE.DD) GO TO 6
      DA=DA-15.0
      IF(DA.LT.10.0) DA=10.0
      GO TO 5
    6 NA=360.0/DA+1.
C     WRITE(6,2000)NL,DL,NA,DA,AINT,A,SS,DD
 2000 FORMAT(16H  DIVDIDE DATA-A, 2(I3,F9.4),4F12.3)
    8 IF(IXY-2)9,30,60
    9 DO 10 I=1,NL
   10 PX(I)=(I-1-N)*RHO/N
      DO 20 I=1,NA
      FCOS=COS((I-1)*AINT)
      FSIN=SIN((I-1)*AINT)
      IF(ABS(FCOS).LE.1.0E-05)FCOS=0.0
      IF(ABS(FSIN).LE.1.0E-05)FSIN=0.0
```

```
      PY(I)=RADOR*FCOS
      PZ(I)=RADOR*FSIN
   20 CONTINUE
      GO TO 90
   30 DO 40 I=1,NL
   40 PY(I)=(I-1-N)*RHO/N
      DO 50 I=1,NA
      FCOS=COS((I-1)*AINT)
      FSIN=SIN((I-1)*AINT)
      IF(ABS(FCOS).LE.1.0E-05)FCOS=0.0
      IF(ABS(FSIN).LE.1.0E-05)FSIN=0.0
      PX(I)=RADOR*FCOS
      PZ(I)=RADOR*FSIN
   50 CONTINUE
      GO TO 90
   60 DO 70 I=1,NL
   70 PZ(I)=(I-1-N)*RHO/N
      DO 80 I=1,NA
      FCOS=COS((I-1)*AINT)
      FSIN=SIN((I-1)*AINT)
      IF(ABS(FCOS).LE.1.0E-05)FCOS=0.0
      IF(ABS(FSIN).LE.1.0E-05)FSIN=0.0
      PX(I)=RADOR*FCOS
      PY(I)=RADOR*FSIN
   80 CONTINUE
C  90 WRITE(6,1000)NL,DL,NA,DA,RHO
 1000 FORMAT(14H  DIVIDE DATA ,2(I5,F10.5),5X,4HRHO=,F10.5)
   90 CONTINUE
      RETURN
      END
      SUBROUTINE ROTATE(X,Y,Z,IXY,RHO)
      DIMENSION X(4),Y(4),Z(4),R(2)
      COMMON/RSTOS/RS ,RD
      COMMON/CORDS/XX(2),YY(2),ZZ(2),CMPI
      J=2
      IXY=1
      OX=(X(1)+X(2))/2.0
      OY=(Y(1)+Y(2))/2.0
      OZ=(Z(1)+Z(2))/2.0
      IF(X(1).GT.X(2)) J=1
      OOX=X(J)-OX
      OOY=Y(J)-OY
      OOZ=Z(J)-OZ
      RHO=SQRT(OOX*OOX+OOY*OOY+OOZ*OOZ)
      F11=OOX/RHO
      F12=OOY/RHO
      F13=OOZ/RHO
      IF(ABS(OOX).LT.ABS(OOY)) GO TO 10
      RHOZX=SQRT(OOX*OOX+OOZ*OOZ)
      F31=-OOZ/RHOZX
      F32=0.0
      F33= OOX/RHOZX
      F21=F32*F13-F33*F12
      F22=F33*F11-F31*F13
      F23=F31*F12-F32*F11
      GO TO 15
   10 IXY=2
      F21=F11
      F22=F12
      F23=F13
```

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      RHOZY=SQRT(OOY*OOY+OOZ*OOZ)
      F31=0.0
      F32=-OOZ/RHOZY
      F33= OOY/RHOZY
      F11=F22*F33-F23*F32
      F12=F23*F31-F21*F33
      F13=F23*F32-F22*F31
   15 DO 20 K=1,2
      R(K)=SQRT((XX(K)-OX)**2+(YY(K)-OY)**2+(ZZ(K)-OZ)**2)
      XX(K)=(XX(K)-OX)*F11+(YY(K)-OY)*F12+(ZZ(K)-OZ)*F13
      YY(K)=(XX(K)-OX)*F21+(YY(K)-OY)*F22+(ZZ(K)-OZ)*F23
      ZZ(K)=(XX(K)-OX)*F31+(YY(K)-OY)*F32+(ZZ(K)-OZ)*F33
   20 CONTINUE
      RS=R(1)
      RD=R(2)
C     WRITE(6,1)IXY,OX,OY,OZ,F11,F12,F13,F21,F22,F23,F31,F32,F33,
C    1(X(K),Y(K),Z(K) ,XX(K),YY(K),ZZ(K),K=1,2)
    1 FORMAT(//,6H IXY= ,I3/(5X,6F10.5))
      RETURN
      END
      SUBROUTINE SINGSC (IK,T2,T1,THS,R,RS,PHLUSS,PHLUSN,AREA)
      DIMENSION FF(20),FN(20),Y(6),Z(6),RA(9),XSECT(3)
      COMMON/RATIO/RA,NF,NNF,MN,MG
      COMMON/SOURSE/SS(20),SN(20),FF,FN,DUMSS(40)
      COMMON/DENT/DDUM(100),FLDEN
      COMMON/CORDS/DUM(6),CMPI
      COMMON/CONST/PYE,RADAP
      COMMON/BOOM/IB,DL
      COMMON/GANXS/FNY(30),XSC(30),NON
      P4R=4.0*PYE*R*R*RS*RS
      IF(IK.EQ.0) GO TO 3
      VOL=PYE*DL*(T2*T2-T1*T1)*CMPI**3
      GO TO 4
    3 VOL=AREA*(T2-T1)*CMPI
    4 PHLUSS=0.0
      IF(MG)6,6,5
    5 DO 10 I=1,NF
      DO=SS(I)
      FO=FF(I)/0.51097
      CALL GTSIGM(3,1,1,FO,XSECT)
      UMU=XSECT(1)
      XKS=CIGMA(FO,THS)
      SSFLXG=DO*FLDEN*UMU*XKS*VOL*1.0E+24/P4R
      PHLUSS=PHLUSS+SSFLXG
C     WRITE(6,110)FO,DO,XKS,UMU,SSFLXG,PHLUSS
  110 FORMAT(25H SINGLE SCATT. FROM GAM. ,6F12.4)
   10 CONTINUE
    6 PHLUSN=0.0
      IF(MN)9,9,7
    7 DO 8 J=1,NNF
      FOO=FN(J)
      DN=SN(J)
      CALL TA(FOO,FNY,NON,1,MOX,MUN,Z ,Y ,XSC,2,[,0)
      UNU=TF(3,Z,Y,FOO)
C  ASSUME NO NEUTRON SINGLE SCATTERINGS
      XKSN=0.0
      SSFLXN=DN*VOL*XKSN*FLDEN*1.0E+24/P4R*UNU
      PHLUSN=PHLUSN+SSFLXN
    8 CONTINUE
C   9 WRITE(6,111)IB,THS,P4R,FLDEN,PHLUSS,PHLUSN
```

```
  111 FORMAT(24H SINGLE SCATTERING DATA ,I2,5E12.4)
    9 CONTINUE
      RETURN
      END
      FUNCTION THICK(EO,UMU,T)
      C= -ALOG(1.-0.99)*UMU/2.
      THICK=1.-EXP(-C*T)
C     WRITE(6,2000)EO,UMU,C,T,THICK
 2000 FORMAT(13H THICK-DATA   ,5E13.4)
      RETURN
      END
      SUBROUTINE UVETOR(K,X,Y,Z,UX,UY,UZ,AREA,NT)
      DIMENSION X(4),Y(4),Z(4),DX(3),DY(3),DZ(3)
      COMMON/CXYZ/XC,YC,ZC
      KE=K-1
      DO 10 I=1,KE
      L=I
      L11=L+1
      DX(L)=X(L11)-X(L)
      DY(L)=Y(L11)-Y(L)
      DZ(L)=Z(L11)-Z(L)
   10 CONTINUE
      K1=1
      K2=2
      GO TO 7
    8 K1=2
      K2=1
    7 VX=DY(K1)*DZ(K2)-DY(K2)*DZ(K1)
      VY=DX(K2)*DZ(K1)-DX(K1)*DZ(K2)
      VZ=DX(K1)*DY(K2)-DX(K2)*DY(K1)
      IF(VX*XC) 8,6,6
    5 IF(VZ*ZC) 8,4,4
    6 IF(VY*YC) 8,5,5
    4 V=SQRT(VX*VX+VY*VY+VZ*VZ)
      AREA=V
      IF(KE.EQ.2)AREA=0.5*V
C   9 WRITE(6,50)VX,VY,VZ,V
   50 FORMAT(22H V-VECTOR VX,VY,VZ,V   ,4E14.4)
      UX=VX/V
      UY=VY/V
      UZ=VZ/V
      IF (NT.LT.0) GO TO 20
      RETURN
   20 UX=-UX
      UY=-UY
      UZ=-UZ
      RETURN
      END
/*
```

APPENDIX IV

CODE SØSC SAMPLE INPUT DATA LISTING

```
// EXEC LINKGO,REGION.GO=250K
//GO.FT06F001 DD SYSOUT=A,DCB=(RECFM=VBA,LRECL=137,BLKSIZE=7265),
//                SPACE=(CYL,(5,5))
//SYSUDUMP DD SYSOUT=A,SPACE=(TRK,(10))
//GO.DATA5 DD *
   1    2    3    4    6    6    7
   0.0       81.0        0.0      240.0       0.0       95.1     1.5839 3.94
   18     2    16     2     0    77     4 5.0      0.1  0.15    2.0     0.08333  0.8
   1    7  12   18
10.0 7.5 5.0 3.0
  0.25  0.35  0.45  0.55  0.65  0.75  0.85  0.95  1.10  1.30  1.50  1.70

  1.90  2.50  3.50  4.50  5.50  6.50
1.6200E&074.7047E&077.9831E&071.8418E&088.4914E&073.2661E&089.7972E&07
5.0233E&077.0597E&074.5001E&074.0440E&073.9699E&073.9455E&076.7414E&08
9.1278E&052.7067E&058.1041E&042.7755E&04
    .1615     0.266     0.4385     0.624      0.801      1.03       1.325
   1.70       2.18      2.795      3.575      4.25       4.82       5.92
   7.605      9.275
1.1044E&062.1724E&063.6796E&063.7262E&066.0516E&068.1668E&069.2204E&06
8.4488E&061.3835E&072.3946E&071.6815E&071.7679E&064.5018E&054.4579E&05
1.2893E&054.0482E&04
20
  ROOM      J-I        IRON
   26    2    1    0.406      0.312      1.0
   7.5    42.5    19.0      0.0      70.0      5.0
    6   -3    4    1    3
   24        7.87      26.0        55.85
   .01  16500.            .015    5380.             .02     2380.
   .03    729.            .04      308.             .05      155.
   .06     91.           .08       38.              .10      19.1
    .15   5.4             .20      2.23             .30      .66
    .40   .29              .50     .16              .60     .10
   .80    .05             1.0      .03              1.5               .032
   2.0             .12    3.0      0.0      .3503   4.0      0.0      .561
   5.0    0.0     0.753   6.0      0.0      0.915   8.0      0.0      1.181
   BOX     ONE       IRON
   26   24    0     0.2       0.0
 85.0    -5.0    30.0    85.0    -5.0    50.0    85.0     5.0    50.0
 85.0     5.0    30.0    85.0    -5.0    50.0    95.0    -5.0    50.0
  95.0    5.0    50.0    85.0     5.0    50.0    85.0    -5.0   30.0
  95.0   -5.0    30.0    95.0    5.0     30.0    85.0    5.0     30.0
  85.0   5.0     30.0    95.0    5.0     30.0    95.0    5.0    50.0
  85.0   5.0     50.0     85.0  -5.0     30.0     95.0   -5.0    30.0
  95.0   -5.0    50.0    85.0   -5.0     50.0    95.0    -5.0   30.0
  95.0   -5.0    50.0    95.0    5.0     50.0    95.0    5.0     30.0
  PLANE      A-2       IRON
   26    4    0    0.125     0.0        0.0
  23.8     13.75     2.5    23.8     13.75   27.5     13.75   23.8      2.5
  13.75     23.8    27.5
  PLANE      A-3       IRON
   26    4    0    0.125     0.0        0.0
  13.75     23.8     2.5    13.75    23.8     27.5      0.0     27.5      2.5
   0.0     27.5     27.5
  PLANE      A-1       IRON
   26    4    0    0.125     0.0        0.0
  27.5      0.0      2.0    27.5      0.0     27.5     23.8     13.75     2.5
  23.8     13.75    27.5
  ROOM       M-F       IRON
   26    2    1    0.406     0.312      1.0
  23.8     13.75    27.5    27.5    46.875   32.5
  ROOM       J-K       IRON
   26    2    1    0.406    -0.312      1.0
   7.5     42.5     19.0    -7.5     42.5     19.0
  ROOM       N-O       IRON
   26    2    1    0.406     0.312      1.0
  87.5      3.75    40.0    47.5     23.75    12.5
  ROOM       P-O       IRON
   26    2    1    0.406     0.312      1.0
  87.5      2.5     25.0    47.5     23.75    12.5
  ROOM       C-O        AL
   13    2    1    0.406     0.312      1.0
```

```
 47.5      22.5     32.5    47.5     23.75    12.5
   6   -3    4
  24         2.699    13.00      26.98
  0.01  1170.0     0.0      0.015 343.0      0.0      0.02  141.0      0.0
  0.03    39.0     0.0      0.04   15.2      0.0      0.05    7.3      0.0
  0.06     4.0     0.0      0.08    1.61     0.0      0.10     .78     0.0
  0.15      .21    0.0      0.20    0.08     0.0      0.30     .02     0.0
  0.40      .01    0.0      0.50    0.       0.0      0.60    0.0      0.0
  0.80    0.0      0.0      1.0     0.       0.0      1.5     0.0      .0076
  2.00    0.0       .03     3.0     0.      0.0862    4.0     0.0      .1406
  5.0     0.0       .187    6.0     0.0       .229    8.0     0.0       .30
CYLINDER    02-01       AL
  13    2    1    8.0       7.5       0.0
 0.0     0.0     32.5     0.0      0.0     71.25
 ANTENA      T-U        AL
  13    2    1    1.875     1.375     1.0
 42.5    0.0     40.00    7.5      0.0     36.25
CYLINDER    02-03       AL
  13    2    1   11.5      11.0       0.0
 0.0     0.0     71.25    0.0      0.0    106.25
 ANTENA      R-T        AL
  13    2    1    1.25      0.75      1.0
 81.0    0.0     61.25   42.5      0.0     40.0
 ANTENA      R'-T'      AL
  13    2    1    1.25      0.75      1.0
 70.02  40.5     61.25   36.8     21.25    40.0
 ANTENA      T'-U'      AL
  13    2    1    1.875     1.375     1.0
 36.8   21.25    40.00    6.49     3.75    36.25
 BOOM       D'-C1       AL
  13    2    1    0.406     0.312     1.0
232.5    0.0     95.0    47.5     22.5     32.5
 BOOM        B1-B2      AL
  13    2    1    0.406     0.312     1.0
146.875  12.50   63.75  146.875 -12.5    63.75
 BOOM         G-H       AL
  13    2    1    0.406     0.312     1.0
 22.5   63.75    18.75  -26.75    11.25    28.75
 BOOM         L-F       AL
  13    2    1   .0.406     0.312     1.0
 13.75   23.8    27.5    27.5     46.875   32.5
 THE SHIELD CONSISTS OF 0.1*LEAD AND 0.9*LIH
    2
 0.1  1  0.9 2
 82. 11.35
 1.00.1040 3.00.7159
   6   -3    4
  27        11.35     82.0      207.21
  0.01 27500.0    0.0    .01307    13200.0    0.0 .01586   45400.0  0.0
 0.02  24000.0    0.0     0.03     7620.0    0.0     0.04     3310.  0.0
  0.05   1740.0   0.0     0.06     1040.0   0.0      0.08     444.0  0.0
.088229   334.0   0.0   0.08823   2510.0   0.0      0.10   1780.0  0.0
  0.15    596.0   0.0     0.20      275.0   0.0      0.30     93.4    0.0
  0.40    45.7   0.0       0.50     26.1   0.0      0.60     17.3   0.0
  0.80    9.5    0.0      1.0      6.2    0.0     1.5      3.0      0.55
  2.0     2.0     1.72     3.0     1.1     3.931   4.0      0.80   5.764
  5.0     0.60    7.259   6.0      0.49    8.49    8.0      0.35   10.53
  24        0.1040     1.0         1.008
  .01   .0046    0.0      .015    .0011   0.0     .02     0.0     0.0
  .03   0.0      0.0      .04     0.0     0.0     .05     0.0     0.0
  .06   0.0      0.0      .08     0.0     0.0     .10     0.0     0.0
  .15   0.0      0.0      .20     0.0     0.0     .30     0.0     0.0
  .40   0.0      0.0      .50     0.0     0.0     .60     0.0     0.0
  .80   0.0      0.0      1.0     0.0     0.0     1.5     0.0    .000044
 2.00    .0      .00018   3.0     0.0    .00052   4.0     0.0     .00087
 5.0     .0      .0012    6.0     0.0    .0015    8.0     0.0     .0022
  24       .7159      3.0         6.94
 0.01    1.0     0.0      0.015    0.3     0.0     0.02    0.1     0.0
  0.03   0.03    0.0      0.04    0.01     .0     0.05   0.006   0.0
 0.06    0.003    .0      0.08    0.002    .0     0.1     0.0     0.0
 0.15    0.0     0.0      0.2     0.0     0.0     0.3     0.0     0.0
 0.4     0.0     0.0      0.5     0.0     0.0     0.6     0.0     0.0
 0.8     0.0     0.0      1.0     0.0     0.0     1.5     0.0    .0004
```

```
  2.0      0.0      .0016    3.0      0.0      .0048    4.0      0.0      .008
  5.0      0.0      0.011    6.0      0.0      0.014    8.0      0.0      0.018
18   11.35    207.21     82.0
   0.1    10.01   0.2     8.0     0.3     7.0     0.34    5.2     0.36    9.8
   0.40   6.0     0.5     3.2     0.55    5.0     0.70    6.8     0.75    5.4
   0.80   5.6     1.0     6.0     1.5     5.4     2.20    6.0     3.0     7.6
   5.0    7.2     8.0     5.3    10.0     5.0
17    0.1041      1.008      1.0
   0.1    12.5    0.2     9.6     0.24    8.8     0.26    8.5     0.28    8.2
   0.32   7.8     0.5     6.2     0.80    4.8     1.0     4.25    2.0     2.9
   3.0    2.25    4.2     1.83    5.0     1.6     6.0     1.42    7.0     1.13
   9.0    1.05   12.0     0.8
17    0.7159      6.94       3.0
   0.1    1.0     0.2     1.7     0.24    7.0     0.26   10.0     0.28    5.5
   0.32   2.0     0.5     1.0     0.98    1.4     1.0     1.5     2.0     1.7
   3.0    2.0     4.2     2.3     5.0     2.25    6.0     2.1     7.0     1.8
   9.0    1.6    12.0     1.5
  -1                     6   7
 THE SHIELD CONSISTS OF 0.9*LIH AND 0.1*LEAD
    2
 0.9  2  0.1 1
 1.00.1040 3.00.7159
 82. 11.35
    6   -3    4
   24         0.1040     1.0        1.008
   .01   .0046    0.0      .015     .0011    0.0      .02      0.0      0.0
   .03   0.0      0.0      .04      0.0      0.0      .05      0.0      0.0
   .06   0.0      0.0      .08      0.0      0.0      .10      0.0      0.0
   .15   0.0      0.0      .20      0.0      0.0      .30      0.0      0.0
   .40   0.0      0.0      .50      0.0      0.0      .60      0.0      0.0
   .80   0.0      0.0      1.0      0.0      0.0      1.5      0.0      .000044
  2.00     .0     .00018   3.0      0.0      .00052   4.0      0.0      .00087
  5.0      .0     .0012    6.0      0.0      .0015    8.0      0.0      .0022
   24        .7159       3.0        6.94
  0.01     1.0      0.0      0.015    0.3      0.0      0.02     0.1      0.0
   0.03    0.03     0.0      0.04     0.01     .0       0.05     0.006    0.0
  0.06     0.003    .0       0.08     0.002    .0       0.1      0.0      0.0
  0.15     0.0      0.0      0.2      0.0      0.0      0.3      0.0      0.0
  0.4      0.0      0.0      0.5      0.0      0.0      0.6      0.0      0.0
  0.8      0.0      0.0      1.0      0.0      0.0      1.5      0.0      .0004
  2.0      0.0      .0016    3.0      0.0      .0048    4.0      0.0      .008
  5.0      0.0      0.011    6.0      0.0      0.014    8.0      0.0      0.018
   27        11.35      82.0      207.21
   0.01 27500.0   0.0    .01307    13200.0    0.0 .01586   45400.0  0.0
  0.02  24000.0   0.0      0.03    7620.0    0.0     0.04     3310.  0.0
   0.05    1740.0   0.0     0.06    1040.0   0.0      0.08    444.0   0.0
.088229    334.0   0.0   0.08823  2510.0   0.0      0.10   1780.0  0.0

   0.15    596.0   0.0      0.20     275.0   0.0      0.30      93.4    0.0
   0.40    45.7   0.0       0.50     26.1   0.0      0.60     17.3   0.0
   0.80    9.5    0.0      1.0      6.2     0.0      1.5     3.0     0.55
   2.0     2.0     1.72     3.0     1.1     3.931   4.0      0.80    5.764
   5.0      0.60     7.259   6.0      0.49     8.49    8.0      0.35    10.53
17    0.1041      1.008      1.0
   0.1    12.5    0.2     9.6     0.24    8.8     0.26    8.5     0.28    8.2
   0.32   7.8     0.5     6.2     0.80    4.8     1.0     4.25    2.0     2.9
   3.0    2.25    4.2     1.83    5.0     1.6     6.0     1.42    7.0     1.13
   9.0    1.05   12.0     0.8
17    0.7159      6.94       3.0
   0.1    1.0     0.2     1.7     0.24    7.0     0.26   10.0     0.28    5.5
   0.32   2.0     0.5     1.0     0.98    1.4     1.0     1.5     2.0     1.7
   3.0    2.0     4.2     2.3     5.0     2.25    6.0     2.1     7.0     1.8
   9.0    1.6    12.0     1.5
18   11.35    207.21     82.0
   0.1    10.01   0.2     8.0     0.3     7.0     0.34    5.2     0.36    9.8
   0.40   6.0     0.5     3.2     0.55    5.0     0.70    6.8     0.75    5.4
   0.80   5.6     1.0     6.0     1.5     5.4     2.20    6.0     3.0     7.6
   5.0    7.2     8.0     5.3    10.0     5.0
/*
/*
```

APPENDIX V

CODE SØSC SAMPLE OUTPUT DATA LISTING

SOURCE DATA

GAMMA SPECTRUM

	ENERGY(MEV)	NO.OF GAMMA/SEC (RADIAL)	NO.OF GAMMA/SEC (AXIAL)	FLUX AT DETECTOR (RADIAL)	FLUX AT DETECTOR (AXIAL)
1	0.2500001E 00	.1620000E 08	0.1349945E 07	0.2729590E 01	0.2274566E 00
2	0.3500000E 00	.4714699E 08	0.3928424E 07	.7927100E 01	0.6605651E 00
3	0.4500000E 00	.7983899E 08	0.6652314E 07	0.1345098E 02	0.1120870E 01
4	0.5500000E 00	0.1841800E 09	.1534771E 08	0.3103308E 02	0.2585986E 01
5	0.6500000E 00	0.8491400E 08	0.7075881E 07	0.1430744E 02	0.1192238E 01
6	0.7500000E 00	0.3266099E 09	0.2721638E 08	0.5503156E 02	0.4585776E 01
7	.8500000E 00	0.9797200E 08	0.8164004E 07	0.1650761E 02	0.1375579E 01
8	0.9500000E 00	0.5023299E 08	0.4185913E 07	0.8463920E 01	0.7052981E 00
9	0.1099999E 01	0.7059699E 08	0.5882845E 07	0.1189512E 02	0.9912196E 00
10	0.1299999E 01	0.4500099E 08	0.3749931E 07	0.7582363E 01	0.6318380E 00
11	0.1500000E 01	0.4044000E 08	0.3369864E 07	0.6813867E 01	0.5677993E 00
12	0.1700000E 01	0.3969899E 08	0.3309116E 07	0.6689012E 01	0.5573952E 00
13	0.1900000E 01	0.3945499E 08	0.3287783E 07	0.6647900E 01	0.5539692E 00
14	0.2500000E 01	.6741399E 09	.5617605E 08	0.1135880E 03	.9465284E 01
15	0.3500000E 01	0.9127800E 06	0.7606188E 05	0.1537972E 00	0.1281591E-01
16	0.4500000E 01	0.2706700E 06	0.2255492E 05	0.4560617E-01	0.3800352E-02
17	0.5500000E 01	0.8104100E 05	0.6753145E 04	0.1365486E-01	0.1137859E-02
18	0.6500000E 01	0.2775500E 05	0.2312823E 04	0.4676528E-02	0.3896949E-03
	TOTAL=	0.1797610E 10	0.1497947E 09	0.3028850E 03	0.2523940E 02

NEUTRON SPECTRUM,

	ENERGY(MEV)	NO.OF NEUT./SEC (RADIAL)	NO.OF NEUT./SEC (AXIAL)	FLUX AT DETECTOR (RADIAL)	FLUX AT DETECTOR (AXIAL)
1	0.1615000E 00	0.1104400E 07	0.8835199E 06	0.1860839E 00	0.1488671E 00
2	0.2660000E 00	0.2172400E 07	0.1737919E 07	0.3660347E 00	0.2928276E 00
3	0.4385000E 00	0.3679600E 07	0.2943579E 07	0.6199877E 00	0.4959900E 00
4	0.6240000E 00	0.3726200E 07	0.2980959E 07	0.6278395E 00	0.5022714E 00
5	0.8010000E 00	0.6051600E 07	0.4841279E 07	0.1019653E 01	0.8157228E 00
6	0.1030000E 01	0.8166800E 07	0.6533439E 07	0.1376050E 01	0.1100840E 01
7	0.1325000E 01	0.9220400E 07	0.7376319E 07	0.1553575E 01	0.1242860E 01
8	0.1700000E 01	0.8448800E 07	0.6759039E 07	0.1423565E 01	0.1138852E 01
9	0.2179999E 01	0.1383500E 08	0.1106800E 08	0.2331103E 01	0.1864882E 01
10	0.2794999E 01	0.2394600E 08	0.1915678E 08	0.4034739E 01	0.3227788E 01
11	0.3575000E 01	0.1681499E 08	0.1345199E 08	0.2833212E 01	0.2266569E 01
12	0.4250000E 01	0.1767900E 07	0.1414319E 07	0.2978792E 00	0.2383032E 00
13	0.4820000E 01	0.4501800E 06	0.3601439E 06	0.7585227E-01	0.6068182E-01
14	0.5919999E 01	0.4457900E 06	0.3566319E 06	0.7511258E-01	0.6009007E-01
15	0.7650000E 01	0.1289300E 06	0.1031439E 06	0.2172383E-01	0.1737906E-01
16	0.9275000E 01	0.4048200E 05	0.3238560E 05	0.6820943E-02	0.5456753E-02
	TOTAL=	0.9999942E 08	0.7999944E 08	0.1684921E 02	0.1347936E 02

DIST. BET. SOURCE AND DETECTOR (CM)= 0.6872E 03 ALLOWED FLUX AT DETECTOR= 0.5000E 01

A

ALBEDO

INPUT	STRU.	NAME	MATERIAL	THICK(CM)	LENGTH(CM)	RADIUS(CM)	AREA(CM**2)	DIST(FR.S)	DIST(FR.D)	NO ABDO FLUX	S-SC FLUX
1	BOOM	J-I	IRON	0.2388E 00	0.8[illegible]66E 02	0.1031E 01	0.0	0.7[illegible]51E 02	0.6520E 03	0.0	0.1724E-01
2	BOX	ONE	IRON	0.5[illegible]0E 00	0.0	0.0	0.1290E 04	0.3330E 03	0.3940E 03	0.0	0.
3	PLANE	A-2	IRON	0.3175E 00	0.0	0.0	0.2292E 04	0.1694E 03	0.5995E 03	0.1[illegible]36E 00	0.0
4	PLANE	A-3	IRON	0.3175E 00	0.0	0.0	0.2297E 04	0.1467E 03	0.6295E 03	0.1128E 00	0.0
5	PLANE	A-1	IRON	0.3175E 00	0.0	0.0	0.2343E 04	0.2028E 03	0.5816E 03	0.0	0.0
6	BOOM	M-F	IRON	0.2388E 00	0.8561E 02	0.1031E 01	0.0	0.1632E 03	0.5742E 03	0.0	0.2297E-01
7	BOOM	J-K	IRON	0.2388E 00	0.3810E 02	0.1031E 01	0.0	0.1091E 03	0.6486E 03	0.0	0.1492E-01
8	BOOM	N-Q	IRON	0.2388E 00	0.1333E 03	0.1031E 01	0.0	0.2510E 03	0.4731E 03	0.0	0.1545E-01
9	BOOM	P-Q	IRON	0.2388E 00	0.1193E 03	0.1031E 01	0.0	0.2478E 03	0.4803E 03	0.0	0.1733E-01
10	BOOM	C-Q	AL	0.2388E 00	0.5090E 02	0.1031E 01	0.0	0.1986E 03	0.5259E 03	0.0	0.7919E-02
11	CYLINDER	O2-O1	AL	0.1270E 01	0.9842E 02	0.2032E 02	0.0	0.2443E 03	0.6194E 03	0.9578E-01	0.0
12	ANTENA	T-U	AL	0.1270E 01	0.8941E 02	0.4762E 01	0.0	0.2361E 03	0.5649E 03	0.0	0.2950E-01
13	CYLINDER	O2-O3	AL	0.1270E 01	0.8890E 02	0.2921E 02	0.0	0.3052E 03	0.6098E 03	0.4574E-01	0.0
14	ANTENA	R-T	AL	0.1270E 01	0.1117E 03	0.3175E 01	0.0	0.2889E 03	0.4666E 03	0.0	0.2227E-01
15	ANTENA	R'-T'	AL	0.1270E 01	0.1115E 03	0.3175E 01	0.0	0.2262E 03	0.4935E 03	0.0	0.3182E-01
16	ANTENA	T'-U'	AL	0.1270E 01	0.8941E 02	0.4762E 01	0.0	0.2066E 03	0.5741E 03	0.0	0.4554E-01
17	BOOM	D'-C1	AL	0.2388E 00	0.4993E 03	0.1031E 01	0.0	0.4290E 03	0.2677E 03	0.0	0.1176E-01
18	BOOM	B1-B2	AL	0.2388E 00	0.6350E 02	0.1031E 01	0.0	0.4558E 03	0.2496E 03	0.0	0.1162E-02
19	BOOM	G-H	AL	0.2388E 00	0.1846E 03	0.1031E 01	0.0	0.1260E 03	0.6482E 03	0.0	0.9633E-02
20	BOOM	L-F	AL	0.2388E 00	0.6940E 02	0.1031E 01	0.0	0.1483E 03	0.5881E 03	0.0	0.3745E-02

TOTAL CALCULATED SCATTERED FLUX = 0.60812E 00

TOTAL SCATTERED FLUX= 0.6081E 00 ALLOWED ATTENUATED FLUX= 0.4392E 01

B

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NOTE: The following output corresponds to the second shield case in the Appendix IV input sample data.

THE SHIELD CONSISTS OF .9#LIH AND .1#LEAD

J	ENERGY(MEV)	WTD-MU(CM-1)	WTD-MU*X	NO.AT SOURCE	BARE FLUX AT D	BUILDUP FACT.	ATT.FLUX AT D	ATT.FAC(XEST)
GAMMA-DATA								
1	.25 E	.69	.1173E 02	.135 E 07	.2275E	.1 E 1	[illegible]E-05	.1929E-04
2	.35 E	.3722E	.6338E 01	.792 E 07	.66 6E	.1 E 1	[illegible]E-02	.2756E-02
3	.45 E	.26 6E	.443 E 1	.6652E 07	.1121E 01	.1 E 1	[illegible]E-01	.1624E-01
4	.55 E	.2164E	.35 9E 01	.1575E 08	.2386E 01	.1 E 1	[illegible]	.3899E-01
5	.65 E	.1747	.3 4E 01	.7 76E 07	.1192E 1	.1 E 1	[illegible] 1	.6117E-01
6	.75 E	.1554	.2642E 01	.2722E 08	.4586E 1	.1 E 1	[illegible]	.8570E-01
7	.85 E	.1412E	.24 1E 01	.8164E 07	.1376E 1	.1 E 1	.1284	.1172E 00
8	.95 E	.1296	.22 3E 01	.4196E 07	.7 53E	.1 E 1	.7793E-01	.1289E 00
9	.11 E 1	.1172	.1993E 01	.5983E 07	.9912E	.1 F 1	.1351E	.1567E 00
10	.13 E 1	.1 5	.1795E 01	.3756E 07	.6318E	.1 F 01	.1 49E	.1883E 00
11	.15 E 1	.965 E-01	.164 E 01	.3371E 07	.5578E	.1 F 1	.11 1E	.2175E 00
12	.17 E 1	.9 73E-01	.1542E 01	.3398E 07	.5574E	.100 F 1	.1192E	.2382E 00
13	.19 E 1	.8626E-01	.1466E 01	.3288E 07	.554 F	.1 E 1	.1278E 00	.2557E 00
14	.25 E 1	.7749E-01	.1317E 01	.5619E 08	.9465E 01	.1 E 1	.2535E 01	.2937E 00
15	.35 E 1	.7 9E-01	.12 7E 01	.76 6E 05	.1282E-01	.1 F 1	.3374E-02	.3256E 00
16	.45 E 1	.6831E-01	.1161E 01	.225 E 05	.38 E-02	.1 F 01	.11 E-02	.3396E 00
17	.55 E 1	.6696E-01	.1138E 01	.6753E 04	.113 E-02	.1 F 1	.3645E-03	.3469E 00
18	.65 E 1	.6639E-01	.112 E 01	.2313E 04	.3397E-03	.1 F 01	.1261E-03	.3501E 00
NEUTRON-DATA								
1	.1615E	.8349E	.1419E 02	.9835E 06	.1489E 00	.1 E 1	.11 4E-04	.1953E-05
2	.266 E	.979 E 00	.1665E 02	.1738E 07	.2928E	.1 E 1	.4163E-05	.1970E-06
3	.4385E	.5755E 00	.9775E 01	.2944E 07	.496 E	.1 E 01	.71 E-03	.1127E-03
4	.624 E	.4641E 00	.789 E 01	.2081E 07	.5 23E	.1 F 01	.2542E-02	.6506E-03
5	.813 E	.4211E 00	.7159E 01	.4841E 07	.8157E	.1 F 01	.6736E-02	.1284E-02
6	.113 E 1	.4811E 00	.8178E 01	.6533E 07	.11 1E 01	.1 F 01	.4592E-02	.4975E-03
7	.1325E 1	.4575E	.778 E 01	.7376E 07	.1243E 1	.1 E 1	.6772E-02	.7209E-03
8	.17 E 01	.4391E 00	.7447E 01	.6759E 07	.1139E 01	.1 E 1	.7753E-02	.9820E-03
9	.218 F 01	.4342E 00	.7381E 01	.11 7E 08	.1865E 01	.1 E 01	.1327E-01	.1745E-02
10	.2795E 1	.4448E	.7561E 01	.1916E 08	.3229E 1	.1 F 1	.2 37E-01	.8836E-03
11	.3575E 01	.4627E 00	.7866F 01	.1345E 08	.2267E 01	.1 F 01	.1166E-01	.6655E-03
12	.425 E 1	.45 E 0	.7829E 01	.1414E 07	.2383E	.1 F 1	.1257E-02	.6993E-03
13	.4920E 1	.4467E	.7594E 01	.36 1E 06	.6 68E-01	.1 F 01	.3744E-03	.8566E-03
14	.592 E 1	.4 87E	.6948E 01	.3566E 06	.6 9E-01	.1 F 1	.5716E-03	.1562E-02
15	.7605E 01	.3319E	.5641E 01	.1 31E 06	.1738F-01	.1 E 01	.3969E-03	.5269E-02
16	.9275E 01	.3 47E	.5179E 01	.3239E 05	.5457E-02	.1 E 01	.1698E-03	.8094E-02

DETECTED FLUX AS A FUNCTION OF SHIELD THICKNESS

X-EST. (CM)	FLUX(NP/CM*CM*SEC)
.1581 E 02	.4391E 01
.15 F 02	.4774E 01
.16 E 02	.43 8 E 01
.17 E 02	.3895E 01

ITERATION NO.=
SHIELD LENGTH(CM) = 15.8 00 WEIGHTED DENSITY= 1.9729 WT.(GRAMS)= .156E 04

```
NUMBER OF PHOTON HISTORIES  10000      INITIAL RANDOM NUMBER          523506365     CYLINDER HEIGHT (CM)      0.15810E 02
NO.SOURCE SPECTRUM ENERGIES     1      CONTROL PARAMETER-NDISTN           1         CYLINDER RADIUS (CM)      0.40230E 01
NO.EQUAL ENERGY INTERVALS       2      LOW ENERGY CUTOFF (MEV)      0.10000E 00     CYLINDER VOLUME (CM**3)   0.15056E 04
                                                 POINT SOURCE IS   0.10000E 02  (CM) BELOW THE CYLINDER Z-AXIS

SOURCE SPECTRUM ENERGIES
     0.25000E 00
SOURCE SPECTRUM INTENSITY DISTRIBUTIONS
     0.10000E 01
ESCAPE SPECTRUM ENERGIES (MC**2)
     0.48927E 00    0.24463E 00    0.19571E 00
ESCAPE SPECTRUM ANGLES (RADIANS)
     0.31416E 01    0.29671E 01    0.27925E 01    0.26180E 01    0.24435E 01    0.22689E 01
     0.20944E 01    0.19199E 01    0.17453E 01    0.15708E 01    0.13963E 01    0.12217E 01
     0.10472E 01    0.87266E 00    0.69813E 00    0.52360E 00    0.34907E 00    0.17453E 00
     0.0
```

D

TALLY UNSCATTERED ESCAPES

SOURCE ENERGY = 0.25000 MEV

J	ANGLES A(J) TO	A(J+1)	SOLID ANGLE	NUMBER	NUMBER/STER	FRACT/STER	PAIR PHOTONS
1	3.14159	2.96706	0.95457E-01	0.0	0.0	0.0	0.0
2	2.96706	2.79253	0.28347E 00	0.0	0.0	0.0	0.0
3	2.79253	2.61799	0.46287E 00	0.0	0.0	0.0	0.0
4	2.61799	2.44346	0.62820E 00	0.0	0.0	0.0	0.0
5	2.44346	2.26893	0.77445E 00	0.0	0.0	0.0	0.0
6	2.26893	2.09439	0.89716E 00	0.0	0.0	0.0	0.0
7	2.09439	1.91986	0.99262E 00	0.0	0.0	0.0	0.0
8	1.91986	1.74533	0.10579E 01	0.0	0.0	0.0	0.0
9	1.74533	1.57080	0.10911E 01	0.0	0.0	0.0	0.0
10	1.57080	1.39626	0.10911E 01	0.0	0.0	0.0	0.0
11	1.39626	1.22173	0.10579E 01	0.0	0.0	0.0	0.0
12	1.22173	1.04720	0.99262E 00	0.0	0.0	0.0	0.0
13	1.04720	0.87266	0.89716E 00	0.0	0.0	0.0	0.0
14	0.87266	0.69813	0.77445E 00	0.0	0.0	0.0	0.0
15	0.69813	0.52360	0.62820E 00	0.0	0.0	0.0	0.0
16	0.52360	0.34907	0.46286E 00	0.15520E 04	0.33530E 04	0.33530E 00	0.0
17	0.34907	0.17453	0.28347E 00	0.40320E 04	0.14224E 05	0.14224E 01	0.0
18	0.17453	0.0	0.95455E-01	0.79000E 02	0.82761E 03	0.82761E-01	0.0

UNSCATTERED ESCAPES = 0.56630E 04

NUMBER AV/STER = 0.1[illegible]225E 04

PAIR PHOTON ESCAPES = 0.0

NO. P P IN FWD CONE = 0.0

E

SOURCE ENERGY = .25 MEV

ESCAPE ENERGY INTERVAL 0.49927 TO 0.24463 INDEX 1

J	ANGLES A(J)	TO A(J+1)	SOLID ANGLE	NUMBER	NUMBER/STER	FRACT/STEP	PAIR PHOTONS
1	3.14159	2.96706	.95457E-01	0.18990E 2	0.19903E 3	0.19903E-01	0.
2	2.96706	2.79253	.28347E 00	.71333E 2	.25165E 3	.25165E-01	0.
3	2.79253	2.61799	.46287E 00	0.11401E 3	.24631E 3	0.24631E-01	0.
4	2.61799	2.44346	.62820E 00	0.15486E 3	.24651E 3	.24651E-01	0.
5	2.44346	2.26893	0.77445E 00	0.15051E 3	0.19434E 3	0.19434E-01	0.
6	2.26893	2.09439	.89716E 00	0.16335E 3	.18207E 3	.18207E-01	0.
7	2.09439	1.91986	0.99262E 00	0.20025E 3	0.20174E 3	0.20174E-01	0.
8	1.91986	1.74533	.10579E 01	0.18597E 3	.17579E 3	0.17579E-01	0.
9	1.74533	1.57080	.10911E 01	0.21258E 3	0.19483E 3	0.19483E-01	0.
10	1.57080	1.39626	.10911E 01	0.24498E 3	0.22454E 3	.22454E-01	0.
11	1.39626	1.22173	.10579E 01	0.24534E 3	0.23191E 3	0.23191E-01	0.
12	1.22173	1.04720	.99262E 00	0.27193E 3	.27400E 3	0.27400E-01	0.
13	1.04720	.87266	0.89716E 00	0.30314E 3	0.33789E 3	0.33789E-01	0.
14	0.87266	.69813	0.77445E 00	0.27598E 3	.35636E 3	0.35636E-01	0.
15	.69813	.52360	0.62821E 00	0.27798E 3	.44250E 3	0.44250E-01	0.
16	.52360	.34907	.46286E 00	0.16000E 3	.34566E 3	0.34566E-01	0.
17	0.34907	.17453	0.28347E 00	0.53997E 2	0.19049E 3	0.19049E-01	0.
18	0.17453	.	.95455E-01	0.14999E 2	0.15714E 3	0.15714E-01	0.

SCATTERED ESCAPES = .312.2E 4

P.E.ABSORPTIONS = 0.387 3E 02

NUMBER AV/STER = .24738E 03

PAIR PHOTON ESCAPES = 0.0

NUMBER IN FWD CONE = 0.0 0.0 0.0

NO.IN FWD CONE/STER = 0.0

ESCAPE ENERGY INTERVAL 0.24463 TO 0.19571 INDEX 2

J	ANGLES A(J)	TO A(J+1)	SOLID ANGLE	NUMBER	NUMBER/STER	FRACT/STEP	PAIR PHOTONS
1	3.14159	2.96706	0.95457E-01	0.61 43E 1	0.63949E 02	0.63949E-02	0.
2	2.96706	2.79253	0.28347E 00	0.71515E 01	0.25229E 02	0.25229E-02	0.
3	2.79253	2.61799	0.46287E 00	0.20006E 02	0.43221E 02	0.43221E-02	0.
4	2.61799	2.44346	0.62820E 00	0.32001E 02	0.50941E 02	0.50941E-02	0.
5	2.44346	2.26893	0.77445E 00	0.20291E 02	0.26201E 02	0.26201E-02	0.
6	2.26893	2.09439	0.89716E 00	0.29009E 02	0.32334E 02	0.32334E-02	0.
7	2.09439	1.91986	0.99262E 00	0.29162E 02	0.29378E 02	0.29378E-02	0.
8	1.91986	1.74533	0.10579E 01	0.28994E 02	0.27405E 02	0.27406E-02	0.
9	1.74533	1.57080	0.10911E 01	0.22995E 02	0.21076E 02	0.21076E-02	0.
10	1.57080	1.39626	0.10911E 01	0.28161E 02	0.25811E 02	0.25811E-02	0.
11	1.39626	1.22173	0.10579E 01	0.21163E 02	0.20005E 02	0.20005E-02	0.
12	1.22173	1.04720	0.99262E 00	0.16995E 02	0.17122E 02	0.17122E-02	0.
13	1.04720	0.87266	0.89716E 00	0.16995E 02	0.18943E 02	0.18943E-02	0.
14	0.87266	0.69813	0.77445E 00	0.90077E 01	0.11631E 02	0.11631E-02	0.
15	.69813	.52360	0.62820E 00	0.89973E 01	0.14322E 02	0.14322E-02	0.
16	0.52360	0.34907	0.46286E 00	0.29985E 01	0.64781E 01	0.64781E-03	0.
17	.34907	0.17453	0.28347E 00	0.0	0.	0.	0.
18	0.17453	0.	0.95455E-01	0.99987E 00	0.10474E 02	0.10474E-02	0.

SCATTERED ESCAPES = 0.391 3E 03

P.E.ABSORPTIONS = 0.15060E 02

NUMBER AV/STER = 0.24655E 02

PAIR PHOTON ESCAPES = 0.

NUMBER IN FWD CONE = . .0

NO.IN FWD CONE/STER = 0.

F

```
NO. OF HISTORIES  INITIAL ENERGY    CUT-OFF ENERGY    TOTAL NO. OF COLLISIONS
    1                 .25  E                 .1  E                        8226

TERMINATION PRIMARY PHOTONS

 1. ENERGY       .741   E   ?

 2. WEIGHT       .12    E   ?

 3. ESCAPE      .  9434   4                    (3./NO. OF HISTORIES)   .  843E

 4. ABSORBED     .315675  3

 5. TOTAL UNSCATTERED ESCAPES   .5663 E  4  (5./NO. OF HISTORIES)   .5663 E

 6. TOTAL SCATTERED ESCAPES     .34213E  4  (6./NO. OF HISTORIES)   .34213E

 7. PHOTOELECTRIC ABSORPTIONS   .34672E  2

 8. PAIR PRODUCTION PHOTONS      .

 TOTAL ESCAPES IN FWD 10-DEG. CONE=  .                 TOTAL IN FWD CONE/STER= .

TERMINATION PAIR PHOTONS

 1. ENERGY       .

 2. WEIGHT       .

 3. ESCAPE       .

 4. ABSORBED     .

 5. TOTAL UNSCATTERED ESCAPES   .

 6. TOTAL SCATTERED ESCAPES      .

 7. PHOTOELECTRIC ABSORPTIONS    .

 8. PAIR PRODUCTION PHOTONS      .

TALLY CHECK =  .99999E  4
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G

NOTE: Output pages D, E and F omitted for 0.85, 1.70 and 6.50 MeV source energies.

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NO. OF HISTORIES  INITIAL ENERGY    CUT-OFF ENERGY    TOTAL NO. OF COLLISIONS
     75               .25   .1           .1  05                   5438

TERMINATION PRIMARY PHOTONS

 1. ENERGY        .318  E  3

 2. WEIGHT        .116  E  3

 3. ESCAPE      .69641E  4                 (3./NO. OF HISTORIES)   .9285E

 4. ABSORBED    .5350 E  3

 5. TOTAL UNSCATTERED ESCAPES     .4258 E 04  (5./NO. OF HISTORIES)   .651 7E

 6. TOTAL SCATTERED ESCAPES     .2 61E 04  (6./NO. OF HISTORIES)   .26748E

 7. PHOTOELECTRIC ABSORPTIONS    .11192E 12

 8. PAIR PRODUCTION PHOTONS      .

 TOTAL ESCAPES IN FWD 10-DEG. CONE= .13422E 02          TOTAL IN FWD CONE/STER= .14961E

TERMINATION PAIR PHOTONS

 1. ENERGY      .

 2. WEIGHT      .

 3. ESCAPE       .

 4. ABSORBED    .

 5. TOTAL UNSCATTERED ESCAPES    .

 6. TOTAL SCATTERED ESCAPES     .

 7. PHOTOELECTRIC ABSORPTIONS    .

 8. PAIR PRODUCTION PHOTONS      .

TALLY CHECK =  .75  E 04
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NO. OF HISTORIES  INITIAL ENERGY    CUT-OFF ENERGY    TOTAL NO. OF COLLISIONS
     5            .17 E 01          .1 E                    4685

TERMINATION PRIMARY PHOTONS

 1. ENERGY       .14662E 03

 2. WEIGHT       .574 7E 02

 3. ESCAPE       .472 9E 04                    (3./NO. OF HISTORIES)   .94416E 0

 4. ABSORBED     .26 25E 03

 5. TOTAL UNSCATTERED ESCAPES      .3675 E 04  (5./NO. OF HISTORIES)   .735 E

 6. TOTAL SCATTERED ESCAPES       .1 458E 04   (6./NO. OF HISTORIES)   .2 916E

 7. PHOTOELECTRIC ABSORPTIONS     .56228E 02

 8. PAIR PRODUCTION PHOTONS       .37939E 02

 TOTAL ESCAPES IN FWD 10-DEG. CONE= .14132E 02          TOTAL IN FWD CONE/STER= .1485E 03
TERMINATION PAIR PHOTONS

 1. ENERGY       .12546E 02

 2. WEIGHT       .84173E 01

 3. ESCAPE       .1363 E 02

 4. ABSORBED     .24221E 02

 5. TOTAL UNSCATTERED ESCAPES     .1 235E 02

 6. TOTAL SCATTERED ESCAPES       .33949E 01

 7. PHOTOELECTRIC ABSORPTIONS     .32587E 01

 8. PAIR PRODUCTION PHOTONS       .37839E 02

TALLY CHECK =  .50 E 04
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NO. OF HISTORIES  INITIAL ENERGY    CUT-OFF ENERGY    TOTAL NO. OF COLLISIONS
     3.0           .6551E 01          .1                    251

TERMINATION PRIMARY PHOTONS

 1. ENERGY        .31855E 02

 2. WEIGHT       0.13591E 02

 3. ESCAPE        .27753E 04                   (3./NO. OF HISTORIES)   .92529E 0

 4. ABSORBED      .54198E 02

 5. TOTAL UNSCATTERED ESCAPES    .24376E 04  (5./NO. OF HISTORIES)   .81233E

 6. TOTAL SCATTERED ESCAPES     0.33884E 03  (6./NO. OF HISTORIES)  0.11295E

 7. PHOTOELECTRIC ABSORPTIONS    .27519E 01

 8. PAIR PRODUCTION PHOTONS     0.33989E 03

 TOTAL ESCAPES IN FWD 1?-DEG. CONE= 0.12349E 02          TOTAL IN FWD CONE/STER= 0.12936E 0
TERMINATION PAIR PHOTONS

 1. ENERGY       0.13378E 03

 2. WEIGHT       0.5 525E 02

 3. ESCAPE       0.12421E 03

 4. ABSORBED      .2157 E 03

 5. TOTAL UNSCATTERED ESCAPES    .89245E 02

 6. TOTAL SCATTERED ESCAPES     0.34967E 02

 7. PHOTOELECTRIC ABSORPTIONS    .31396E 02

 8. PAIR PRODUCTION PHOTONS      .33989E 03
```

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J	ENERGY(MEV)	AT -MU(CM-1)	STD-MU*X	NO.AT SOURCE	BARE FLUX AT D	BUILDUP FACT.	ATT.FLUX AT D	ATT FAC(XEST)
GAMMA-DATA								
1	.25 E	.60 [illegible]	.1242E 2	.135 E 7	.2274E	.1 [illegible] 1	.917[illegible]	.1327E-04
2	.35 E	.372[illegible]	.5711E 1	.392 E 7	.56[illegible]	.1 13E 1	.81[illegible]- 3	.2317E-02
3	.45 E	.26[illegible]	.4631E 1	.[illegible]52E 7	.1121E 1	.1 [illegible] 1	.1 [illegible] 1	.1439E- 1
4	.55 E	.2 [illegible]	.3715E 1	.15[illegible] 8	.[illegible] 1	.1 [illegible] 1	.651 [illegible] 1	.3478E-01
5	.55 E	.17[illegible]	.3191E 1	.7 76E 7	.1102E 1	.1 62E 1	.[illegible] 1	.5634E-01
6	.75 E	.19[illegible]	.2707E 1	.2722E 8	.4596E 1	.1 72E 1	[illegible]	.7072E-01
7	.85 E	.141[illegible]	.2542E 1	.8164E 7	.1376E 1	.1 70E 1	[illegible]	.1 4E [illegible]
8	.95 E	.12[illegible]	.2332E 1	.4186E 7	.7053E [illegible]	.1 76E 1		.1214E [illegible]
9	.11 E 1	.117[illegible]	.211 E 1	.8883E 7	.2212E [illegible]	.1 7[illegible]		.1484E [illegible]
1	.13 E 1	.1[illegible]	.19 1E 1	.275 E 7	.6719E [illegible]	.1 [illegible]		.1793E [illegible]
11	.15 E 1	.955 E- 1	.1777E 1	.337 E 7	.5678E [illegible]	.1 61E 1		.2 79E [illegible]
12	.17 E 1	.9 73E- 1	.1633E 1	.33 8E 7	.5574E [illegible]	.1 55E 1		.2284E [illegible]
13	.19 E 1	.8636E- 1	.1553E 1	.2982E 7	.554 E	.1 59E 1	.1224[illegible]	.2456E [illegible]
14	.25 E 1	.7749E- 1	.1395E 1	.5619E 8	.9465E 1	.1 41E 1	.24 7E 1	.2834E [illegible]
15	.35 E 1	.7 [illegible]E- 1	.1278E 1	.76 6E 5	.1292E- 1	.1 31E 1	.3681E- 2	.315 E [illegible]
16	.45 E 1	.6871E- 1	.127 E 1	.2255E 5	.38[illegible]E- 2	.1 29E 1	.1144E- 2	.3290E [illegible]
17	.55 E 1	.66[illegible]E- 1	.12 5E 1	.6753E 4	.1135E- 2	.1 39E 1	.353[illegible]E- 3	.3363E [illegible]
18	.65 E 1	.6678E- 1	.1195E 1	.2313E 4	.3897E- 3	.1 56E 1	.124[illegible]E- 3	.3398E [illegible]
NEUTRON-DATA								
1	.1515E [illegible]	.934[illegible]	.1513E 2	.8835E 6	.1482E [illegible]	.1[illegible]E 1	.6312E- 5	.1257E-05
2	.255 E	.270[illegible]	.1764E 2	.1738E 7	.2328E [illegible]	.1 E 1	.215[illegible]E- 5	.1186E-06
3	.4385E [illegible]	.575 E [illegible]	.1 35E 2	.2944E 7	.496 E [illegible]	.1[illegible]E 1	.483[illegible]E- 3	.8629E-04
4	.624 E	.4641E [illegible]	.8354E 1	.2081E 7	.5 23E [illegible]	.1 E 1	.186[illegible]E- 2	.5244E-03
5	.8 1 E [illegible]	.4211E [illegible]	.7590E 1	.4841E 7	.8157E [illegible]	.1[illegible]E 1	[illegible]	.1 56E-02
6	.1 3 E 1	.4811E [illegible]	.8659E 1	.6533E 7	.11 1E 1	.1 E 1	.3327E- 2	.3978E-03
7	.1325E 1	.4576E [illegible]	.8237E 1	.7376E 7	.1243E 1	.1 E 1	.4984E- 2	.5828E-03
8	.17 E 1	.4381E [illegible]	.7995E 1	.6759E 7	.1130E 1	.1 E 1	.5781E- 2	.8 11E-03
9	.219 E 1	.4342E [illegible]	.7815E 1	.11 7E 8	.1865E 1	.1[illegible]E 1	.0924E- 2	.9537E-03
10	.2795E 1	.444[illegible]	.8 6E 1	.1216E 8	.3228E 1	.1 E 1	.1512E- 1	.7186E-03
11	.3575E 1	.4627E [illegible]	.9328E 1	.1745E 8	.2267E 1	.1[illegible]E 1	[illegible]	.5367E-03
12	.425 E 1	.46 E [illegible]	.8289E 1	.1414E 7	.2393E	.1 E 1	.0234E- 3	.5564E-03
13	.482 E 1	.4467E [illegible]	.8 41E 1	.36 1E 6	.6[illegible]E- 1	.1[illegible]E 1	.2776E- 3	.6966E-03
14	.592 E 1	.4 87E [illegible]	.7357E 1	.3566E 6	.6 9E- 1	.1[illegible]E 1	.4347E- 3	.1292E-02
15	.76 5E 1	.3319E [illegible]	.5973E 1	.1 31E 6	.1738E- 1	.1[illegible]E 1	.3179E- 3	.4516E-02
16	.2275E 1	.3 47E [illegible]	.5484E 1	.3239E 5	.5457E- 2	.1[illegible]E 1	.1384E- 3	.7 25E- 2

DETECTED FLUX AS A FUNCTION OF SHIELD THICKNESS

X-EST. (CM)	FLUX(NO/CM*CM*SEC)
0.16275E 2	0.43919E 1
0.16[illegible]E 2	0.45157E 01
.17 E 2	0.4 84 E 01
.18 E 02	0.36996E 01

ITERATION NO.= 1
SHIELD LENGTH(CM) = 16.2748   WEIGHTED DENSITY= 1.5792   WT.(GRAMS)= 0.1551E 4

ACCURACY FRACTION = . 2057   ARRESTING CRITERION = .13

THE SHIELD CONSISTS OF 0.9*LIH AND 0.1*LEAD

END OF CALCULATION FOR SHIELD NUMBER * 2*

(C)

APPENDIX VI

SUMMARY OF NUS-600 DETAIL EVALUATION

APPENDIX VI

SUMMARY OF NUS-600 DETAIL EVALUATION

Sample results obtained with the SØSC component codes are reviewed. They consist of shield thickness and weight evaluations for assumed typical SNAP-27 RTG source strengths and spectral distributions. Example results obtained for the scattering from spacecraft structural members are presented, and the significance of various factors discussed.

The calculations described in this Appendix are generally based on a RTG gamma photon emission distribution similar to that of the Martin Cronus[32] (thermal loading of 4100 watts) normalized to a total emission of 1×10^9 λ/sec. The RTG fast neutron emission distribution was based on SNAP-27-1 reported data from reference (1); a source emission rate of 5.7×10^8 n/sec was assumed. For both fast-neutrons and gamma photons, axial and axially perpendicular emission rates were taken as identical, although this is not true in fact. This assumption was necessitated by the lack of actual encased RTG source data in the early phase of the work program. The assumed source emission spectrum is given in Table VI-1 for gamma photons and in Table VI-2 for fast neutrons.

The typical spacecraft for which the calculations were carried out is that of Figure 1 (section 2.1 of this report). The dimensions of this spacecraft were obtained from NASA-GSFC preliminary drawings. Figure VI-1 shows a schematic outline of the spacecraft for the discussions in this section.

Gamma photon cross-section data were taken from references (17) through (21). Neutron cross-section data were obtained from reference (22).

The Table VI-1 source spactrum is that for a three (3) year old PuO_2 SNAP-27 as opposed to the five (5) year PuO_2 used in section 3.3.5 of this report. Calculations in reference (32) indicate that the total gamma emission rate increases by a factor of ~ 4 over the first 18 years. Table VI-3, reproduced from the reference, indicates that the energy groups 0.2 to 0.3, and 2.0 to 3.0 MeV are the most critical, e.g. the 2.0 to 3.0 MeV group (2.62 MeV ThC") increases by a factor of more than 100 in the first 10 years. This age effect on shielding requirements was not studied during this report period because of lact of reliable source data.

The scattering of source gamma photons to the detector by aluminum boom tubing proximate to the source (or the detector) was investigated. The boom axis was assumed as perpendicularly bisection a 16" long unit (1 γ/sec) source of 0.75 MeV photons. The calculations assumed a line source and a single scattering model for a boom tube volume of 0.79 cc/cm. The results of the calculations are shown in Figure VI-2 along with the calculation geometry. In the figure it may be seen that the calculations considered boom tubing coming as close as 10 cm to the source whereas GSFC drawings indicated actual closest point of boom as 25 cm distant. The detector-incident flux scattered by a typical boom, boom (1,2) in Figure VI-1, is obtained from Figure VI-2 after integration over r, between 25 and 80 cm, as $\phi_{\alpha S}(E_\alpha) = 1.3 \times 10^{11}$ γ/cm^2-sec. Assuming boom (1,2) as typical, where r_1 ranges from 25 to 80cm, i.e. a length of 55cm, the total scattered flux from 6 such booms (6 per side) and 4 sources would be ~ 3×10^{-10} γ/cm^2-sec. If the actual source strength are taken as 10^9 γ/sec, then < total flux of ~ 0.3 γ/cm^2-sec is obtained. The use of the single scattering model as opposed to the albedo method for boom structure calculations, was investigated. A 1 cm length of 1 inch diameter aluminum boom was considered as located 100 cm from both a point source and a detector, with source and detector 141 cm apart. For

E_o = 0.75 MeV, a unit source (1 γ/sec), a boom wall thickness of 0.04 inches and a boom volume 0.79 cc/cm, the calculated fluxes at the detector were

$$\phi_{\alpha s}\ (E_\alpha) = 3.6 \times 10^{-12},\ \gamma/cm^2\text{-sec},$$

and

$$\phi_{\alpha ss}\ (E_\alpha) = 6.4 \times 10^{-12},\ \gamma/cm^2\text{-sec}.$$

The difference in these calculations diminishes if it is assumed, in the case of the albedo result, that photons penetrating the relatively thin (0.04") tube frontal wall may be backscattered from the tube interior wall surface ie, if either the wall thickness or scattering area is doubled for the calculation, then

$$\phi_{\alpha s}\ (E_\alpha) = 7.0 \times 10^{-12},\ \gamma/cm^2\text{-sec}.$$

This result indicates a very good agreement between the single scatter and albedo methods for small finite geometries.

A similar calculation for a large iron cylinder, in the physical position of the spacecraft cupola, was also carried out. The cylinder dimensions were taken as 20" x 38.5" x 0.5" (dia. x lt. x thickness). A unit source of 0.75 MeV photons was assumed. The source, detector and cupola were locate located per the spacecraft dimensions.

$$\phi_{\alpha s}\ (E_\alpha) = 2.4 \times 10^{-9}\ \gamma/cm^2\text{-sec},$$

and

$$\phi_{\alpha ss}\ (E_\alpha) = 2.7 \times 10^{-9}\ \gamma/cm^2\text{-sec}.$$

The same configuration for an aluminum cylinder of 1 inch wall thickness, gave a single scatter flux of

$$\phi_{\alpha ss}(E_\alpha) = 1.8 \times 10^{-9} \ \gamma/\text{cm}^2\text{-sec.}$$

Taking an actual cupola "flat", A, as in Figure VI-1, with the dimensions 13.2" x 25.5" x 1" (width x lt. x thickness) and assuming the material to be aluminum, the albedo and single scatter fluxes were determined as

$$\phi_{\alpha s}(E_\alpha) = 1.8 \times 10^{-10}, \ \gamma/\text{cm}^2\text{-sec,}$$

and

$$\phi_{\alpha s}(E_\alpha) = 1.9 \times 10^{-10}, \ \gamma/\text{cm}^2\text{-sec.}$$

The above calculations were based on a single RTG source of 1 photon/sec, and $E_o = 0.75$.

Figures VI-3 and VI-4 are sodium-iodide scintillation detector spectra reproduced from reference ( ). They indicate the energy distribution of backscattered photons as a function of t, θ_s and θ_o, respectively, for graphite as the backscattering material. The prominent peak in these spectra corresponds to single scatter the 'arrow-indicated' peak corresponds to double scatter and the continuum represents multiple scatter.

If this photon scattering is considered significant enough to require shielding (~ C, the criterion flux) then such shielding would be a minimum weight if designed to attenuate the scattered photons as opposed to the primaries. Figures VI-3 and VI-4 show that the scattered photon energies will generally be in the range, 0.10 to 0.5 MeV, and thus can be readily attenuated by a relatively thin and thus low weight, shield located at the detector.

Examples of energy-integrated shield-scattered photon angular distributions are presented in Figure VI-5. The angular categorization in this figure is referenced to the shield geometric center. The distributions were determined by an early version of the Monte Carlo subprogram: NUGAM1. The current code version additionally determines the photon distribution to which the detector is specifically exposed, i.e., photons escaping from the side of the shield cannot intercept the detector.

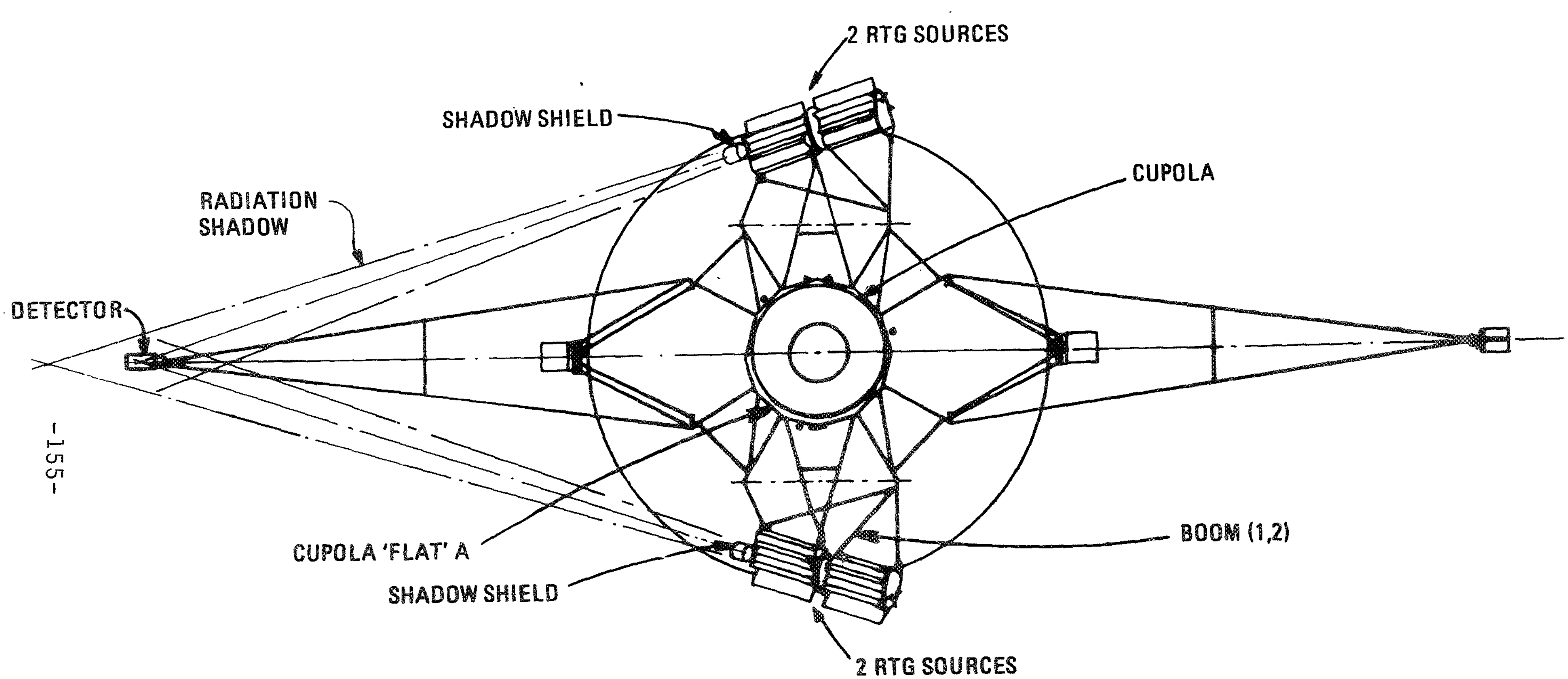


FIGURE VI—1

SCHEMATIC DRAWING OF SPACECRAFT
SHOWING SPECIFIC STRUCTURAL MEMBERS

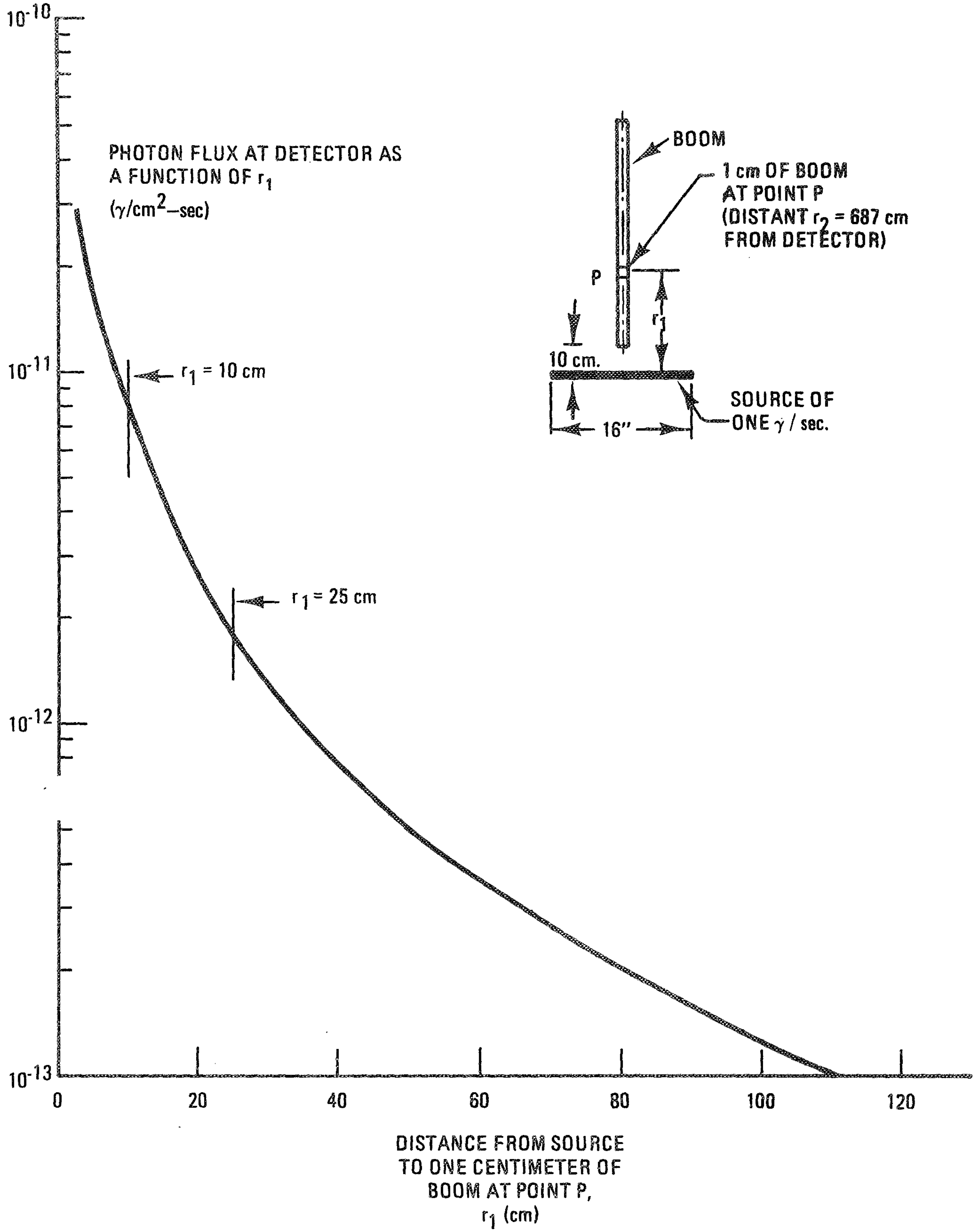


FIGURE VI - 2

BOOM SCATTER INTENSITY AS A FUNCTION OF SOURCE-TO-BOOM DISTANCE

400 Min; X = Material Thickness

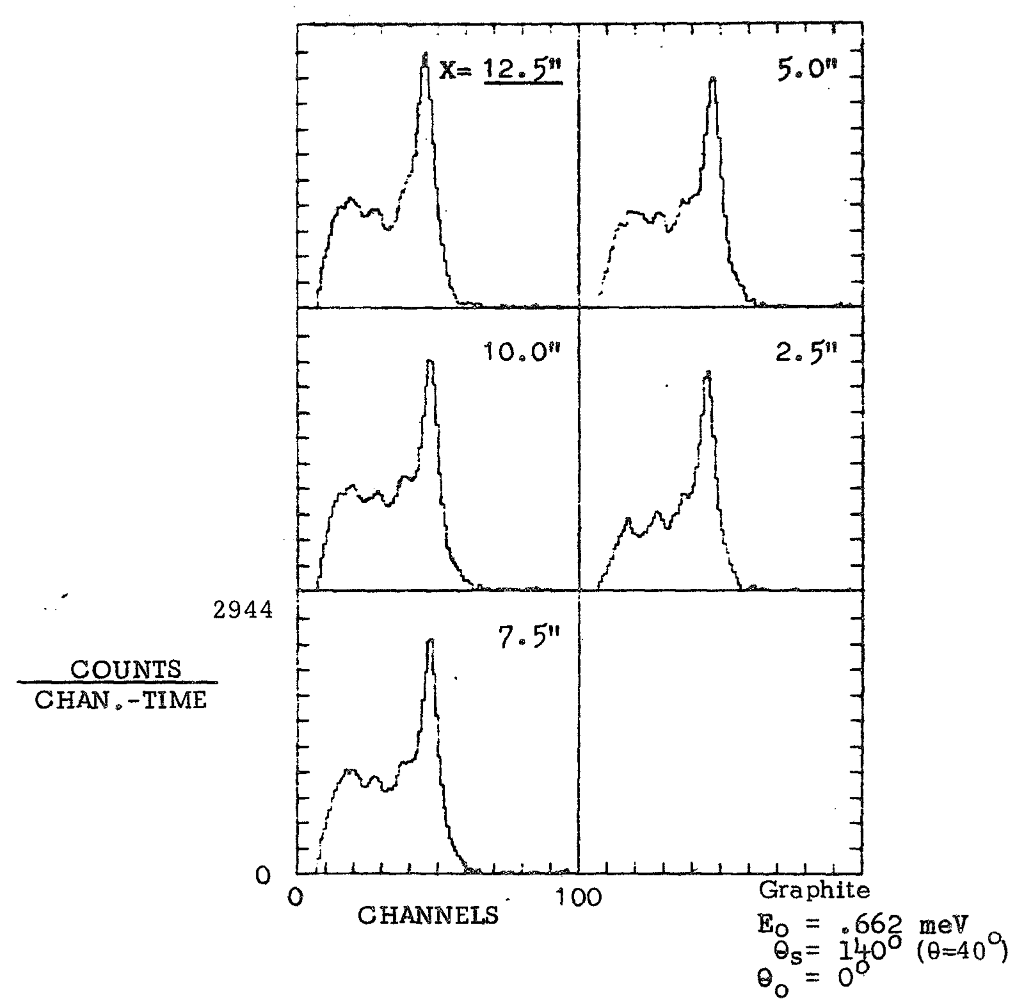
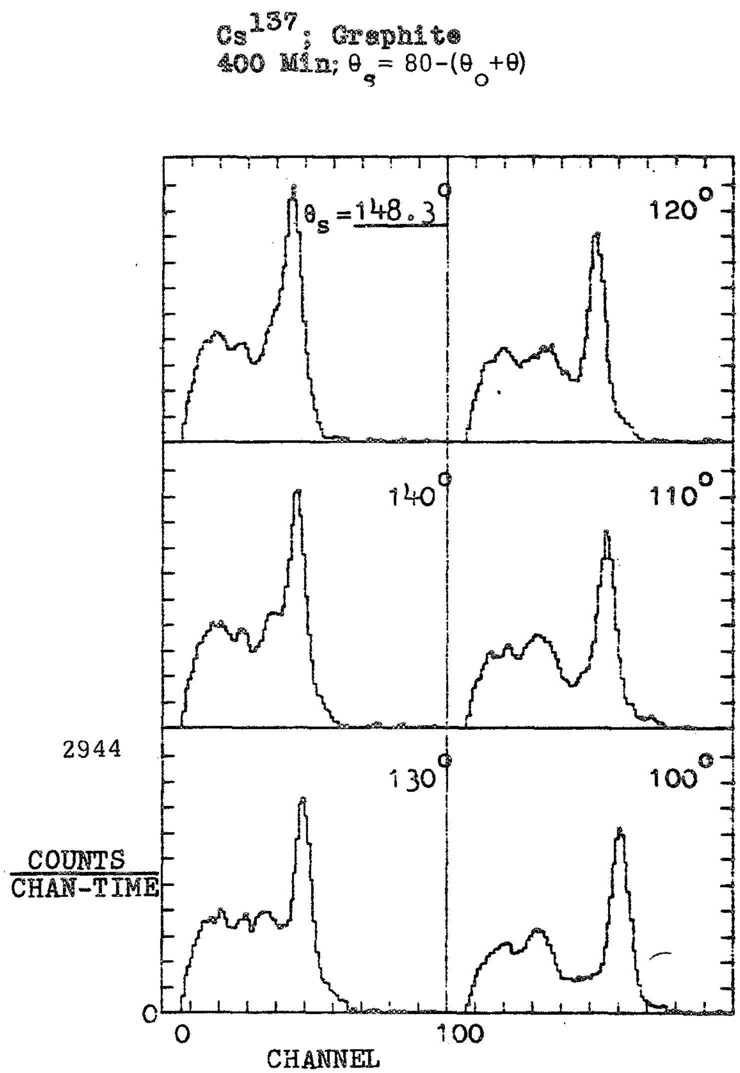
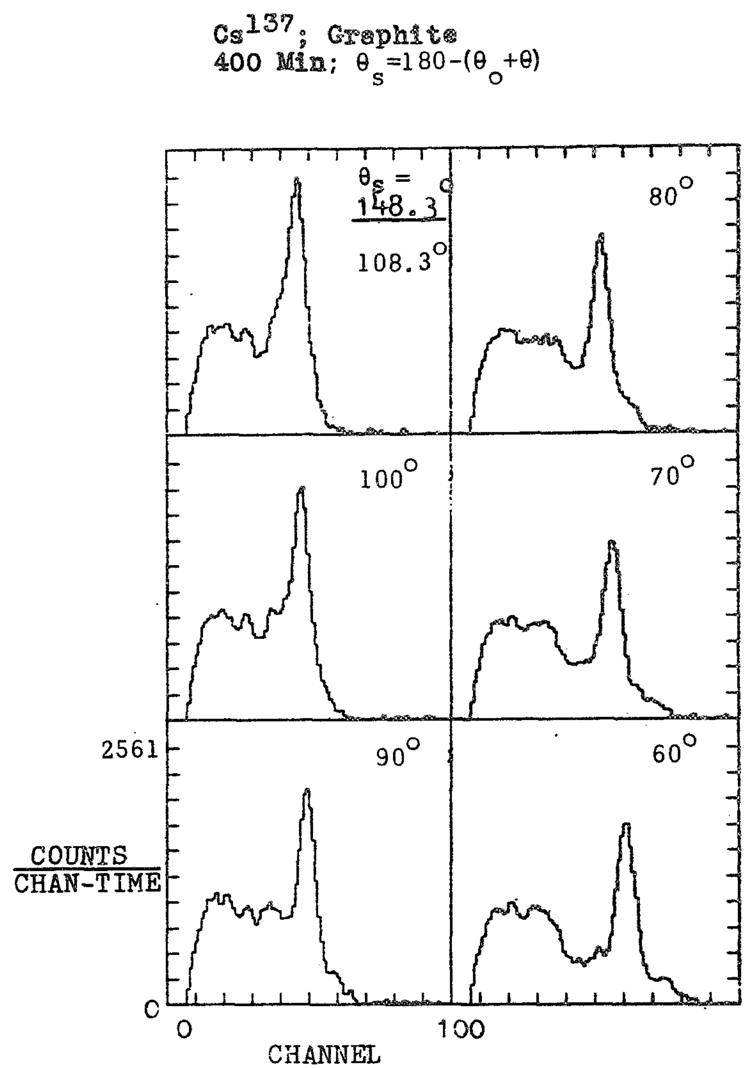


FIGURE VI-3

NaI(Tl) Scintillation Spectra Showing Gamma Photon Backscatter Distribution as a Function of Scattering Material Thickness



8 (a) Perpendicular Incidence:
Spectral Distribution as a Function of Scatter Angle θ_s for $E_o = 0.662$ MeV and $\theta_o = 0^\circ$



8 (b) Slant Incidence:
Spectral Distribution as a Function of Scatter Angle θ_s for $E_o = 0.662$ MeV and $\theta_o = 40^\circ$

FIGURE VI-4

NaI(Tl) Scintillation Spectra Showing Gamma Photon Scatter Distribution as a Function of Incident-Angle, θ_o

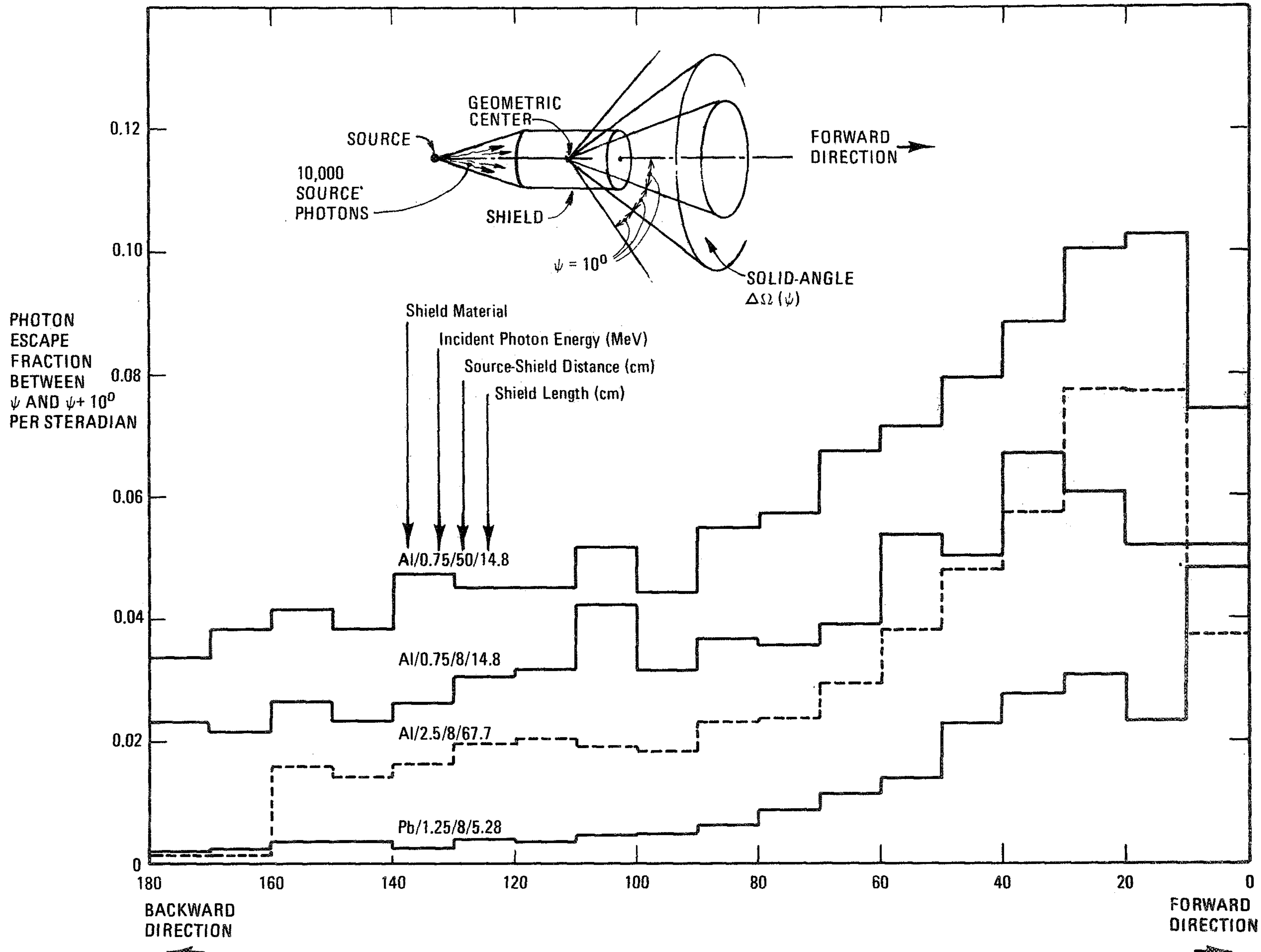


FIGURE VI-5

ENERGY-INTEGRATED ANGULAR DISTRIBUTION
OF SHIELD SCATTERED PHOTONS

TABLE VI-1

Assumed SNAP-27 Gamma Photon Emission Spectrum
Based On Martin Cronus Data[32]

Energy Interval (MeV)	Assumed Energy (MeV)	Photon Emission Rate (γ/MeV-sec)
0.044 - 0.2	0.15	6.54×10^{7}
0.2 - 0.3	0.24	6.87×10^{7}
0.3 - 0.4	0.311	7.88×10^{7}
0.4 - 0.5	0.414	7.86×10^{7}
0.5 - 0.6	0.583	8.03×10^{7}
0.6 - 0.7	0.650	7.33×10^{7}
0.7 - 0.8	0.766	2.26×10^{8}
0.8 - 0.9	0.851	1.40×10^{8}
0.9 - 1.0	1.00	6.65×10^{6}
1.0 - 1.2	1.10	1.87×10^{7}
1.2 - 1.4	1.40	1.73×10^{7}
1.4 - 1.6	1.59	7.71×10^{6}
1.6 - 1.8	1.63	1.63×10^{7}
1.8 - 2.0	1.90	1.54×10^{7}
2.0 - 3.0	2.61	1.07×10^{8}
3.0 - 4.0	3.50	3.03×10^{5}
4.0 - 5.0	4.50	9.10×10^{3}
5.0 - 6.0	5.50	3.01×10^{4}

TABLE VI-2

SNAP-27-1 Fast Neutron Emission Spectrum[1]

Energy Interval (MeV)	Neutron Emission Rate (n/MeV-sec)
0 - 1.0	5.06×10^7
1.0 - 3.0	4.16×10^7
3.0 - 4.0	1.79×10^7
4.0 - 5.0	3.56×10^6
5.0 - 6.0	1.90×10^6
6.0 - 8.0	4.50×10^5
8.0 - 10.0	1.14×10^5

Energy Integrated Emission Rate = 5.7×10^7 n/sec.

TABLE VI-3

Reproduced from Reference[32]

Gamma spectra, photons/cm^2-sec for RTG at various times after plutonium separation (Normalized to 1.0 for energy interval 0.5-1.0 MeV at 18 years)

Energy (MeV)	0 year	1 year	5 year	10 year	18 year
0.04 - 0.5	0.12	0.16	0.56	0.90	1.0
0.5 - 1.0	0.23	0.25	0.30	0.33	0.35
1.0 - 2	0.096	0.096	0.096	0.096	0.096
2 - 3	0.003	0.018	0.18	0.32	0.37
3 - 5	0.0003	0.0003	0.0003	0.0003	0.0003
5 - 7	0.00003	0.00003	0.00003	0.00003	0.00003

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■ 2351 RESEARCH BOULEVARD, ROCKVILLE, MARYLAND 20850, U.S.A. ■ TELEPHONE (301) 948-7010 CABLE: NUSWASH