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COHORT-II – A MONTE CARLO GENERAL PURPOSE SHIELDING COMPUTER CODE

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16. Abstract

COHORT-II is a Monte Carlo general purpose shielding computer program written completely in FORTRAN-IV for the IBM-7094 computer. In its present form, it represents a major revision and modernization of the original COHORT code. It has been integrated into a single package with more flexible geometry and biasing. The code method employed is the conventional one where individual particles are generated, tracked, and analyzed. The shielding geometry allowed is flexible with space divided into homogeneous regions bounded by surfaces describable by a general quadratic equation. Spherical, cylindrical, and rectangular parallelepipeds are allowed for the source particles from preferred locations energies and directions. The exponential transform can also be used during particle tracking. Secondary gammas can be generated and placed on tape during a neutron problem to be tracked during a subsequent computer run. Output includes number fluxes in energy bins at arbitrarily located point detectors and averaged over regions. Energy integrated quantities such as dose rates are also obtainable.

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SUMMARY

COHORT-II is a Monte Carlo general purpose shielding computer program written completely in FORTRAN-IV for the IBM-7094 computer. In its present form, it represents a major revision and modernization of the original COHORT code. It has been integrated into a single package with more flexible geometry and biasing.

Given an initial source distribution of neutrons or photons, the code calculates number fluxes for these particles in energy bins for arbitrarily located point detectors and track length fluxes averaged over the regions of a reactor-shield geometry as specified by the user. Energy integrated quantities such as dose rates are also obtainable.

The code method employed is the conventional one where individual particles are generated, tracked, and analyzed. The shielding geometry allowed is flexible with space divided into homogeneous regions bounded by surfaces describable by a general quadratic equation. Spherical, cylindrical, and rectangular parallelepipeds are allowed for the source regions. Biasing options include selection of source particles from preferred locations, energies, and directions. The exponential transform can also be used during particle tracking. Secondary gammas can be generated and placed on tape during a neutron problem to be tracked during a subsequent computer run. Variable dimensioning is employed for efficient use of computer storage.

INTRODUCTION

COHORT-II is a Monte Carlo general purpose shielding computer code. Given an initial source distribution of neutrons or photons, it computs number fluxes for these source particles at arbitrarily located points or track length fluxes averaged over the regions of a reactor-shield geometry. It is written in FORTRAN-IV for the IBM-7094 computer.

In its present form, it represents a major revision and modernization of the original COHORT code (refs. 1 and 2). The code CAVEAT (ref. 3) similarly has been derived from COHORT. This report is intended as a guide to assist potential users in data pre-

paration and explanation of the COHORT-II code method and is intended to stand alone without requiring the user to refer to references 1 and 2. Those interested in CAVEAT should consult reference 3.

Many features of the original code have been retained such as the specialized input libraries which are used to describe the geometry, the cross sections, and the use of the exponential transform. In addition, the collision mechanics (except for low energy neutron scatter) and the basic scoring methods in the original code, including statistical estimation of fluxes at point detectors and track lengths in volume detectors, have been retained largely intact.

The principal modifications and additions made in COHORT-II include (1) an extension of the geometry capability to allow for reactor-shield geometries that may be described by a general quadratic surface (with suitable choice of the coefficients), (2) addition of source particle biasing to allow preferential selection of source particle coordinates, directions, or energies, (3) introduction of an estimate of the statistical precision for the calculated results, (4) integration of the separate segments of the code to allow a complete problem, from source particle generation to output of fluxes at point detectors and in regions, to be run in a single pass on the computer, and (5) addition of variable dimensioning to allow for more efficient use of limited computer core storage. A brief description of the COHORT-II code follows.

The code can track either primary neutrons or photons born in rectangular parallelepiped, spherical, or cylindrical source regions that are oriented parallel to the coordinate axes. Primary particles are generated from previously known spatial, angular, and energy distributions supplied by the user. Secondary photons born anywhere within the reactor-shield geometry can also be tracked in a subsequent run. The shield geometry is more flexible than the primary source geometry. Space is divided into homogeneous regions bounded by surfaces that can be described by a general quadratic equation with suitable choice of coefficients. This allows a description of such surfaces as cylinders, cones, ellipsoids, planes, etc., at an arbitrary orientation to the coordinate axes.

The code requires input cross-section data in its own specialized format and cannot accept multigroup cross-section data as used in conventional transport codes. Preparation of cross-section data, particularly for neutrons, is tedious because it has not yet been completely automated. A library of neutron cross sections in the required format has been compiled for about a dozen elements and is available with the code. Details of this library are given in the section CROSS SECTIONS. Preparation of photon cross-section data is considerably simpler and can easily be done by the user.

Biasing features of the code include preferential source particle selection and the exponential transform, or path-stretching, during particle tracking. The degree to which the exponential transform is applied can be varied depending on the direction of the particle and the region it is located in.

Particles are tracked one at a time. Histories are terminated when a particle escapes from the system under consideration, when its energy or weight falls below a previously assigned cutoff value, or when it has undergone more than a previously specified number of collisions. When secondary gammas are to be generated, neutron collision data are written on a tape and stored for future use. If leakage particles are to be used as a source in a subsequent problem, a leakage tape can be generated for this purpose.

Code printed output includes number fluxes that are averaged over regions and fluxes that are at arbitrarily located point detectors. The volume averaged region fluxes can be sorted according to arbitrary energy bins. The point-detector fluxes list uncollided (for isotropic sources only) and scattered flux contributions separately and can be sorted according to their polar and azimuthal angles of arrival at the detector as well as their energies. An estimate of the statistical precision is included for both volume and point detectors. Energy integrated quantities such as dose rates, heating rates, reaction rates, and fluxes greater than a given energy can also be computed for both volume and point detectors by entering suitable response functions. Where only one type of detector is of interest, the computation associated with the other type can be omitted to save time. All scoring, both for volume and point detectors is performed by statistical estimation.

The program does not require the user to handle tapes except when a leakage or a secondary gamma tape has been requested. A complete analysis of a typical reactor-shield problem would require three separate Monte Carlo problems to be run on the computer. These runs would be used to track and analyze, respectively, primary neutrons, primary photons, and secondary photons. A physical source tape for the secondary gamma problem would be generated during the primary neutron run.

The sections that follow describe the code method and input data requirements in detail. Sample problem input and output are discussed in appendix A. Flow charts for each subroutine in the code are also included and shown in figures 5 through 23.

CODE METHOD

GEOMETRY

The geometry of a problem is defined by identifying regions and their bounding surfaces. A region is a localized part of three-dimensional space bounded by one or more surfaces (up to a maximum of 12 boundaries per region). The nuclear composition of the material within a region must be the same for every point within it.

The geometry calculation performed by the code has two basic functions. Given the spatial coordinates and direction cosines of a particle, these are (1) to determine the

region the particle is located in, and (2) to compute the distance from the particle to the nearest boundary in its direction of travel.

Geometry Method

The geometry method used is the same as that of the QAD point-kernal shielding computer code (ref. 4) and will be described only briefly. The shapes of the regions that can be described are limited to those whose bounding surfaces can be expressed as special cases of a general quadratic equation. In the code the basic equation and four special forms are included to simplify input data. These equations are as follows:

$$Ax^2 + By^2 + Cz^2 + Exy + Fxz + Gyz + Hx + Jy + Kz - D = r \tag{1}$$

$$A(x - x_0)^2 + B(y - y_0)^2 + C(z - z_0)^2 - D = r \tag{2}$$

$$x - D = r \tag{3}$$

$$y - D = r \tag{4}$$

$$z - D = r \tag{5}$$

Equation (1) is the general quadratic equation and can be used to describe such convex surfaces as spheres, cylinders, cones, ellipsoids, hyperboloids, and planes at arbitrary locations and orientations to the coordinate axes by suitable choices of the coefficients. Equation (2) can be used to describe spheres, cylinders, ellipsoids, and hyperboloids parallel to the coordinate axes. Finally, equations (3) to (5) represent planes perpendicular to the x, y, and z axes, respectively. The user should try to select the simplest equation needed to describe the required surface since this not only reduces required input data, but computer time as well.

The variable r, also known as the residual, defines how an arbitrary point in space with coordinates (x, y, z) is related to the surface. The expression $r(x, y, z) < 0$ defines all points on one side of the surface, and $r(x, y, z) > 0$ defines those points on the other side. The residual is zero for all points on the surface. For each surface bounding a region, a direction index j that has a value of either +1 or -1 must be defined. The value of the direction index is chosen so that the product of j and the residual $r(x, y, z)$ is negative if the point (x, y, z) lies inside the region. This is the same convention used in the QAD code. Each j must be chosen properly according to the type of bounding

surface. If the bounding surface is closed (i.e., sphere, ellipsoid, etc.), a region inside the surface would have $j = +1$, and a region outside would have $j = -1$. An open bounding surface (i.e., cylinder, paraboloid, cone, etc.), would have $j = +1$ for a region between the surface and the axis of the figure and $j = -1$ for all other space. A plane surface would have $j = +1$ for a region to the left side of the plane and $j = -1$ for a region to the right side.

A single bounding surface may be used in the definition of many regions. The region definition requires the number of bounding surfaces (NB) of that region. If NB is entered with a positive sign, this indicates that the region is an inside region, while a negative sign affixed to NB indicates that the region is an outside region. Once a particle enters an outside region its history is terminated. Thus, regions that are of no interest in particle tracking can be designated as outside regions and their outermost boundaries need not be defined. An outside region should not be embedded within one or more inside regions, however, because particles will not be tracked across the outside region.

The region definition also requires a list of each bounding surface (IBN) that the region comprises. The sign affixed to the bounding surface IBN serves as the j index discussed previously. In addition, for each IBN listed, the user must also read in the most probable region a particle will enter when it leaves the region being defined.

To illustrate this, consider the simple example of describing a right circular cylinder bounded by two parallel planes. A sketch is shown in figure 1. The regions are indicated by numbers enclosed in a circle, and the boundaries are indicated by numbers enclosed in a square, one line of which is the boundary involved. A sketch of the problem geometry, with suitable identification of regions and boundaries, is strongly recommended as the starting point for making out the geometry input.

Boundaries 1 and 2 are planes parallel to the z-axis (type 5), located at $z = 0$ and 10, respectively; boundary 3 is a cylinder parallel to the z-axis (type 2) with a radius of 5. Region 1 consists of all points that have z values ($0 \leq z \leq 10$) and are simultaneously within the cylinder. The points of region 2 have the same z values but are outside the cylinder. Regions 3 and 4 are the sets of points with $z < 0$, and $z > 10$, respectively.

We now wish to determine the direction indices of region 1 for each of its three boundaries. The direction index of boundary 1 with respect to region 1 is -1. This is because boundary 1 has the form $z - 0 = r$. All points in region 1 have positive z, thus the residual r for boundary 1 is positive. Since the product of the residual and direction index must be negative, this is achieved by setting $j = -1$. By the same reasoning, the direction index of boundary 2 with respect to region 1 is +1, and the direction index of boundary 3 is +1.

In defining region 2, it can be seen that it has the same three boundaries as region 1. The direction indices of boundaries 1 and 2 with respect to region 2 have the same values as those with respect to region 1. But since region 2 defines those points outside the cylinder, the direction index of boundary 3 with respect to region 2 is now -1. Regions 3 and 4 are easily defined. Each has but one boundary. The direction index of boundary 1 with respect to region 3 is +1, and the index of boundary 2 with respect to region 4 is -1. For detailed input instructions, see the section Input Data.

Region Location

To determine the region a particle is located in, the code commences searching through the regions, one at a time. For each region, the product of the residual r and the direction index j is computed for every one of its boundaries. If this quantity is negative for every boundary in the region, the particle is concluded to be in the region. If the product is positive for any boundary of a region, the search in that region is abandoned immediately and proceeds to the numerically next higher region. If the code cycles completely through the regions and fails to place the particle in one of them, a geometry error is printed out and the problem is terminated. When a particle crosses a boundary from one region to another, the region search begins with the most probable region entered as defined in the region description.

Distance to Nearest Boundary

Once a particle has been located in a region, the distance to the nearest boundary of the region along its direction of travel is then computed by checking the distance to all the boundaries of the region. If the particle coordinates are x', y', and z', if its direction cosines are α, β, and γ, and if the distance to the nearest boundary along its direction of travel is S, the coordinates of intersection (x, y, z) of the particle's path with the boundary are

$$\begin{aligned} x &= x' + \alpha S \\ y &= y' + \beta S \\ z &= z' + \gamma S \end{aligned} \tag{6}$$

Since the point of intersection x, y, z is simultaneously on the particle flight path and on the boundary, equations (6) and the appropriate boundary equation can be solved simultaneously to yield an equation which in general is quadratic in S. This equation can be written in the form

$$P_1 S^2 + 2P_2 S + P_3 = 0 \tag{7}$$

where P_1, P_2, and P_3 are functions given in terms of the boundary equation coefficients and particle direction cosines. This equation is then solved for S. The physical intersection of the particle with the boundary is given by the smallest, nonnegative, real value of S. Then S is calculated for all the other boundaries of the region and compared. The smallest, nonnegative, real value is retained as the distance to the nearest boundary in the direction of travel. A small quantity EPSL is added to step the particle across the boundary. If a particle is located in a given region, but the routine is unable to calculate a satisfactory distance to one of its boundaries, an error message is printed out and the problem is terminated.

CROSS SECTIONS

This section is intended to describe the type of cross-section data required and how the data are handled in the code. As mentioned in the INTRODUCTION, a library of neutron cross sections in the required format has also been prepared and is available with the code. The elements in this library are hydrogen, lithium 6 and 7, carbon, oxygen, sodium, aluminum, chlorine, calcium, iron, tungsten, and lead. The sources of these data are noted on the comments cards included with the code. Additional details about this library are given in the next section.

Input Requirements

Cross-section input data for tracking neutrons are entered into the code in three groups of data designated as library numbers 6, 9, and 10. For gammas, only library 6 data are required. In both cases, these are entered as microscopic cross sections, with material or atom densities entered separately. Macroscopic cross sections are computed internally.

Library 6 data are the various reaction cross sections at discrete energies with energy points spaced arbitrarily by the person generating this table. Actual values of the cross sections for a particle at a specific energy are obtained by linear interpolation

within the table. The interpolation routine performs efficiently by progressively halving the energy range of the search. The elements in the library 6 neutron data package, available with the code, cover the energy range from 18 MeV to 0.025 eV in 90 discrete energy points, with a resolution of 10 energy points per decade. This resolution is believed to be adequate for those shield problems where an integral answer such as total dose rate or heating is of primary concern; but is inadequate for those problems where highly detailed spectral information is desired.

For neutrons this table lists the energy, the total cross section, the elastic plus inelastic scattering cross section, and the elastic scattering cross section. Those reactions resulting in the disappearance of a neutron such as (n, γ), (n, α), (n, p), etc., are represented by internal computation of the total cross section minus the sum of the elastic and inelastic scattering cross section. Neutron interactions considered are neutron absorbtion (or disappearance), elastic scattering, and inelastic scattering. The (n, 2n) reaction is handled in the data package as an inelastic scattering.

For gammas, library 6 lists the energy, total cross section, Compton scattering plus pair-production cross section, and the Compton scattering cross section. Gamma interactions considered are photoelectric absorption, pair production, and Compton scattering. Photoelectric absorption of gammas is computed as the difference between the total and the sum of the Compton plus pair-production cross sections. No library of gamma cross sections has been included with the code, because of the relative ease of preparation of these data from available compilations. However, a gamma cross-section library is available on request.

Library 9 data are required for those elements undergoing neutron inelastic scattering. The energy levels E_j of the nuclide, a list of incident neutron energies E_i, and a two-dimensional array P_{ij} are required for each element. The array P_{ij} represents the cumulative probability of a neutron of incident energy E_i exciting the nuclide to an energy level E_j. The probability for neutrons at an arbitrary incident energy E is obtained from the probabilities for the largest value of E_i less than E. When an inelastic scatter occurs, the energy level E_j to which the nuclide is excited is computed by choosing a random number R_1 and finding the smallest value of j that satisfies

$$\sum_j P_{ij} \geq R_1$$

Library 10 data are required for all elements except hydrogen. This library describes the anisotropic neutron elastic scattering in the center-of-mass system. A list of incident neutron energies is entered. A two-dimensional array listing cosines of the scattering angle (center of mass) for each incident neutron energy is also required. The

values of these cosines are obtained by integrating the differential elastic scattering cross section and finding values of the cosines of the scattering angle that divide the integral into a number of equal parts. The cosine values that define the histogram are the bulk of the library 10 data. The number of segments of the histogram can be varied to adequately represent the differential scattering cross section. The library data included with the code divide the integral into 20 equal parts. When an elastic scattering has taken place and the polar angle of scattering is required, a random number is chosen. Because each segment of the histogram represents a probability P_i of the neutron having scattered through that angle, the segment where scattering occurs for a given history is computed as

$$\sum_{i=1}^{n} P_i \geq R$$

Once the segment is defined, a second random number is chosen, and the exact angle of scattering is located at random within the segment.

The remaining required input data to describe the nuclear properties of the materials are the atom densities and the atomic weights (not needed for gammas).

Internal Data Preparation

After the cross sections have been read in, the macroscopic material cross sections are computed for neutrons or gammas using the atom densities and the library 6 tabulations. Certain probabilities are then computed for use in later calculations. For neutrons, the probability of a scatter collision being an elastic scattering event P_{el} is defined to be

$$P_{el} = \frac{\sigma_{el}}{\sigma_{el} + \sigma_{inel}}$$

and is computed for each element. For gammas, similarly, the probability that a given scatter is a Compton scatter

$$P_c = \frac{\sigma_{compt}}{\sigma_{compt} + \sigma_{pair}}$$

is computed. It should be noted in this regard that pair production can be regarded as a type of scatter since photons resulting from the pair annihilation emerge from this event.

Cross-Section Requirements for Secondary Gammas

Input cross sections for capture gamma source generation consist of a set of tables for each element where capture gammas are possible. These tables include (1) a list of incident neutron energies, (2) a list of gamma energies, and (3) a two-dimensional array N_{jk}, giving the number of photons of gamma energy E_k produced by an incident neutron of energy E_j.

Since inelastic gammas are determined from the library 9 data, no additional cross sections are required to generate the inelastic gamma ray sources.

PRIMARY SOURCE PARTICLE GENERATOR

General

The primary source particle generator is a procedure for generating nine parameters used to define each primary neutron or photon. These parameters are the three spatial coordinates of its birthplace, three direction cosines of its initial direction, its initial energy, weight (different from unity if source biasing is performed), and region of birth. The parameters are written on a tape consisting of 100 particles per record and are used as input to the particle tracking routines.

The basic assumption of the method is that the total distribution defining the source can be separated into distributions which define the spatial, direction and energy parameters independently of one another. In addition, the spatial distribution is assumed to be separable and can be defined as the product of three independent, single-coordinate distributions.

In keeping with these assumptions, the code link SOURCE contains four subroutines labelled SOURCE, DIRCOS, COORD, and ENERGY. SORCE is the main routine and uses the others to independently select, respectively, direction cosines, spatial coordinates, and the energy of each particle. These are then combined and a suitable weight is computed.

Source geometry options available to the user include specification of a point source or of a rectangular parallelepiped, cylindrical, or spherical volume sources. Angular options include monodirectional sources or isotropic and anisotropic sources. Energy options include monoenergetic or arbitrary energy spectrum sources.

A useful tool available to the user is the ability to perform biasing in the selection of any or all of the source particle parameters. For example, source energy biasing may be accomplished by reading in two energy distributions: the actual one and a biased distribution. The particle energy is selected from the biased distribution, but its weight is computed as the ratio of the actual to the biased distribution, thereby removing the bias. Similarly, directional source biasing can be performed, for example, for an isotropic angular distribution, by starting more particles, each of a lower weight, in a preferred direction than would normally come from an unbiased isotropic source. Biasing the initial polar (measured from the z-axis) or azimuthal angle can be performed independently, if desired. Finally, the selection of the particles initial spatial coordinates can also be biased. Biasing for one coordinate can be performed independently of the others.

Source Spatial Coordinate Selection

The initial spatial distribution of the primary particles, indicated by the control parameter IC, may be for a point source or for rectangular parallelepiped, cylindrical, or spherical volume sources (with or without biasing).

The option IC = 0 indicates that a point source is desired. Three spatial coordinates x, y, and z are entered and all source particles are born at this point. A spatial weight W_{sp} of 1.0 is assigned to each particle.

The options IC = 1, 2, or 3 refer, respectively, to the rectangular parallelepiped, cylindrical, and spherical volume source geometries. The spatial distributions and coordinate values are entered, in pointwise fashion, for each of the three coordinates defining the source. For the users convenience, the input spatial distributions need not be the actual probability density functions, but may be relative distribution functions. The code reads in all the relative spatial distributions, integrates them over their respective coordinates by trapezoidal integration, and normalizes them internally to obtain actual probability density functions.

Having obtained the probability density function $f(\eta)$ for each coordinate, the probability P_i, that a particle's coordinate n is located in the i^{th} interval between η_i and η_{i+1} is given by

$$\int_{\eta_i}^{\eta_{i+1}} f(\eta)\, d\eta = P_i$$

A random number R_1 is chosen, and the coordinate interval is selected by taking the smallest value of i that satisfies

$$\sum_{i} P_i \geq R_1$$

The actual value of the coordinate η is determined by selecting a second random number and evaluating η at random within the interval. A spatial weight of 1.0 is also assigned to each particle.

When spatial biasing is to be performed, a negative sign is affixed to the IC parameter. In addition to the actual distributions for each coordinate, the user must also read in biased distributions for all coordinates, even though spatial biasing is to be performed for only one. If the biased and the actual spatial distributions are identical for a given coordinate, then, effectively, no biasing in the selection of that coordinate is performed. As with the actual distributions, the biased distributions entered may be relative ones and are normalized internally to obtain biased probability density functions $f^*(\eta)$. The coordinate interval and value are selected in a similar manner as that discussed previously, except that samples are taken from the biased probability density function P_i^*. A coordinate weight W_c is computed as

$$W_c = \frac{\int_{\eta_i}^{\eta_{i+1}} f(\eta)\, d\eta}{\int_{\eta_i}^{\eta_{i+1}} f^*(\eta)\, d\eta}$$

and a spatial weight W_{sp} is computed as the product of the three coordinate weights.

Source Direction Cosine Selection

The initial angular distribution of the primary particles, indicated by the control parameter, ID, may be monodirectional, isotropic (with or without biasing), or anisotropic.

The option ID = 1, indicates that the source particles are monodirectional. A set of direction cosines α, β, and γ are input to the program, and all source particles

are emitted with these specified direction cosines. An angular weight of 1.0 is assigned to each particle.

The option ID = 2 is used when source particles are emitted isotropically. The direction cosines are determined by a rejection technique that was developed by Kahn (ref. 5) and is shown in figure 2. Each particle is given an angular weight of 1.0. No additional input is required for this option.

If particles are to be emitted isotropically but biased in either the polar or azimuthal angular directions, the option ID = -2 is used. The cosines defining each polar angular interval and the probability of particle emission within each interval are read in. Similarly, the angles defining each azimuthal angular bin and the probabilities of particle emission in each is also required. The cosine of the polar angle is selected by obtaining a random number R_1 and choosing the smallest value of i for which

$$\sum_i P_i (\cos \theta) \geq R_1$$

where $P_i(\cos \theta)$ is the probability (biased) of particle emission in the i^{th} polar angular interval.

With the polar angular interval known, the cosine of the polar angle γ is chosen at random within the interval by requiring that

$$\gamma = \gamma_i + R_2(\gamma_{i+1} - \gamma_i)$$

where γ_i and γ_{i+1} are the values of the cosines defining the i^{th} interval and R_2 is a random number.

A polar angular weight W_θ is then calculated as the unbiased divided by the biased probability of emission per interval as

$$W_\theta = \frac{\gamma_i - \gamma_{i+1}}{2P_i(\cos \theta)}$$

Calculation of the azimuthal angle is done similarly by choosing the smallest value of i such that

$$\sum_i P_i(\varphi) \geq R_3$$

The azimuthal angle is then computed as

$$\varphi = \varphi_i + R_4(\varphi_{i+1} - \varphi_i)$$

An azimuthal angular weight is computed as

$$W_\varphi = \frac{\varphi_{i+1} - \varphi_i}{2\pi P_i(\varphi)}$$

An angular weight is computed as the product of the polar and the azimuthal weights. The direction cosines α and β are given by

$$\alpha = \left(1 - \gamma^2\right)^{1/2} \cos \varphi$$

and

$$\beta = \left(1 - \gamma^2\right)^{1/2} \sin \varphi$$

The option ID = 3 is used to specify an anisotropic angular distribution. Input is the same as that for the ID = -2 option. The selection of polar and azimuthal angles are performed identically, but an angular weight of 1.0 is assigned to each particle.

Source Energy Selection

The initial energy distribution of the primary particles, indicated by the control parameter, IE, may be monoenergetic or may be selected from an arbitrary distribution.

The option IE = 1 indicates that the particle energies are to be monoenergetic and the energy value (E) is entered as input. An energy weight of 1.0 is assigned to each particle.

Option IE = 2 is used when energies are selected from a continuous energy spectrum. The spectrum is divided into intervals. The probability that a particle is emitted in the i^{th} interval $P_i(E)$ is read in for every interval. The interval of the source particle is selected by choosing a random number R_1 and computing the smallest value of i for which

$$\sum_i P_i(E) \geq R_1$$

The actual particle energy is obtained from

$$E = E_i + R_2(E_{i+1} - E_i)$$

where E_i is the lower bound of the i^{th} energy interval. An energy weight of 1.0 is assigned.

Option IE = -2 allows the user to perform energy source biasing. As before, the probability of particle emission in the i^{th} energy interval $P_i(E)$ is required for every interval. In addition, the biased probability emission per interval $P_i^*(E)$ is also required. The code determines the energy of the source particle the same as in option IE = 2, except that sampling is performed from the biased probability distribution. An energy weight is calculated as

$$W_E = \frac{P_i(E)}{P_i^*(E)}$$

Stratified Selection of Source Particle Parameters

Since the distribution of the primary source particles in space, direction, and energy is known, a stratification procedure can be used to assign the source particle parameters. If the probability of a particle being located in interval i is P_i, then the total number of particles to be located in the i^{th} interval is NP_i, where N is the total number of source particles to be generated. This procedure, known as stratification, is more desirable than choosing the interval by comparing a random number with the cumulative probability distribution. The stratification procedure will always select exactly NP_i particles within the interval; whereas, the probability selection procedure only does so on the average.

Stratification in the selection of all of the primary source particle parameters is impractical, however. Imagine a typical problem where the spatial coordinates are divided into 10 intervals for each coordinate, the angular coordinates are divided into five intervals each, and the energy spectrum is divided into 20 intervals. If the selection probability per interval is equally likely, the probability of a particle being located in a cell defined by the coordinates x, y, z, θ, φ, and E becomes

$$P = P_x P_y P_z P_\theta P_\varphi P_E \approx 10^{-6}$$

To locate just one particle per cell would require generation of about 10^6 source particles. If the probabilities for each cell are not equal, as is more likely, assuring at least one particle per cell requires even larger N. Monte Carlo calculations are time consuming, and typical problems involve generation of about 10^4 to 10^5 primary particles.

By proper designation of an input parameter (see the section Input Requirements for details), the code allows any one of the primary particle source coordinates such as energy, polar angle, etc., to be selected for stratification.

The number of particles located within an interval of a stratified coordinate is NP_i, where P_i is the probability of a particle being born within the interval. The intervals for the remaining coordinates are selected by comparing a random number with the cumulative probability distribution of that coordinate. No more than one coordinate can be stratified, or, if the user wishes, none of the coordinates need be selected by stratification.

PARTICLE TRACKING AND SCORING

The particle tracking and scoring routines compose the third link of the COHORT-II program. For convenience, the discussion is divided into particle tracking and particle scoring. In the code, a given routine may perform part of both functions, for greater overall efficiency. Four routines are in this link. They are HTA, HISTRC, SCATR, and GEOMT. HTA acts as an overall executive routine in the particle tracking, but it also computes the uncollided fluxes at point detectors and performs preliminary statistical tallying. HISTRC is concerned primarily with particle tracking between collisions, and it performs the exponential transform and calculates fluxes within regions. SCATR handles the collision processes, energy, and directions after scatter and also computes scattered fluxes at point detectors. Finally, GEOMT is concerned only with geometry calculations and has been discussed previously. (See GEOMETRY section.)

The following sections discuss these functions in more detail.

Particle Tracking

Distance to collision. - The number of mean free paths $D\Sigma_T(E)$ that a particle will travel on its flight to its next collision is selected from the exponential distribution

$$P\left[X < D\Sigma_T(E) < (x + dx)\right] = e^{-x}\, dx$$

by taking

$$D = \frac{-\ln R_1}{\Sigma_T(E)}$$

where R_1 is a random number, and $\Sigma_T(E)$ is the total macroscopic cross section.

After D is computed, a check is made to determine whether the flight path is confined to one region, in which case calculation of the collision location is straightforward. If the particle leaves the region, the exit position is determined and the path length S in the region is computed.

The distance the particles can travel in the new region entered is computed by the equation

$$D' = (D - S)\frac{\Sigma_T(E)}{\Sigma'_T(E)}$$

where $\Sigma'_T(E)$ and $\Sigma_T(E)$ are the total macroscopic cross sections for the region entered and the region just crossed, respectively. If D' is less than the distance across the new region, the collision occurs within it. If D' is greater, the process is repeated as often as necessary.

Collision process. - This discussion covers how the types of collisions undergone by neutrons and gamma rays are treated in the code and the determination of the energy and direction after scattering.

Only scattering collisions are treated specifically in the code. These include elastic and inelastic scattering for neutrons and Compton scatter and pair production for gamma rays. To account for particle absorption, the weight of the particle after a collision is computed as the product of the weight before collision and the probability that the collision was a scattering event. Thus,

$$W' = WP_s(E)$$

where W and W' are the particle weights before and after collision, respectively, and $P_s(E)$ is the scattering probability for particles of incident energy E. The sequence of events in the code in handling the collision processes for both neutrons and photons is as follows: (1) the scattering element or nuclide is determined, (2) the particle is tested

to determine whether it is a neutron or a photon, (3) the type of scatter event is determined (elastic against inelastic for neutrons; Compton against pair-production for photons), (4) the polar scattering angle and the energy after collision are found using the appropriate scattering laws, depending on the type of particle and type of scatter event, (5) the azimuthal scattering angle is computed, and, finally, (6) new direction cosines after scattering are computed from a knowledge of the values before scattering and the polar and azimuthal scattering angles. These six steps are discussed in further detail in the remainder of this section.

When a collision occurs, first the scattering nuclide is selected by determining the smallest value of i for which

$$\frac{1}{\Sigma_S(E)} \sum_i N_i \sigma_{si}(E) \geq R$$

where $\Sigma_S(E)$ is the macroscopic scattering cross section of the material, $\sigma_{si}(E)$ is the microscopic scattering cross section for the i^{th} element, and N_i is the atom density for the i^{th} element. A test is then made to determine whether the particle is a neutron or photon.

For gamma rays, the type of scattering event is determined by comparing a random number to $P_c(E)$, the probability that a given scatter is a Compton scatter. If $P_c(E) \geq R_1$, the event is a Compton scatter. Otherwise, pair production results. If the event is a Compton scatter, the energy and direction after scattering are selected from the Klein-Nishina formula by use of a rejection technique developed by Kahn (ref. 5). This rejection technique is illustrated in figure 3. If a pair production event occurs, it is assumed that the electron-positron pair are annihilated immediately, resulting in two isotropically emitted photons, each of energy 0.511 MeV. Only one photon is followed in the code, but its weight is doubled. The direction cosines of the isotropically emitted photon are obtained via a standard rejection technique.

For neutrons, the type of scattering event (elastic or inelastic) is chosen by picking a random number R_1 and comparing it to $P_{el}(E)$, the probability that a given scatter is elastic. If $P_{el}(E) \geq R_1$, the event is taken as an elastic scatter. If not, the scatter is inelastic.

The polar scattering angle in the center-of-mass (CM) system is then determined. Neutron elastic scattering is assumed to be isotropic in the center-of-mass system if the neutron incident energy is less than an input parameter ESI(J), which is entered for each of the J elements. If the incident energy is greater than ESI(J), elastic scattering is taken to be anisotropic. For isotropic elastic scattering, the polar scattering angle in the center-of-mass system λ is computed from the equation

$$\cos \lambda = 2R - 1$$

where R is a random number. For anisotropic elastic scattering, the cosine of the polar scattering angle in the center-of-mass system is determined from input cumulative probability distribution tables (library 10 data) as a function of incident neutron energy and element.

Inelastic neutron scattering is assumed to be isotropic in the center-of-mass system for all elements. The polar scattering angle is computed as

$$\cos \lambda = 2R - 1$$

where R is a random number.

The energy after scattering is then calculated. A parameter B is assigned a value, depending on the type of scattering event. For neutron elastic scattering, B = 1. For neutron inelastic scattering, B is defined as

$$B = \left[1 - \left(\frac{A + 1}{A} \right) \frac{E_x}{E} \right]$$

where E_x is the excitation energy which is selected from a probability distribution table (library 9 data) for each element, E is the neutron incident energy, and A is the atomic weight for the element. The energy after scattering E' is then computed to be

$$E' = \frac{E}{(A + 1)^2} \left(1 + A^2 B + 2AB^{1/2} \cos \lambda \right)$$

where the same equation is used for both elastic and inelastic scatter events, substituting the proper value for B. Use of this equation with different definitions of B, depending on elastic or inelastic scatter, is taken from the original versions of the code (refs. 1 and 2) and has been retained for economy of programming and convenience.

The polar scattering angle in the laboratory system ψ is then calculated from the center-of-mass system angle by means of the equation

$$\cos \psi = \frac{(1 + AB^{1/2} \cos \lambda)}{\left(1 + A^2 B + 2AB^{1/2} \cos \lambda \right)^{1/2}}$$

where again the same equation is used for both elastic and inelastic scattering by substituting the appropriate value for B.

A simple case arises if the element is hydrogen. Neutron scattering in hydrogen is assumed to be isotropic in the center-of-mass system, and in addition there is no inelastic scattering. The preceding equations take on a particularly simple form since A = B = 1. The equation for the polar scattering angle becomes;

$$\cos \lambda = 2R - 1$$

for the energy after collision,

$$E' = \frac{E}{2}(1 + \cos \lambda)$$

and, for the laboratory scattering angle,

$$\cos \psi = \left(\frac{1 + \cos \lambda}{2}\right)^{1/2}$$

Eliminating $(1 + \cos \lambda)$ from the second and third equations and substituting the first equation into the third, we obtain

$$E' = E \cos^2 \psi$$

and

$$\cos \psi = \sqrt{R}$$

The cosine of the laboratory scattering angle is computed somewhat more quickly by restoring to a scheme developed by Kahn (ref. 5). Two random numbers are chosen, and the largest of these is taken to be equal to the cosine of the scattering angle. Thus,

$$\cos \psi = \sqrt{R} = \max (R_1, R_2)$$

Another special case arises if the neutron energy is below an input value ETM, where ETM is assumed to be a thermal energy level. Neutrons with energy less than ETM are scattered isotropically in the laboratory system without energy change.

For those particles not isotropically scattered in the laboratory system (Compton scattered photons and neutrons with energy greater than ETM), the azimuthal scattering angle φ is next selected from a uniform distribution in the interval from 0 to 2π. A proper choice of φ would be $2\pi R$, where R is a random number. However, since $\sin \varphi$ and $\cos \varphi$ are desired, a commonly used rejection technique is employed for efficiency. Two random numbers are chosen, and the sum of the squares $S = R_1^2 + R_2^2$ is tested. If $S \leq 1$, then

$$\cos \varphi = \frac{R_1^2 - R_2^2}{S}$$

and

$$\sin \varphi = \frac{2R_1R_2}{S}$$

If $S > 1$, two other random numbers are chosen and the cycle is repeated.

The direction cosines of the particle after collision is computed from a knowledge of the polar and azimuthal scattering angles ψ and φ in the laboratory system and from the direction cosines α, β, and γ of the particle before collision. The new direction cosines are computed as follows: when $(1 - \gamma^2) \geq 0.0001$,

$$\alpha' = \frac{\alpha\gamma \sin \psi \cos \varphi - \beta \sin \psi \sin \varphi}{\left(1 - \gamma^2\right)^{1/2}} + \alpha \cos \psi$$

$$\beta' = \frac{\alpha \sin \psi \sin \varphi + \gamma\beta \sin \psi \cos \varphi}{\left(1 - \gamma^2\right)^{1/2}} + \beta \cos \psi$$

and

$$\gamma' = \gamma \cos \psi - \left(1 - \gamma^2\right)^{1/2} \sin \psi \cos \varphi$$

when $(1 - \gamma^2) < 0.0001$,

$$\alpha' = \sin \psi \cos \varphi$$

$$\beta' = \sin \psi \sin \varphi$$

and

$$\gamma' = \cos \psi$$

Exponential transform. - The exponential transform finds its greatest application in deep penetration problems, where it effectively serves to stretch the path length of the particle between collisions. To achieve a high degree of flexibility, the code, by means of input parameters, allows the transform to be varied depending on the region the particle is in, the direction it is heading in, and whether the particle is on its first flight.

A pseudototal macroscopic cross section is defined for each region as follows:

$$\Sigma_T^*(E) = \Sigma_T(E)(1 - XK(K) \cdot EXT(K))$$

where $\Sigma_T^*(E)$ and $\Sigma_T(E)$ are the pseudototal and actual total cross sections, respectively, XK(K) is a direction dependent option which is input for each of the K regions, and EXT(K) is a parameter (usually between 0 and 1) which controls the intensity of the transform within a given region.

The quantity XK(K) controls how the transform shall be applied depending on particle direction within a region. The allowable options for XK within a region are

$$XK = 1,\ \alpha,\ \beta,\ \gamma,\ -\alpha,\ -\beta,\ -\gamma$$

where α, β, γ are the particle direction cosines. If, for example, XK(K) equals 1, this signifies that the transform will be applied to all particles within that region independently of direction, with an intensity controlled by EXT(K). If XK is chosen to be γ, for example, then all particles headed in the positive z direction will be biased. A particle headed parallel to the z axis ($\gamma = 1$) will be biased more heavily than one whose direction cosine with the z axis is smaller. The value of XK chosen for each of these particles will, in fact, be its z axis direction cosine. Particles headed backwards ($\gamma < 0$) undergo no exponential transformation of their flight path.

The quantity EXT(K) controls the intensity of the transform within a given region, independently of particle direction. Setting EXT(K) = 0 is equivalent to not using the transform since for this case

$$\Sigma_T^* = \Sigma_T(1 - 0) = \Sigma_T$$

Whenever the transform is applied, the pseudototal cross section Σ_T^* is used in place of the actual cross section Σ_T to compute the path length to the next collision. When EXT is chosen between 0 and 1, Σ_T^* is smaller than Σ_T, and this serves to

stretch the path length between collisions. This is the usual case. It should be pointed out that EXT can also be chosen to be negative (EXT < 0), in which case Σ_T^* is larger than Σ_T. This serves to compress the path length, if desired.

An additional input parameter KBIAS, also allows some control of the exponential transform. Setting KBIAS = 0 causes the transform to be applied to all flight paths of the particle, while setting KBIAS = 1 causes the transform to be applied only on the first flight of the particle, from its birth as a source particle to its first collision point.

Since the exponential transform is a biasing technique, the bias introduced by its use must be removed by suitable modification of the particle weight. If the transform is applied within a region and the particle crosses the region without a collision, the bias is removed at the boundary crossing by modifying the weight as follows:

$$W' = W\, e^{-S\left[\Sigma_T(E) - \Sigma_T^*(E)\right]}$$

If the particle crosses several regions, the weight correction formula is applied at each boundary crossing. When the particle reaches the scattering center at a distance D within a region, the bias is removed by modifying the particle weight as follows:

$$W' = W\, \frac{\Sigma_T(E)}{\Sigma_T^*(E)}\, e^{-D\left[\Sigma_T(E) - \Sigma_T^*(E)\right]}$$

History termination. - Particle histories are terminated whenever one of the following events occurs:

(1) The particle's energy is reduced below a specified minimum energy, EMIN.

(2) The number of collisions in the particle's history exceeds a maximum allowable, MAXCOL.

(3) The particle's weight is reduced below a specified minimum weight, WMIN.

(4) The particle escapes into an unbounded region.

The quantities EMIN, MAXCOL, and WMIN are problem input parameters. Whenever the particle weight drops below WMIN, Russian Roulette is played to determine whether the history is to be terminated or continued. The Russian Roulette input parameter RR is compared with a random number R. If RR $\geq$ R, the history is continued with a new particle weight W' = W/RR. If RR $<$ R, the history is terminated.

Particle Scoring

Uncollided flux at a point detector. - To compute the uncollided flux at a point detector, the assumption is made that each particle can be regarded as a microscopic point source, emitting $1/4\pi$ neutrons or photons per unit solid angle. The geometry routine computes the total number of mean free paths along the flight path and the uncollided flux from each particle becomes

$$\varphi_{unc} = \frac{W\, e^{-\lambda}}{4\pi d^2}$$

where W is the weight of the particle, λ is the total number of mean free paths between particle and detector, and d is the distance between particle and detector. Because of these assumptions, the uncollided flux calculation has no meaning for a monodirectional or anisotropic source.

Scattered flux at a point detector. - In addition to the uncollided flux, the code estimates the scattered flux at each detector point by computing the probability at every collision that a particle will scatter in a direction so as to be headed towards the detector and will arrive there with no further collisions.

The equation used to estimate the scattered flux at a point detector from each collision is given by

$$\varphi_{sc} = \frac{W}{d^2} \frac{\frac{d\sigma}{d\Omega}(\psi, E)}{\sigma(E)} e^{-\lambda}$$

where W is the particle weight after collision, d is the distance from collision point to detector, $d\sigma/d\Omega(\psi, E)$ and $\sigma(E)$ are, respectively, the differential and total scattering cross sections for a particle of energy E, and λ is the total number of mean free paths from the collision point to the detector. The ratio $(d\sigma/d\Omega)/\sigma$ represents the probability of a particle scattering through an angle ψ in the laboratory system, so as to be headed towards the detector; $1/d^2$ is the solid angle subtended by a unit sphere at the detector; and finally, $e^{-\lambda}$ is the probability of the particle arriving at the detector with no further collisions. The flux estimator is computed and stored for each detector as a function of the particle energy and also, if desired, the polar and azimuthal angles of arrival at the detector.

The computation of the scattered flux at a point detector begins with the calculation of the polar scattering angle in the laboratory system. Let the spatial coordinates of a

point detector and a particle be x_i, y_i, z_i, and X, Y, and Z, respectively. Then the distance between the particle and the i^{th} detector is given by

$$d_i = \left[(X - x_i)^2 + (Y - y_i)^2 + (Z - z_i)^2\right]^{1/2}$$

and the direction cosines of the flight path to the detector are

$$\alpha_i = \frac{x_i - X}{d_i}$$

$$\beta_i = \frac{y_i - Y}{d_i}$$

$$\gamma_i = \frac{z_i - Z}{d_i}$$

If the direction cosines of the particle before collision are α, β, and γ, then the laboratory system polar scattering angle through which the particle must scatter in order to be headed toward the detector is given by

$$\cos \psi = \alpha\alpha_i + \beta\beta_i + \gamma\gamma_i$$

Turning first to the treatment for gamma rays, the angular scattering probability in the laboratory system is next computed from the Klein-Nishina formula by use of the expression

$$\frac{\frac{d\sigma}{d\Omega}(\psi, E)}{\sigma_c(E)} = \frac{r_o^2}{2} \frac{(P + P^3 - P^2 \sin^2 \psi)}{\sigma_c(E)}$$

where

$$P = \frac{1}{1 + \frac{E}{0.511}(1 - \cos \psi)}$$

r_o is the classical electron radius, and $\sigma_c(E)$ is the gamma-ray scattering cross section per electron at energy E. The cross section $\sigma_c(E)$ is computed from the formula

$$\sigma_c(E) = 2\pi r_o^2 \left\{ \frac{1+Q}{Q^3} \left[\frac{2Q(1+Q)}{1+2Q} - \ln(1+2Q) \right] + \frac{1}{2Q} \ln(1+2Q) - \frac{1+3Q}{(1+2Q)^2} \right\}$$

where $Q = E/0.511$ for the gamma-ray energy in MeV. These equations are computed using the gamma-ray energy after scattering which is given by

$$E' = \frac{E}{1 + \frac{E}{0.511}(1 - \cos\psi)}$$

where E is the gamma-ray energy before collision.

The treatment is not as simple for neutrons as for the gamma rays. A conversion must be made from the laboratory scattering angle ψ to the center-of-mass scattering angle λ to find the angular scattering probability. The angular scattering probability, computed in the center-of-mass system, must then be reconverted to the laboratory system. The center-of-mass scattering angle λ is given by

$$\cos\lambda = \frac{\cos^2\psi - 1 + \cos\psi\sqrt{\cos^2\psi + A^2B - 1}}{AB^{1/2}}$$

where A and B have been previously defined. (See Collision Processes section.)

The angular scattering probability in the center-of-mass system is next computed. For those cases in which elastic scattering is isotropic in the center-of-mass system and for all inelastic scattering events, the probability of scattering per unit solid angle into the angle λ is $1/4\pi$.

When neutron elastic scattering is anisotropic in the center-of-mass system, the probability of scattering per unit solid angle into the angle λ is computed from the cumulative probability distribution tables (library 10 data) for the element of the collision.

The scattering probability in the center-of-mass system is then converted to the laboratory system by means of the equation

$$\frac{\frac{d\sigma}{d\Omega}(\psi, E)}{\sigma_c(E)} = \frac{\frac{d\sigma}{d\Omega}(\lambda, E)}{\sigma_c(E)} \frac{\left(A^2 + 2A\cos\lambda + 1\right)^{3/2}}{A^2|A + \cos\lambda|}$$

The equation used to compute the neutron energy after scattering is the same as that used in the collision processes, namely,

$$E' = \frac{E}{(A+1)^2}(1 + A^2B + 2AB^{1/2}\cos\lambda)$$

As in the collision processes, hydrogen scattering allows for a much simpler calculation. For hydrogen, the scattering probability per unit solid angle in the center-of-mass system is isotropic. Therefore,

$$\frac{\frac{d\sigma}{d\Omega}(\psi, E)}{\sigma_c(E)} = \frac{1}{4\pi} 2^{3/2} (1 + \cos\lambda)^{1/2}$$

and

$$\cos\lambda = 2\cos^2\psi - 1$$

Combining these, we obtain for hydrogen

$$\frac{\frac{d\sigma}{d\Omega}(\psi, E)}{\sigma_c(E)} = \frac{\cos\psi}{\pi}$$

with the special case $E' = E\cos^2\psi$ for hydrogen. When scattering in hydrogen is involved, if the laboratory scattering angle ψ is larger than 90^o ($\cos\psi < 0$), the calculation of the flux at the detector is terminated since neutron scattering in hydrogen cannot physically occur through angles larger than 90^o.

Region averaged fluxes. - The flux per unit source strength for a region is obtained by estimating the expected track length per unit source strength through the region divided by the volume of the region. The track lengths in each region are summed for all particles that can reach the region. The expected track length per unit source particle is the sum of the track lengths divided by the number of source particles.

The expected track length through a region J for a particle is given by

$$TL_J = W \int_0^S p(x)x\,dx + W \cdot S\, e^{-\Sigma S}$$

where TL_J is the expected track length through region J, W is the weight of the particle, S is the distance across region J, Σ is the total macroscopic cross section for region J, and p(x) is the probability per unit distance of a particle making a collision at x.

The first term of the preceding equation gives the expected track length contribution for those particles traveling a distance x less than S, and the second term gives the expected track length contribution for region J for those particles that travel beyond it. Since $p(x) = \Sigma\, e^{-\Sigma x}$, the equation becomes

$$TL_J = W \int_0^S \Sigma x\, e^{-\Sigma x}\, dx + WS\, e^{-\Sigma S}$$

$$= \frac{W}{\Sigma}\left[1 - e^{-\Sigma S}(1 + \Sigma S)\right] + WS\, e^{-\Sigma S}$$

$$= \frac{W}{\Sigma}\left[1 - e^{-\Sigma S}(1 + \Sigma S - \Sigma S)\right] = \frac{W}{\Sigma}(1 - e^{-\Sigma S})$$

When the material in the region is a vacuum the expected track length through the region is simply

$$TL_{vac} = W \cdot S$$

The weight of the particle entering a region not containing the collision point is redefined at the boundary as

$$W' = W\, e^{-EXP}$$

where EXP is the sum of the mean free paths traveled by the particle since the last boundary.

Particle leakage tape and printout table. - Particles leaking out of the system may be tracked in a subsequent problem, if desired, by generating a leakage tape. Also, a leakage printout table that sorts the particles leaking out according to energy and angle of emission with the Z-axis can be obtained. These options are available only if region averaged fluxes are requested. (For details, see the section DATA INPUT.)

The spatial location, direction cosines, energy, weight, and region number of the particle at the time of its escape are recorded on the leakage tape. Since these are the same parameters written by the primary particle source generator, this tape can be

used in a subsequent run and the leakage particles can be tracked. The leakage printout table can sometimes be used to obtain the angular and energy distribution for a point source representation of the system.

Energy deposition. - Energy deposition for neutrons and photons is computed at each collision whenever the incident particle energy E is greater than an input parameter (ELD). The energy deposition from a neutron or photon absorption is computed as

$$ED(1) = W\ E(1 - P_s(E))$$

where W is the particle weight before collision, E is the particle incident energy, $P_s(E)$ is the scattering probability for particles of energy E, and $1 - P_s(E)$ is the absorption probability for particles of energy E.

The energy deposition from neutron or photon scattering is computed by use of the formula

$$ED(2) = W\ P_s(E)(E - E' - E_x)$$

In order to use the same formula for energy deposition from scattering for both neutrons and photons, the quantities E' and E_x must be defined differently depending on the type of particle and type of scatter event.

For neutrons, E' is defined as the neutron energy after scattering. For neutron elastic scattering $E_x = 0$, but for neutron inelastic scattering E_x is the excitation energy of the nuclide. The excitation energy E_x is given off in the form of inelastic gamma rays, and the energy deposition from these should be treated as a separate problem.

For gammas, if the event is a Compton scatter, E_x is zero, and E' is the photon energy after scatter. If the event is a pair production, then $E' = E_x = 0.511$ MeV, since, for a pair production event, the original photon disappears and is replaced by two photons, each of energy 0.511 MeV.

Statistical analysis. - The program calculates the standard deviation σ and the percent deviation for (1) energy deposited in regions, (2) fluxes at point detectors, and (3) track length fluxes in regions. The method used in the code is that of reference 6. The random variables (energy deposition, fluxes, track lengths) are tallied as group scores accumulated from tracking a group of n histories. The group size n is an input parameter chosen by the user for the N histories in which $G = N/n$ groups are processed in the problem. The value of n should be chosen so that $G > 10$ for best statistical results.

The basic equation used in the calculation of the standard deviation per history is given by

$$\sigma = \frac{1}{n} \frac{1}{\sqrt{G - 1}} \sqrt{\overline{S_g^2} - (\overline{S})^2}$$

where

$$\overline{S} = \frac{\sum_{g=1}^{G} S_g}{G}$$

$$\overline{S_g^2} = \frac{\sum_{g=1}^{G} S_g^2}{G}$$

The percent deviation (PC DEV) of each random variable x is the standard deviation divided by the average.

$$\text{PC DEV} = 100 \frac{\sigma}{\overline{X}}$$

where $\overline{X}$ is the calculated average value of x.

History Tracking Techniques

During particle tracking, the code makes four passes through the geometry to determine (1) distance to the next collision, (2) estimated track lengths in regions, and (3) uncollided and (4) scattered fluxes at point detectors. Since the program repeats (1), (2), and (4) at each collision, a significant amount of computing time is spent in geometry calculations. The program has built-in features to aid in reducing geometry tracking time.

As the code calculates the distance to the next collision, track length estimation and particle tracking proceed together up to the collision point. The track lengths in the remaining regions beyond the collision point in the direction of travel are then calculated before the code resumes history tracking.

Geometry tracking can be reduced by terminating the track length estimation when the contribution from that collision becomes negligible. The code provides a cutoff option to accomplish this. When the number of mean free paths of the track length is

greater than the input cutoff parameter (TLCUT), the track length calculation is terminated and history tracking resumed.

A cutoff may also be used to terminate the estimation of fluxes at point detectors when these become negligible. The input parameter EPC(K) is a detector dependent quantity, which may vary for each of the K detector points. When the cumulative number of mean free paths from the collision point to the K^{th} detector is greater than EPC(K), flux estimation to this detector is terminated, and the code proceeds to the next detector.

The setting of these cutoff values are at the complete control of the user.

SECONDARY GAMMA SOURCE GENERATOR

The function of the secondary gamma source generator is to generate secondary gamma photons resulting from inelastic scatter (n, n', γ) or from neutron capture (n, γ) reactions with the shield materials and to write a secondary gamma source tape. The main features are summarized as follows: (1) Secondary gammas are generated for only two interactions, inelastic scatter n, n', γ or neutron captures n, γ. (2) The routine randomly selects only one gamma ray from a capture gamma spectrum, but calculates a weight that preserves the total energy released per capture. (3) The code analyzes collisions that give rise to inelastic or capture gammas in a single computer run. The code requires, as input for the secondary gamma-ray analysis, a collision parameter tape and a card input deck for the neutron capture gamma spectrum for each element of interest. Card input is not required to generate gamma rays resulting from inelastic scatter.

The output is a gamma-ray source tape to be used as input for a subsequent analysis of the secondary gamma sources. Written on the tape are the spatial coordinates x, y, and z, direction cosines α, β, and γ, energy E, weight W, and region number NR of each secondary gamma-ray source particle. A code option INEL, allows the user to get inelastic and capture gamma sources on separate tapes, or both types of gamma-ray sources on a single tape.

Generation of secondary gammas from inelastic scatter is the simpler of the two methods. The initial energy E and final energy, E' of the inelastically scattered neutron are taken from the collision tape. The gamma-ray energy E_γ is simply the difference in these energy values:

$$E_\gamma = E - E' \tag{1}$$

The weight of the gamma ray W_γ is equal to the weight of the incident neutron times the probability that no absorption took place. Thus

$$W_\gamma = W_n P_s(E) \tag{2}$$

where $P_s(E)$ is the scattering probability at energy E. The spatial coordinates $x, y,$ and z and the region of birth of the gamma ray (NR) are taken directly from the collision tape.

The angular distribution of the secondary gamma rays is assumed to be isotropic in the laboratory system. Consequently the initial direction cosines $\alpha, \beta,$ and γ are chosen at random by use of the rejection technique illustrated in figure 2.

The geometric parameters for capture gamma sources ($x, y, z, \alpha, \beta, \gamma$, NR) are obtained the same way as outlined for inelastic gamma sources. The calculations of the gamma-ray energy E_γ and weight W_γ however, are more involved.

The chief input data for generating capture gammas is a table which gives the number of photons $N_{j,l,k}$, at gamma energy E_k, emitted when a neutron of incident energy E_l is captured by element j. When a neutron of energy E_l is captured in element j the total energy released $Q(E_l)$ is

$$Q(E_l) = \sum_k N_{l,k} E_k \tag{3}$$

For a given element, the probability $P_{l,k}$ of picking a single gamma photon of energy E_k is

$$P_{l,k} = \frac{N_{l,k} E_k}{\sum_k N_{l,k} E_k} = \frac{N_{l,k} E_k}{Q(E_l)} \tag{4}$$

The table $N_{j,l,k}$ is input for each element that can produce capture gammas. Then $Q(E_l)$ is computed internally for each neutron incident energy and element. The probability table $P_{l,k}$ is then constructed for each element and further modified to a cumulative probability distribution $P'_{l,k}$. The element in which the absorption occurs is available from the neutron collision tape. The energy of the secondary gamma photon E_k is chosen from the cumulative probability distribution by obtaining a random number R_1 and choosing the smallest value of k such that

$$\sum_k P'_{l,k} \geq R_1 \tag{5}$$

The number of gamma rays n' of energy E_k required to preserve the total energy per capture $Q(E_l)$ is

$$n' = \frac{Q(E_l)}{E_k} \tag{6}$$

Only one photon of energy E_k is created, but the factor n' is used in determining the weight of the photon.

The weight of the photon created W_γ is calculated as the product of the neutron weight W_n, the probability of an absorption $\left[1 - P_s(E)\right]$, where $P_s(E)$ is the scattering probability and the total energy per capture weighting factor n'. Thus

$$W_\gamma = W_n\left[1 - P_s(E)\right]n' \tag{7}$$

The absorption probabilities are calculated from the microscopic cross sections used in the history tracking analysis.

This procedure generates capture gammas at every collision point where the absorption probability is nonzero. This can result in the generation of an excessive number (from a computer time viewpoint) of secondary gammas originating from a relatively few primary neutrons.

At the user's option capture gammas can be generated either at every collision where the absorption probability is nonzero or only for those collisions where the absorption probability $\left[1 - P_s(E)\right]$ is greater than a random number. For this second option, the absorption probability is compared with a random number at every collision point. If the probability is less than the random number, no capture gamma is generated. If the probability is greater, a gamma is generated. Its energy is obtained as described previously, but its weight W_γ is given by

$$W_\gamma = W_n n'$$

This procedure, which can be regarded as a form of Russian Roulette, yields a smaller number of secondary gammas and is more economical of computer time.

PREPARATION OF INPUT DATA

CODE DESCRIPTION

The code is written completely in FORTRAN-IV for the IBM 7094 computer. The overlay feature has been used to allow sufficient storage for large problems; variable

dimensioning has been incorporated. The program consists of a main link and five dependent links (see fig. 1). At any given time, the main link and only one of the dependent links are stored in core; the remaining links are stored on the overlay tape.

The main link acts as an executive routine, calling in the other links as required to manipulate data or perform calculations. The first link reads in and prints out input data and cross sections and computes the storage requirements of the problem. The second link calculates primary particle source parameters from spatial, angular, and energy distributions read in by the user. These parameters are written on a tape and used by the particle tracking routines. If secondary gammas or leakage particles are being tracked from a previous problem, then a physical source tape will be available for this run. In this case the second link is bypassed with control proceeding directly from the first link to the third link.

The great majority of computing time is spent in the third link which actually tracks and scores the particles. After the desired number of particles has been followed, control passes to the fourth link which prints out the problem results.

If no secondary gamma source is to be written, the problem terminates at this point; otherwise control proceeds to the fifth link, which generates a secondary gamma source tape. When this link is completed the problem ends.

The last random number is punched out at the end of each run and is available for use in starting a new sequence of random numbers for subsequent problems.

DATA INPUT

The code requires that all input data defining the problem be read in on cards at execution time. A summary of the read order for the data follows:

(1) Read in the problem control parameters.

(2) Read in the additional problem input consisting of atomic weights, atom densities, printout bounds for energy, polar and azimuthal angles, and point detector data.

(3) Read in the input library data. These include libraries 1, 2, and 7 which give the boundary descriptions, region descriptions, and exponential transform instructions, respectively. Also, required is one library 6 for each element, and for neutron problems libraries 9 and 10 are required for those elements where inelastic scatter or anisotropic elastic scatter occurs. For the user's convenience, the library data may be read in any order. For example, library 6 for a given element can be read first, followed by libraries 1, 7, etc., etc.

(4) Read in the primary source generator control parameters.

(5) Read in remainder of primary source generator input.

Items (4) and (5) are not required if an external source tape from a previous run is supplied.

(6) Read in response function data, where desired.

(7) Read in capture gamma input data, for those problems where a secondary gamma source tape is to be generated.

The format for preparing a problem data deck is given in tables I to XII.

Problem control parameters. - The problem control parameters, consisting of fixed and floating point data, are required input for every problem. The fixed point parameters are used in determining the amount of storage required for the problem. The floating point and fixed point parameters are both used as limiting controls on various aspects of the problem during execution. The format for preparing these data are given in table I.

Problem description data. - The atomic weights and atomic densities are required to describe the material of the problem. Also, the energy and angular bin values for the printout of the energy and angular fluxes must be read in. Table II gives the format for preparing these data.

Library 1. - Library 1 contains information describing boundaries for the problem geometry. The formats to be used are given in table III. Library 1 is necessary for every problem.

Library 2. - In library 2 the various regions in the geometry are described by giving the number of boundaries and the sign of each boundary that defines the region, along with the material number and the volume of the region. One library 2 is necessary for every problem. Table IV shows the format to be used in preparing a library 2. The material within any region must be the same for all points within the region.

Usually, the first region described is the source region. Regions may be listed in any order desired, but other arrangements may prove to be more economical. For computer economy the number of regions in the geometry should be kept to a minimum, consistent with accuracy of representation and type of output desired.

Library 6. - A library 6 is required for every element in the problem. This library, for which the input format is given in table V, lists, for arbitrary energy values, the total, scattering (elastic plus in-elastic), and elastic scattering cross sections for neutrons or the total, Compton plus pair production, and Compton scattering cross sections for gamma rays. The energy values must be the same for every element in the problem. The cross sections are listed for the highest energy first and then in descending order to the lowest energy. The library 6's may be loaded behind the problem input data in any order convenient to the user.

TABLE I. - PROBLEM CONTROL PARAMETERS

Card group	Format	Card column	Input item	Description
1	12A6	1 - 72	Title	Any alphanumeric identification in card columns 1 to 72
2	O18	1 - 18	RMN	Starting random number
3	14I5	1 - 5	IDP	Problem ID number (any fixed point number for user's convenience)
		6 - 10	NRG	Particle type: NRG = 0, neutrons; NRG = 1, gammas
		11 - 15	NGPSZ	Number of particles per group (for statistical grouping)
		16 - 20	NEL	Number of elements in problem
		21 - 25	MAT	Number of materials in problem
		26 - 30	NREG	Number of regions in problem
		31 - 35	NBD	Total number of boundaries
		36 - 40	NBDMX	Maximum number of boundaries in any given region
		41 - 45	INLIBR	Number of libraries to be read in (The code compares this number with number of libraries actually supplied and with a number internally calculated to be necessary. If the three numbers are not the same, an error message will be printed out.)
		46 - 50	NGY	Number of energy values in library 6 cross section tables
		51 - 55	NXSEC	Cross-section printout option: NXSEC = 0, does not print out cross sections; NXSEC = 1, prints out cross-section data
		56 - 60	ND	Number of point detectors: ND = 0, does not calculate flux at point detectors; ND = K, calculates flux at K point detectors
		61 - 65	NTLF	Region flux option: NTLF = 0, does not calculate fluxes in regions; NTLF = 1, calculates fluxes in regions (by track length method); NTLF = 2, same as NTLF = 1, but also prints leakage data; NTLF = 3, same as NTLF = 2 but also writes leakage tape
		66 - 70	LTNO	Tape number to be assigned to leakage tape (ignore unless NTLF = 3.)

TABLE I. - Continued. PROBLEM CONTROL PARAMETERS

Card group	Format	Card column	Input item	Description
4	9I5	1 - 5	IEP	Number of output energy bins
		6 - 10	IGP	Number of output polar angle bins
		11 - 15	IPP	Number of output azimuthal angle bins
		16 - 20	NSOR	Region number in which source is located
		21 - 25	ISTAP	Source tape option: ISTAP = 0, source particles are generated internally by primary particle source generator; ISTAP = K, source particle data are available on tape number K
		26 - 30	MAXCOL	Maximum number of collisions per particle allowed (Any particle undergoing a larger number of collisions will have its history terminated.)
		31 - 35	KBIAS	Exponential transform on first flight option: KBIAS = 0, exponential transform applied (as determined by library 7) for all flight paths of the particle; KBIAS = 1, exponential transform applied only for first flight path of particle (No transform applied for succeeding flight paths)
		36 - 40	ISPON	Response function option: ISPON = 0, does not compute response function results; ISPON = K, computes results for ($0 \leq K \leq 8$) response functions entered
		41 - 45	NSEG	Collision tape write option: NSEG = 0, does not write collision parameters on tape; NSEG = 1, writes collision parameters on scratch tape for use in secondary gamma generator
5[a]	6I5	1 - 5	NL9	Number of elements that require library 9 data
		6 - 10	INE9	Maximum number of incident neutron energies in any library 9 for this problem
		11 - 15	IEX	Maximum number of nucleus excitation levels in any library 9 for this problem
		16 - 20	NL10	Number of elements that require library 10 data
		21 - 25	INE10	Maximum number of incident neutron energies in and library 10 data
		26 - 30	IPR	Maximum number of cosines of scattering angles in any library 10 for this problem

[a]Omit card 5 for gamma problems.

TABLE I. - Concluded. PROBLEM CONTROL PARAMETERS

Card group	Format	Card column		Description
6	8E9.4	1 - 9	HIST	Number of particle histories to be tracked
		10 - 18	EMAX	Maximum energy (MeV) for any particle or cross-section table in this problem
		19 - 27	EMIN	Minimum energy (MeV) for this problem; also, cutoff energy for any particle, below which its history will be terminated
		28 - 36	WMIN	Weight cutoff for particle
		37 - 45	ELD	Energy deposition cutoff value (MeV); energy deposited below this value will be assumed to be negligible
		46 - 54	ETM	Thermal energy value (MeV); neutrons below this value scatter isotropically without energy loss (Ignore for gammas.)
		55 - 63	RR	Russian Roulette parameter (Russian Roulette played with particles whose weight is less than WMIN; RR is their chance of surviving.)
		64 - 72	EPSL	Small incremental distance used to move a particle's position off the boundary in geometry calculations
7	2E9.4	1 - 9	CTIME	Cutoff time parameter (The clock is read at the completion of every batch of 100 histories, and the time remaining is computed (Estimated time for problem minus elapsed time.) If the time remaining is greater than CTIME, another batch of 100 histories will be tracked. If not, tracking is abandoned and the output is compiled for those histories already completed. CTIME is a device for obtaining at least partial results when a problem runs longer than the time required to track 100 histories. Except for this, no specific recommendations are given. Try CTIME = 1.0 min for a start.)
		10 - 18	TLCUT	Track length cutoff parameter (If a particle's cumulative number of mean free paths through the geometry exceeds TLCUT, the track length calculation is abandoned for that particle.)

TABLE II. - PROBLEM DESCRIPTION DATA

Card group	Format	Card column	Input item	Description
1	(8E9.4)	1 - 72[a]	ATWT(I) (I = 1, NEL)	Atomic weights of elements (For neutrons, the atomic weights of elements requiring libraries 9 and 10 should be read in first.)
2	(8E9.4)	1 - 72	DN(J, I) (J = 1, MAT) (I = 1, NEL)	Atomic density of element I in material J. All the densities for elements of material 1 are read in first, followed by all the densities for the elements of material 2, etc.
3	(8E9.4)	1 - 72	ESI(J) (J = 1, NEL)	Energy below which elastic scattering of neutrons with element J is assumed to be isotropic in the center-of-mass system (Omit for gammas.)
4	(8E9.4)	1 - 72	EPRINT(K) (K = 1, IEP+1)	Energies bounding the output energy bins (Read-in MeV and, in ascending order, the first energy bound should be EMIN and the remaining values the upper bounds of each of the output energy bins.)
5	(8E9.4)	1 - 72	GPRINT(L) (L = 1, IGP+1)	Angles bounding polar angle output bins (Read-in degrees and in ascending order.)
[b]6	(8E9.4)	1 - 72	PPRINT(L) (L = 1, IPP+1)	Angles bounding the azimuthal angle output bins (Read in degrees and in ascending order.)
[c]7	(8E9.4)	1 - 9 37 - 45	EPC(K)	Cutoff parameter for detector K, in mean free paths
		10 - 18 46 - 54	XD1(K)	Rectangular spatial coordinates for detector K
		19 - 27 55 - 63	YD1(K)	
		28 - 36 64 - 72	ZD1(K)	

[a]1 - 72 implies that data are read according to the format in 8 fields, 9 columns wide, for the entire card.

[b]Omit cards 6 and 7 if ND = 0.

[c]Read order: Two sets of detector parameters per card as follows:
EPC(K), XD1(K), YD1(K), ZD1(K), EPC(K + 1), XD1(K + 1) YD1(K + 1), ZD1(K + 1).

TABLE III. - LIBRARY 1 INPUT DATA FORMAT

Card group	Format	Card column	Input item	Description
1	2I9	1 - 9	LIBT	Library type (LIBT = 1 for library 1)
		10 - 18	I	Number of boundaries describing the geometry (I = NBD)
[a]2	(I9, 7E9.4)	1 - 9	IBT(K)	Boundary type; IBT(K) = 1, general quadratic equation; IBT(K) = 2, spheres, cylinders; IBT(K) = 3, planes perpendicular to the X-axis; IBT(K) = 4, planes perpendicular to the Y-axis; IBT(K) = 5, planes perpendicular to the Z-axis
		10 - 18	AF(K)	Coefficients for boundary K
		19 - 27	BF(K)	
		28 - 36	CF(K)	
		37 - 45	XF(K)	
		46 - 54	YF(K)	
		55 - 63	ZF(K)	
		64 - 72	DF(K)	
[b]2(a)	(I9, 3E9.4)	1 - 9	IBT(K)	Boundary type coefficients for boundary K
		10 - 18	EF(K)	
		19 - 27	FF(K)	
		28 - 36	GF(K)	

[a]One card 2 is required for each boundary.

[b]Card 2(a) is needed only when a type 1 boundary is specified. It immediately follows card 2 for the same boundary.

TABLE IV. - LIBRARY 2 INPUT DATA FORMAT

Card group	Format	Card column	Input item	Description
1	I5	1 - 9	LIBT	Library type (LIBT = 2 for library 2)
		10 - 18	I	Number of regions in problem (I = NREG)
[a]2		1 - 5	NB(J)	Number of boundaries defining region J. (Max. of 10). Negative sign on NB(J) indicates that region J is an outside region
	I4	6 - 9	MATREG(J)	Material number in region J
	E9.4	10 - 18	V(J)	Volume of region J in cm^3 (Enter any nonzero number unless region fluxes are being computed for region J, in which case the correct volume is required.)
	6(I5, I4)	Begin 19 - 23	IBN(J,K)	K^{th} boundary surrounding region J. (K = 1, NB(J)). (Note: Boundary numbers must be given a plus or minus sign that corresponds to the direction index as discussed in section Geometry Method.)
		Begin 24 - 27	MPR(J,K)	Most probable region of entry across the K^{th} boundary from region J

[a]One card 2 is required for each region. The reading order is as follows: (NB(J), MATREG(J), V(J), IBN(J,1), MPR(J,1), IBN(J,2) MPR(J,2). . . IBN(J,K), MPR(J,K)).

TABLE V. - LIBRARY 6 INPUT DATA FORMAT

Card group	Format	Card column	Input item	Description
1	3I9	1 - 9	LIBT	Library type (LIBT = 6)
		10 - 18	I	Number of energy values at which cross sections are read in (I = NGY)
		19 - 27	J	Element number (elements are numbered in same order that their atomic weights are listed)
2	8E9.4	1 - 9	[a]ENERGY(L)	Energy value in MeV
		10 - 18	TM(J, L)	Total microscopic cross section for element J
		19 - 27	SM(J, L)	Microscopic scattering cross section for element J (elastic plus inelastic scattering cross section for neutrons or Compton plus pair-production cross section for gamma rays)
		28 - 36	ESM(J, L)	Microscopic elastic scattering cross section for neutrons or Compton scattering cross section for gammas for element J.
		64 - 72		

[a]Reading Order: (ENERGY(L), TM(J, L), SM(J, L), ESM(J, L), ENERGY(L + 1), TM(J, L + 1), SM(J, L + 1), ESM(J, L + 1)).

The units used for library 6 cross sections must be consistent with the units specified earlier for the atomic density DN(J, I) of element I in material J, since the product of a library 6 cross section and DN must have the units of inverse length. Two consistent sets that satisfy this requirement occur if the library 6 cross section is in square centimeters per gram and DN is in grams per cubic centimeter, or if the library 6 cross section is in barns per atom and DN is in atoms per barn-centimeter.

Library 7. - One library 7 is necessary for each problem. Library 7 describes how the exponential transformation will be applied in each region of the problem and the biasing parameter used to obtain a pseudo cross section which is used in the sampling of path lengths. The input format for preparing a library 7 is shown in table VI.

Library 9. - This library is omitted for gamma-ray problems. For neutron problems, a library 9 is required for every element where inelastic scattering can occur. The library lists the cumulative probability of exciting each energy level for various incident neutron energies. The format for preparing a library 9 is shown in table VII.

Library 10. - A library 10 is required for each element in which neutron elastic scattering is anisotropic in the center-of-mass system. If the energy values ESI(J) for the element J is less than the maximum energy EMAX, a library 10 is required for this element. A library 10 is not required for neutron elastic scattering by hydrogen or for gamma-ray problems.

Library 10 lists the cosines of the center-of-mass scattering angles that divide the integral of the differential elastic scattering cross section over the solid angle into equal parts. The cosines are listed for various incident neutron energies. The format for preparing library 10 data is shown in table VIII.

Primary source control parameters. - The controls are required to generate the source particle parameters for the option specified by the user. The format for preparing these input data is shown in table IX.

Primary source generator input. - The source input requires a set of relative power distributions to completely describe the spatial (rectangular, cylindrical, or spherical) distributions of the source (neutrons or gammas). Distributions giving the fraction of particles in each energy or angular interval are also required to define the energy and angular distributions of the primary source. The format for preparing these data are given in table X.

Response function data. - Table XI gives the input format for the response function data. This table is omitted when ISPON = 0. For ISPON = N ($0 \leq N \leq 8$), N sets of cards are read in. The first card identifies the response function, and the rest the actual data. It should be emphasized that the response function data are entered as averages over the output energy bins.

TABLE VI. - LIBRARY 7 INPUT DATA FORMAT

Card group	Format	Card column	Input item	Definition
1	2I9	1 - 9	LIBT	Library type (LIBT = 7)
		10 - 18	I	Number of regions (I = NREG)
[a]2	(4(I9, E9.4)	1 - 9	NEXT(M)	Exponential transform direction option for region M:
		19 - 27		NEXT(M) = 1, XK = 0 (transform not used)
		37 - 45		NEXT(M) = 2, XK = 1 (transform applied independently of direction)
		55 - 63		NEXT(M) = 3, XK = α } (transform applied to
				NEXT(M) = 4, XK = $-\alpha$ } x or -x component)
				NEXT(M) = 5, XK = β } (transform applied to
				NEXT(M) = 6, XK = $-\beta$ } y or -y component)
				NEXT(M) = 7, XK = γ } (transform applied to
				NEXT(M) = 8, XK = $-\gamma$ } z or -z component)
		10 - 18	EXT(M)	Exponential transform intensity parameter
		28 - 36		for region M ($0 \leq$ EXT(M) < 1.0)
		46 - 54		
		64 - 72		

[a]Reading Order for card 2 is as follows: (NEXT(1), EXT(1), NEXT(2), EXT(2). . . . NEXT(NREG), EXT(NREG).

[b]XK and EXT are used to calculate a pseudo cross section by the following expression: $\overset{*}{\sum_{T}}(E) = \sum_{T}(E)(1 - XKT(M))$.

TABLE VII. - LIBRARY 9 INPUT DATA FORMAT

Card group	Format	Card column	Input item	Description
1	4I9	1 - 9	LIBT	Library type (LIBT = 9)
		10 - 18	NMESH(J)	Number of incident neutron energies entered for element J
		19 - 27	J	Element number (Elements are numbered in same order as atomic weights.)
		28 - 36	NEXP(J)	Number of nuclear levels entered for element J
2	8E9.4	1 - 72	EEK(J,N) (N = 1,NEXP(J))	Excitation levels for element J in MeV (listed in ascending order, first excitation level should be zero)
3	8E9.4	1 - 72	EMESH(J,K) (K = 1,NMESH(J))	Incident neutron energies for element J in MeV (These energies may differ for each element and are listed in decending order.)
4	8E9.4	1 - 72	SEP(J,K,N)	Cumulative probability of incident neutron of energy K exciting energy level N of element J (Cumulative probabilities are entered for every excitation level for the first neutron incident energy, then for every excitation level for the second incident energy and so on.)

TABLE VIII. - LIBRARY 10 INPUT DATA FORMAT

Card group	Format	Card column	Input item	Description
1	4I9	1 - 9	LIBT	Library type (LIBT = 10)
		10 - 18	IPROB(J)	Number of cosines of the scattering angle listed for element J
		19 - 27	J	Element number (elements are numbered in same order as atomic weights.)
		28 - 36	NCROS(J)	Number of neutron incident energies entered for element J
2	(8E9.4)	1 - 72	ESCAT(J, N) (N = 1, NCROS(J))	Incident neutron energies (MeV) (listed in descending order from 1 to NCROS(J) for element J
3	(8E9.4)	1 - 72	DES(J, N, K) (N = 1, NCROS(J)) (K = 1, IPROB(J))	Cosines of the center-of-mass scattering angle for a neutron of incident energy N with element J; IPROB cosine values are entered, in descending order from +1 to -1, for the first incident neutron energy, then another set of IPROB cosine values for the second incident neutron energy, and so on

TABLE IX. - PRIMARY SOURCE CONTROL PARAMETERS

Card group	Format	Card column		Description
1	10I5	1 - 5	IC	Source geometry option: IC = 0, point source IC = 1, rectangular parallelepiped source IC = -1, rectangular parallelepiped source with spatial biasing IC = 2, cylindrical source IC = -2, cylindrical source with spatial biasing IC = 3, spherical source IC = -3, spherical source with spatial biasing
		6 - 10	ID	Source angular distribution option: ID = 1, monodirectional source ID = 2, isotropic angular distribution ID = -2, isotropic angular distribution with polar and azimuthal angular biasing ID = 3, anisotropic angular distribution
		11 - 15	IE	Source energy option: IE = 1, monoenergetic source IE = 2, energy spectrum IE = -2, energy spectrum with energy biasing
		16 - 20	NX	Number of spatial intervals of source in first coordinate direction (Ignore for IC = 0); see table below to determine which is first, second, etc., direction depending upon source geometry
		21 - 25	NY	Number of spatial intervals of source in second coordinate direction (Ignore for IC = 0)
		26 - 30	NZ	Number of spatial intervals of source in third coordinate direction (Ignore for IC = 0)
		31 - 35	NSGY	Number of energy intervals defining source spectrum (Ignore for IE = 1)
		36 - 40	NANP	Number of polar angular intervals used to describe the source angular distribution (used only for ID = -2 or ID = 3)
		41 - 45	NANZ	Number of azimuthal angular intervals used to describe source angular distribution (Used only for ID = -2 or ID = 3)
		46 - 50	ITRAN	Source particle translation option ITRAN = 0, does not translate particle coordinates ITRAN = 1, translates particle coordinates by X_0, Y_0, Z_0 (where X_0, Y_0, Z_0 are entered separately)

Source geometry	Coordinate direction		
	First	Second	Third
Rectangular	x	y	z
Cylindrical	r	θ	z
Spherical	r	θ	φ

TABLE X. - PRIMARY SOURCE GENERATOR INPUT

Card group	Format	Card column	Item	Description
[a]1	7E9.4	1 - 9	E	Energy in MeV of monoenergetic source particle when IE = 1; leave blank if IE ≠ 1
		10 - 18	XO	Source spatial coordinates translation vector. Leave blank if ITRAN = 0
		19 - 27	YO	
		28 - 36	ZO	
		37 - 45	ALPHA	Monodirectional source particle direction cosines when ID = 1; leave blank if ID ≠ 1
		46 - 54	BETA	
		55 - 63	GAMMA	
2	(8E9.4)	1 - 72	X(1, I) (I = 1, NX + 1)	Values of FIRST spatial coordinate of the source
3	(8E9.4)	1 - 72	FX(1, I) (I = 1, NX + 1)	Values of relative power distribution in FIRST spatial coordinate
[b]4	(8E9.4)	1 - 72	FXS(1, I) (I = 1, NX + 1)	Values of relative biased power distribution in FIRST spatial coordinate
5	(8E9.4)	1 - 72	X(2, I) (I = 1, NY + 1)	Values of SECOND spatial coordinate of source
6	(8E9.4)	1 - 72	FX(2, I) (I = 1, NY + 1)	Values of relative power distribution in SECOND spatial coordinate
[b]7	(8E9.4)	1 - 72	FXS(2, I) (I = 1, NY + 1)	Values of relative biased power distribution in SECOND spatial coordinate
8	(8E9.4)	1 - 72	X(3, I) (I = 1, NZ + 1)	Values of THIRD spatial coordinate of source
9	(8E9.4)	1 - 72	FX(3, I) (I = 1, NZ + 1)	Values of relative power distribution in THIRD coordinate
[b]10	(8E9.4)	1 - 72	FXS(3, I) (I = 1, NZ + 1)	Values of relative biased power distribution in THIRD coordinate
[c]11	(8E9.4)	1 - 72	FAP(I) (I = 1, NANP)	Fraction of source particles emitted in I^{th} polar angular interval
[c]12	(8E9.4)	1 - 72	CP(I) (I = 1, NANP + 1)	Cosine values of polar angles bounding angular intervals
[c]13	(8E9.4)	1 - 72	FAZ(I) (I = 1, NANZ)	Fraction of source particles emitted in each azimuthal angular interval
[c]14	(8E9.4)	1 - 72	AZ(I) (I = 1, NANZ + 1)	Azimuthal angle values (in radians) bounding azimuthal angular intervals
[d]15	(8E9.4)	1 - 72	EG(I) (I = 1, NSGY + 1)	Energy values bounding source energy spectrum
[d]16	(8E9.4)	1 - 72	ECP(K) (K = 1, NSGY)	Fraction of source particles emitted in each energy interval
[c]17	(8E9.4)	1 - 72	EBP(K) (K = 1, NSGY)	Biased fraction of source particles emitted in each energy interval

[a]Omit card 1 unless IC = 0, or ID = 1, or IE = 1.
[b]Omit unless IC 0.
[c]Omit cards 11 to 14 unless ID = -2 or ID = 3.
[d]Omit unless IE = 2.
[e]Omit unless IE = -2.

TABLE XI. - RESPONSE FUNCTION INPUT DATA

Card group	Format	Card column	Item	Description
1	(12A6)	1 - 72	RSP(J, I) (I = 1, 12)	Alpha-numeric identification for the J^{th} response function
2	(8E9.4)	1 - 72	RESPFN(J, K) (K = 1, IEP)	Response function data for the J^{th} response at the K^{th} output energy bin

TABLE XII. - CAPTURE GAMMA-RAY SOURCE GENERATOR INPUT

Card group	Format	Card column	Item	Description
1	7I5	1 - 5	NEC	Total number of elements for which gamma rays are born from neutron capture
		6 - 10	MNIC	Maximum number of incident neutron energies in capture energy range for given element
		11 - 15	MNGC	Maximum number of different gamma-ray energies resulting from neutron captures for a given element
		16 - 20	INEL	Problem type: INEL = -1, inelastic gammas only; INEL = 0, capture gammas only; INEL = +1, both inelastic and capture gammas
		21 - 25	IOP	Option on number of capture gammas produced: IOP = 0, capture gammas are picked at random; IOP = 1, each neutron collision produces gamma ray
		26 - 30	IETPE	Tape number for inelastic gamma sources
		31 - 35	ICTPE	Tape number for capture gamma sources
[a]2	(3I9)	1 - 9	J	Element number
		10 - 18	NII	Number of incident neutron energies for element J over capture energy range
		19 - 27	NGG	Number of gamma energies for element J
	(3E9.4)	28 - 36	BLANK	Leave blank
		37 - 45	ELMAX(J)	Maximum neutron energy (MeV) at which captures occur for element J
		46 - 54	ELMIN(J)	Minimum neutron energy (MeV) at which captures occur for element J
[a]3	(8E9.4)	1 - 72	ENC(J, L) (L = 1, NII)	Incident neutron energy values (MeV) for which neutron capture data are given for element J (Loaded in ascending order)
[a]4	(8E9.4)	1 - 72	EGAMC(J,K) (K = 1, NGG)	Gamma energy values (MeV) resulting from neutron capture in element J (ascending order)
[a]5	(8E9.4)	1 - 72	GPC(J, L, K)	Number of gammas, $N_{j,l,k}$, of k^{th} energy released when neutron of incident energy L is captured by element J (Read in all gamma energies for the first incident neutron energy, followed by all gamma energies for the second incident neutron energy, and so on.)

[a]Cards 2 to 5 are read in for each element where capture gammas can occur. Reading order is cards 2, 3, 4, 5 for the first element, cards 2, 3, 4, 5 for the second element, and so on.

Capture gamma-ray source input. - The secondary gamma source generator requires a set of fixed point control parameters to determine the storage required for the secondary gamma problem. A table of secondary gamma production cross sections are also required. The format for preparing these data are shown in table XII.

SUMMARY

A modification and reprogramming of the COHORT general purpose Monte Carlo shielding program has resulted in a code that has the following features:

1. The code can track either neutrons or gammas in any shield geometry that can be described by quadratic surfaces.

2. Complete results from source generation to final output are obtainable in one single computer run for primary neutrons or gammas. For secondary gamma analysis, a source tape containing the secondary gamma source parameters is generated during primary neutron tracking for later re-use.

3. Biasing features include the exponential transform during tracking and the selection of primary source particles with respect to preferred locations, energies, and directions. All biasing is optional.

4. Output is in the form of number fluxes sorted according to energy for volume detectors or number fluxes sorted according to angle and energy for point detectors. Standard deviations on all fluxes are computed. Quantities such as dose rate or heating rates are also obtainable from input response functions.

5. The code is completely written in FORTRAN-IV. Variable dimensioning is employed to make maximum use of computer memory.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, October 22, 1970,
120-27.

APPENDIX - SAMPLE PROBLEM INPUT AND OUTPUT

This section lists the input data and printed output from the code for a sample problem. The sample problem is that of a point isotropic monoenergetic source of 3-MeV gamma rays in an aluminum sphere with a radius of 20 mean free paths. Point detectors are located at 1, 2, and 4 mean free paths. Region averaged fluxes are also computed.

Program storage requirements are first printed out followed by a listing of the problem control parameters. Next is printed a listing of the atomic weights, atom densities, the output energy, polar angle, and azimuthal angle bins, followed by a listing of the point detector coordinates. The sample output is shown under that heading.

The library data are then printed out. Libraries 1 and 2, giving the boundary and region descriptions, respectively, are first printed.

This is followed by a printout of library 7 which describes how the exponential transform is applied in each region. The exponential transform is not applied for the sample problem.

Next is printed a listing of library 6 for each element present. This is followed by tabulations of internally computed probabilities and macroscopic cross sections. This printout may be deleted if desired.

The control parameters for the primary particle source generator are next printed. The energy of the particles generated are listed. Since polar angle biasing is used in starting the photons for the sample problem, the listing gives the polar angle bins and the fractions of the particles assigned to each bin. A statement then follows that a source tape has been generated. The number of particles, total weight of the particles, number of records, and type of particle are listed. Where preferential selection of source particles is used, as for the sample problem, tables showing the distribution of the particle number and weight are then listed. In the sample problem, only polar angle biasing is used and a table of the polar angle bins and the number of particles in each bin is given. The azimuthal angle table shows that no source biasing has been used for the particles azimuthal angle.

This completes the printout of the input data. The next two statements, BEGIN HTA and HTA COMPLETED FOR 31, indicate, respectively, that the tracking routines have been entered and have been successfully completed for the number of particles requested.

The output data are then printed. First is a table listing how many particle histories have been terminated and for what reason.

This is followed by a table giving the total energy deposition in each region in units of MeV per source particle. The energy deposition is broken down into energy deposition

due to particle absorption, scattering, or particle terminations due to minimum weight or energy. In addition, the total number of collisions in each region are also shown. In addition to the energy deposition, the standard deviation and the percent deviation (standard deviation times 100 divided by the value) of the energy deposition are also given. Totals for each region and each process are also computed and listed. The same table is then repeated in units of MeV per cubic centimeter per source particle. This listing is valid only when the correct volume for a region has been entered, as in the case of regions 2, 4, and 6. Regions 2, 4, and 6 are thin spherical shells where region averaged fluxes correspond to those of detector points 1, 2, and 3, respectively.

A listing of the output energy grid and any response functions entered is then given.

Next are printed the region averaged fluxes for each region as a function of the energy bins selected. The flux, standard deviation, and percent deviation are given.

The region averaged fluxes are then multiplied by the response functions present, and a tabulation of the region averaged response functions are then listed.

Flux and response function output for the point detectors are then printed out. The detector number and its spatial coordinates are given. Fluxes at point detectors are sorted according to the energy bins previously read in and are also broken down into uncollided (UFLUX) and scattered flux (SFLUX) components. These are added to give a total flux (TFLUX). Standard deviations and percent deviations are also listed.

A listing of the final random number used completes the problem output. The execution time on the IBM 7094 for 1000 histories of this problem was 2.9 minutes.

Sample Problem Listing

```
POINT ISOTROPIC(BIASED) SOURCE OF 3.0 MEV GAMMAS IN ALUMINUM
    033101574101                                                              RND NO
 20     1    50     1     1     8     7     2     4    25     1     3     1     0  CONTL 1
  8     1     1     1     0    12     0     1     0                                CONTL 2
1.0E+03   3.0       0.2       1.0 E-06    0.0        0.0        0.1        0.001   CONTL 3
0.3      20.0                                                                      CONTL 4
26.93                                                                              ATWT
.0603                                                                              DN
.2        .4        .6        1.         1.5        2.         2.5        2.999   EPRINT 1
 3.                                                                                EPRINT 2
0.0        180.                                                                    GPRINT
0.0        360.                                                                    PPRINT
20.         0.         0.  10.5        20.         0.         0.         21.       DET 1,2
20.       0.        0.        42.                                                  DET 3
      1         7                                                                  LIBR 1
      2 1.          1.         1.                                      100.00    RD 1
      2 1.          1.         1.                                      121.00    RD 2
      2 1.          1.         1.                                      420.25    RD 3
      2 1.          1.         1.                                      452.25    RD 4
      2 1.          1.         1.                                     1722.25    RD 5
      2 1.          1.         1.                                     1806.25    RD 6
      2 1.          1.         1.                                        1.5    +RD 7
      2         8                                                                  LIBR 2
   1   1  1.           1    2                                                      REG 1
   2   1  62.973       2    3    -1    1                                           REG 2
   2   1  1.0          3    4    -2    2                                           REG 3
   2   1 131.947       4    5    -3    3                                           REG 4
   2   1  1.0          5    6    -4    4                                           REG 5
   2   1 263.894       6    7    -5    5                                           REG 6
   2   1  1.0          7    8    -6    6                                           REG 7
  -1   0  1.0         -7    7                                                      REG 8
      6         26          1                                                      LIBR 6
15.         .964      .964      .49      10.        1.024     1.024     .553     6 AL 1
 8.        1.078     1.078      .778      6.        1.231     1.231     .952     6 AL
 5.        1.164     1.164     1.077      4.        1.3875    1.3875   1.247     6 AL 3
 3.        1.5822    1.5822    1.476      2.        1.933     1.933    1.903     6 AL 4
 1.5       2.2376    2.2376    2.23       1.        2.75      2.75     2.75      6 AL
  .8       3.06      3.06      3.05        .6       3.43      3.43     3.43      6 AL 6
  .5       3.76      3.76      3.75        .4       4.13      4.12     4.12      6 AL 7
  .3       4.52      4.6       4.6         .2       5.37      5.29     5.29      6 AL 8
  .15      5.98      5.77      5.77        .1       7.19      5.41     5.41      6 AL 9
  .08      8.33      5.72      5.72        .05     11.1       7.1      7.1       6 AL 10
  .05     14.59      7.29      7.29        .04     22.71      7.51     7.51      6 AL 11
  .03     45.76      7.75      7.76        .02    149.03      8.03     8.03      6 AL 12
  .015   353.18      8.18      8.18        .01   1180.        8.32     8.32      6 AL 13
      7         8                                                                  LIBR 7
      1   0.               1   0.               1   0.               1   0.        EXPTRF 1
      1   0.               1   0.               1   0.               1   0.        EXPTRF 2
  0   -2    1    0    0    0    0   -5    1    0                                   SOURCE
3.                                                                                 E
 .1         .35        .25         .15         .1         .05                      POL FRCT
1.        .9998555 .995196  .965933   .86603    .7071       -1.                    COS THET
1.                                                                                 AZM FRCT
0.         6.28                                                                    AZM ANGL
           GAMMA DOSE RATE   (R/HR PER PHOTON/CM2-SEC)
5.06   -7 1.0526-6 1.5129-5 2.2727-5 2.8095-5 3.5 33-5 4.0815-5 4.335 -5R/HR

*01* UNIT 5, EOF.                                                    REC= 00000 FIL= 00002
```

Sample Problem Output

```
                     POINT ISOTROPIC(BIASED) SOURCE OF 3.0 MEV GAMMAS IN ALUMINUM

      945 = STORAGE REQUIRED FOR PROBLEM EXECUTION
     1243 = STORAGE REQUIRED FOR OUTPUT

                                         PROBLEM CONTROLS
INITIAL RANDOM NO.=033101574101
IDP     PROBLEM ID NO.                                  20      NRG     PARTICLE TYPE 0/1, N/G                        1
NGPSZ   NO. OF PARTICLES/GROUP                          50      NEL     NO. OF ELEMENTS                               1
MAT     NO. OF MATERIALS                                 1      NREG    NO. OF REGIONS                                8
NBD     NO. OF BOUNDARIES                                7      NBDMX   MAX. NO. OF BOUNDARIES/REGION       [illegible]
NLIBR   NO. OF INPUT LIBRARIES                           4      NGY     NO. OF ENERGIES IN LIB. 6                    25
NXSEC   CROSS-SECTION PRINT OPTION 0/1, NO/YES           1      ND      NO. OF POINT DETECTORS
NTLF    REG. FLUXES 0/1/2/3, NO/YES/1+TABLE/2+TAPE       1      LTND    LEAKAGE TAPE NO.                    [illegible]
IEP     NO. OF OUTPUT ENERGY BINS                        8      IGP     NO. OF OUTPUT POLAR ANGLE BINS                1
IPP     NO. OF OUTPUT AZIMUTHAL ANGLE BINS               1      NSOR    NO. OF SOURCE REGION                          1
ISTAP   SOURCE TAPE OPTION 0/K, INTERNAL/TAPE K          0      MAXCOL  MAX. NO. COLLISIONS/PARTICLE                 12
KBIAS   EXPO. TRANS. ON 1ST FLT. 0/1, ALL/1ST ONLY       0      ISPON   NO. OF RESPONSE FUNCTIONS                     1
NSEG    COLLISION TAPE OPTION 0/1, NO/YES                0
HIST    NO. OF HISTORIES                        1.0000E+03      EMAX    MAX. ENERGY VALUE(MEV)              [illegible]
EMIN    MIN./CUTOFF ENERGY(MEV)                 2.0000E-01      WMIN    PARTICLE WT. CUTOFF                 [illegible]
ELD     ENERGY DEPOSITION CUTOFF(MEV)           0.              ETM     THERMAL ENERGY(MEV)                 [illegible]
RR      RUSSIAN ROULETTE PARAMETER              1.0000E-01      EPSL    EPSILON FOR GEOM. CALCS             [illegible]
CTIME   CUTOFF TIME(MIN.)                       3.0000E-01      FLCUT   NO. M.F.P.S FOR REGION FLUX CUTOFF  [illegible]
```

```
ATWT(NEL)
      26.980

DN(MAT,NEL)
  6.0300E-02

ESI(NEL)
  0.

 OUTPUT ENERGY BOUNDS
  2.000E-01   4.000E-01   6.000E-01   1.000E+00   1.500E+00   2.000E+00   2.500E+00   2.999E+00   3.000E+00

 OUTPUT POLAR ANGLE BOUNDS
       0.          180.000

 OUTPUT AZIMUTHAL ANGLE BOUNDS
       0.          360.000

 POINT DETECTOR LOCATIONS
   L      EPS(L)       XDI(L)       YDI(L)       ZDI(L)
   1    2.000E+01     0.           0.           1.050E+01
   2    2.000E+01     0.           0.           2.100E+01
   3    2.000E+01     0.           0.           4.200E+01

 LIBRARY TYPE  1  BOUNDARY DESCRIPTION
   NO.   IBT(J)       AF(J)        BF(J)        CF(J)        XF(J)        YF(J)        ZF(J)        DF(J)
   1         2     1.000E+00    1.000E+00    1.000E+00   -0.          -0.          -0.          1.000E+02
   2         2     1.000E+00    1.000E+00    1.000E+00   -0.          -0.          -0.          1.210E+02
   3         2     1.000E+00    1.000E+00    1.000E+00   -0.          -0.          -0.          4.202E+02
   4         2     1.000E+00    1.000E+00    1.000E+00   -0.          -0.          -0.          4.622E+02
   5         2     1.000E+00    1.000E+00    1.000E+00   -0.          -0.          -0.          1.722E+03
   6         2     1.000E+00    1.000E+00    1.000E+00   -0.          -0.          -0.          1.896E+03
   7         2     1.000E+00    1.000E+00    1.000E+00   -0.          -0.          -0.          1.600E+05

 LIBRARY TYPE  2  REGION DESCRIPTION
       NB    MAT     VOL.       (IBN, MPR .....................)
                                      1            2
1      1     1   1.0000E+00      1    2
2      2     1   6.2973E+01      2    3    -1    1
3      2     1   1.0000E+00      3    4    -2    2
4      2     1   1.3195E+02      4    5    -3    3
5      2     1   1.0000E+00      5    6    -4    4
6      2     1   2.6389E+02      6    7    -5    5
7      2     1   1.0000E+00      7    8    -5    6
8     -1     0   1.0000E+00     -7    7

 LIBRARY TYPE  7  EXPONENTIAL TRANSFORM
REGIONS       1       2       3       4       5       6       7       8
NEXT(J)       1       1       1       1       1       1       1       1
EXT(J)       0.      0.      0.      0.      0.      0.      0.      0.

 LIBRARY TYPE  6  CROSS-SECTIONS

                                        I      ENERGY(I)         TM(J,I)        SM(J,I)        ESM(J,I)

ELEMENT NO.= 1  ATWT(J)=  26.980
                                        1   0.150000E+02   0.964000E+00   0.954000E+00   0.490000E+00
                                        2   0.100000E+02   0.102400E+01   0.102400E+01   0.663 00E+00
                                        3   0.800000E+01   0.107800E+01   0.107800E+01   0.778000E+00
                                        4   0.600000E+01   0.128100E+01   0.128100E+01   0.952000E+00
                                        5   0.500000E+01   0.116400E+01   0.116400E+01   0.107700E+01
                                        6   0.400000E+01   0.138750E+01   0.138750E+01   0.124700E+01
                                        7   0.300000E+01   0.158220E+01   0.158220E+01   0.149600E+01
                                        8   0.200000E+01   0.193300E+01   0.193300E+01   0.190300E+01
                                        9   0.150000E+01   0.223760E+01   0.223750E+01   0.223000E+01
                                       10   0.100000E+01   0.275000E+01   0.275000E+01   0.275000E+01
                                       11   0.800000E+00   0.306000E+01   0.306000E+01   0.306000E+01
                                       12   0.600000E+00   0.348000E+01   0.348000E+01   0.348000E+01
                                       13   0.500000E+00   0.376000E+01   0.376000E+01   0.376000E+01
                                       14   0.400000E+00   0.413000E+01   0.412000E+01   0.412000E+01
                                       15   0.300000E+00   0.462000E+01   0.460000E+01   0.460000E+01
                                       16   0.200000E+00   0.537000E+01   0.529000E+01   0.529000E+01
                                       17   0.150000E+00   0.598000E+01   0.577000E+01   0.577000E+01
                                       18   0.100000E+00   0.719000E+01   0.641000E+01   0.641000E+01
                                       19   0.800000E-01   0.833000E+01   0.672000E+01   0.672000E+01
                                       20   0.600000E-01   0.111000E+02   0.710000E+01   0.710000E+01
                                       21   0.500000E-01   0.145900E+02   0.729000E+01   0.729000E+01
                                       22   0.400000E-01   0.227100E+02   0.751000E+01   0.751000E+01
                                       23   0.300000E-01   0.457600E+02   0.776000E+01   0.776000E+01
                                       24   0.200000E-01   0.149000E+03   0.803000E+01   0.803000E+01
                                       25   0.150000E-01   0.353180E+03   0.818000E+01   0.818000E+01
                                       26   0.100000E-01   0.118000E+04   0.832000E+01   0.832000E+01
```

COLLISION PROBABILITY TABLES

ENERGY(NGY), NGY= 26

1.5000E+01	1.0000E+01	3.0000E+00	6.0000E+00	5.0000E+00	4.0000E+00	3.0000E+00	2.0000E+00	1.5000E+00	1.0000E+00
8.0000E-01	5.0000E-01	5.0000E-01	4.0000E-01	3.0000E-01	2.0000E-01	1.5000E-01	1.0000E-01	8.0000E-02	6.0000E-02
5.0000E-02	4.0000E-02	3.0000E-02	2.0000E-02	1.5000E-02	1.0000E-02				

COMPTON/ELASTIC SCATTER PROBABILITIES FOR ELEMENT 1

0.508299	0.647461	0.721707	0.743159	0.925258	0.898574	0.945519	0.984480	0.996503	1.000000
1.000000	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000
1.000000	1.000000	1.000000	1.000000	1.000000	1.000000				

TOTAL MACROSCOPIC CROSS SECTIONS FOR MATL 1

0.05813	0.06175	0.06500	0.07724	0.07019	0.08357	0.09541	0.11556	0.13493	0.16382
0.18452	0.20984	0.22673	0.24904	0.27859	0.32381	0.36059	0.43356	0.50230	0.66933
0.87978	1.36941	2.81963	8.98651	21.29575	71.15400				

PRIMARY SOURCE GENERATOR CONTROLS

IG	SOURCE GEOM. 0/1/2/3, PT./RECT./CYL./SPH.	0	ID	SOURCE ANG. DISTRIB. 1/2/3 ,MONO/ISO/ANISO	-2
IE	SOURCE ENERGY DISTRIB. 1/2 ,MONO/SPECT	1	NX	NO. OF SPATIAL INTERVALS IN 1ST DIR.	0
NY	NO. OF SPATIAL INTERVALS IN 2ND DIR.	0	NZ	NO. OF SPATIAL INTERVALS IN 3RD DIR.	0
NSGY	NO. OF ENERGY BINS IN SOURCE SPECTRUM	0	NANP	NO. OF POLAR ANGLE BINS IN SOURCE DIST.	-6
NANZ	NO. OF AZIMUTHAL ANG. BINS IN SOURCE DIST.	1	ITRAN	SOURCE COORD. TRANSLATION 0/1 ,NO/YES	0

ENERGY OF MONOENERGETIC SOURCE 3.0000E+00MEV

SOURCE FRACTION IN EACH POLAR INTERVAL
1.0000E-01 3.5000E-01 2.5000E-01 1.5000E-01 1.0000E-01 5.0000E-02

COSINES OF ANGULAR INTERVALS
1.0000E+00 9.9986E-01 9.962DE-01 9.6593E-01 8.6603E-01 7.0710E-01 -1.0000E+00

SOURCE FRACTION IN EACH AZIMUTHAL INTERVAL
1.0000E+00

AZIMUTHAL ANGLES
0. 6.2800E+00

SOURCE PARTICLE PARAMETERS HAVE BEEN GENERATED AND WRITTEN ON SCRATCH TAPE NO. 2.
THIS TAPE CONTAINS -
1.000000E+03 = NUMBER OF SOURCE PARTICLES
9.994880E+02 = THE TOTAL WEIGHT OF THE SOURCE PARTICLES
11 = NUMBER OF LOGICAL RECORDS (MAX. OF 100PARTICLES PER RECORD)
100 = NUMBER OF PARTICLES IN LAST RECORD
1 = TYPE OF SOURCE PARTICLE/ 0=NEUTRONS/ 1=GAMMAS/

POLAR ANGLE AND WEIGHT DISTRIBUTION FOR A BIASED ISOTROPIC SOURCE

INTERVAL NO.	COSINE THETA	NO. OF PARTICLES	ANGULAR WEIGHT
1	1.0000 - 0.9999	100	7.224328E-02
2	0.9999 - 0.9962	350	1.829749E+00
3	0.9962 - 0.9659	250	1.513148E+01
4	0.9659 - 0.8660	150	4.995148E+01
5	0.8660 - 0.7071	100	7.946496E+01
6	0.7071 - -1.0000	50	8.535500E+02
	TOTALS	1000	9.999999E+02

AZIMUTHAL ANGLE AND WEIGHT DISTRIBUTION FOR A BIASED ISOTROPIC SOURCE

INTERVAL NO.	ANGLE LIMITS(RADIANS)	NO. OF PARTICLES	ANGULAR WEIGHT
1	0. - 6.2800	1000	9.994880E+02
	TOTALS	1000	9.994880E+02

BEGIN HTA

PARTICLE HISTORY TERMINATIONS

NUMBER OF PARTICLES	REASONS FOR TERMINATIONS
0.	NUMBER OF COLLISIONS = 12, THE MAXIMUM ALLOWED
1.000000E+03	THE SCATTERED ENERGY IS LESS THAN 2.0000E-01 MEV, THE MINIMUM ALLOWED
0.	THE WEIGHT IS LESS THAN 1.0000E-06, THE MINIMUM ALLOWED
0.	ESCAPES FROM SOURCE REGION UNCOLLIDED
0.	ESCAPES FROM SOURCE REGION AFTER ONE OR MORE COLLISIONS
0.	ESCAPES FROM SHIELD GEOMETRY
1.000000E+03	THE NUMBER OF HISTORIES ACTUALLY PROCESSED IN THIS PROBLEM WITHIN THE CUT-OFF TIME LIMIT
4.331000E+03	THE NUMBER OF EXPONENTIAL CUT-OFFS IN TRACK LENGTH ANALYSIS
4.331000E+03	TOTAL NUMBER OF COLLISIONS

TOTAL ENERGY DEPOSITION BY REGION IN UNITS OF (MEV/SOURCE PARTICLE)

PROCESS	REGION NUMBER 1 ENERGY	STD DEV	PC DEV	2 ENERGY	STD DEV	PC DEV	3 ENERGY	STD DEV	PC DEV
NO. COLS.		1497			151			1254	
ABSORPTION	1.025E-03	2.291E-04	2.234E+01	8.658E-05	3.458E-05	3.989E+01	1.331E-03	2.531E-04	1.977E+01
SCATTERING	1.465E+00	1.944E-01	1.327E+01	2.707E-02	9.128E-03	3.371E+01	8.115E-01	1.732E-01	2.135E+01
MIN WT+ENGY	4.933E-02	1.008E-02	2.043E+01	6.379E-03	4.051E-03	6.351E+01	5.677E-02	1.327E-02	2.337E+01
TOTALS	1.515E+00	2.002E-01	1.321E+01	3.354E-02	1.309E-02	3.902E+01	8.695E-01	1.849E-01	2.127E+01

PROCESS	REGION NUMBER 4 ENERGY	STD DEV	PC DEV	5 ENERGY	STD DEV	PC DEV	6 ENERGY	STD DEV	PC DEV
NO. COLS.		87			1030			31	
ABSORPTION	1.544E-04	9.377E-05	6.071E+01	1.235E-03	3.093E-04	2.505E+01	5.044E-06	2.057E-06	4.077E+01
SCATTERING	3.079E-02	1.637E-02	5.318E+01	4.451E-01	1.420E-01	3.191E+01	1.256E-03	5.198E-04	4.137E+01
MIN WT+ENGY	5.933E-03	3.758E-03	6.334E+01	5.207E-02	1.441E-02	2.768E+01	2.825E-04	1.312E-04	4.642E+01
TOTALS	3.588E-02	1.720E-02	4.665E+01	4.984E-01	1.535E-01	3.083E+01	1.544E-03	5.834E-04	3.778E+01

PROCESS	REGION NUMBER 7 ENERGY	STD DEV	PC DEV	8 ENERGY	STD DEV	PC DEV	TOTALS ENERGY	STD DEV	PC DEV
NO. COLS.		261			0				
ABSORPTION	7.332E-05	4.259E-05	5.809E+01	0.	0.	0.	3.910E-03	5.897E-04	1.508E+01
SCATTERING	4.165E-02	2.310E-02	5.546E+01	0.	0.	0.	2.822E+00	3.167E-01	1.122E+01
MIN WT+ENGY	1.837E-03	4.274E-04	2.325E+01	0.	0.	0.	1.726E-01	2.207E-02	1.279E+01
TOTALS	4.356E-02	2.309E-02	5.301E+01	0.	0.	0.	2.998E+00	3.175E-01	1.059E+01

TOTAL ENERGY DEPOSITION BY REGION IN UNITS OF (MEV/CM**3/SOURCE PARTICLE)

PROCESS	REGION NUMBER 1 ENERGY	STD DEV	PC DEV	2 ENERGY	STD DEV	PC DEV	3 ENERGY	STD DEV	PC DEV
NO. COLS.		1497			151			1254	
ABSORPTION	1.025E-03	2.291E-04	2.234E+01	1.376E-05	5.491E-07	3.989E+01	1.331E-03	2.531E-04	1.977E+01
SCATTERING	1.465E+00	1.944E-01	1.327E+01	4.299E-04	1.450E-04	3.371E+01	8.115E-01	1.732E-01	2.135E+01
MIN WT+ENGY	4.933E-02	1.008E-02	2.043E+01	1.013E-04	6.433E-05	6.351E+01	5.677E-02	1.327E-02	2.337E+01
TOTALS	1.515E+00	2.002E-01	1.321E+01	5.326E-04	2.078E-04	3.902E+01	8.695E-01	1.849E-01	2.127E+01

PROCESS	REGION NUMBER 4 ENERGY	STD DEV	PC DEV	5 ENERGY	STD DEV	PC DEV	6 ENERGY	STD DEV	PC DEV
NO. COLS.		87			1030			31	
ABSORPTION	1.170E-06	7.106E-07	6.071E+01	1.235E-03	3.093E-04	2.505E+01	1.911E-08	7.793E-09	4.077E+01
SCATTERING	2.333E-04	1.241E-04	5.318E+01	4.451E-01	1.420E-01	3.191E+01	4.761E-06	1.970E-06	4.137E+01

MIN WT+ENGY	4.496E-05	2.848E-05	6.334E+01	5.207E-02	1.441E-02	2.758E+01	1.071E-06	4.971E-07	4.642E+01
TOTALS	2.795E-04	1.304E-04	4.665E+01	4.984E-01	1.535E-01	3.083E+01	5.851E-06	2.211E-06	3.778E+01

PROCESS	REGION NUMBER 7			8			TOTALS		
	ENERGY	STD DEV	PC DEV	ENERGY	STD DEV	PC DEV	ENERGY	STD DEV	PC DEV
NO. COLS.		261			0				
ABSORPTION	7.332E-05	4.259E-05	5.809E+01	0.	0.	0.	3.656E-03	5.897E-04	1.508E+01
SCATTERING	4.165E-02	2.310E-02	5.545E+01	0.	0.	0.	2.754E+00	3.167E-01	1.122E+01
MIN WT+ENGY	1.837E-03	4.274E-04	2.325E+01	0.	0.	0.	1.632E-01	2.207E-02	1.279E+01
TOTALS	4.356E-02	2.309E-02	5.301E+01	0.	0.	0.	2.927E+00	3.175E-01	1.069E+01

RESPONSE FUNCTION INPUT

OUTPUT ENERGY BOUNDS
2.0000E-01 4.0000E-01 5.0000E-01 1.0000E+00 1.5000E+00 2.0000E+00 2.5000E+00 2.9990E+00 3.0000E+00

GAMMA DOSE RATE (R/HR PER PHOTON/CM2-SEC)
5.060E-07 1.053E-06 1.613E-06 2.273E-06 2.899E-06 3.509E-06 4.082E-06 4.336E-06

FLUXES VERSUS REGION AND ENERGY
LOWER ENERGY = 2.000E-01 MEV

UPPER ENEGY BDS(MEV)	REGION NUMBER 1 FLUX	STD DEV	PC DEV	2 FLUX	STD DEV	PC DEV	3 FLUX	STD DEV	PC DEV
4.000E-01	1.551E+00	3.465E-01	2.234E+01	2.613E-03	1.082E-03	4.140E+01	1.979E+00	4.459E-01	2.254E+01
6.000E-01	1.096E+00	2.764E-01	2.522E+01	2.340E-03	1.003E-03	4.288E+01	1.191E+00	2.537E-01	2.214E+01
1.000E+00	4.544E-01	1.906E-01	4.195E+01	9.111E-04	4.290E-04	4.709E+01	7.042E-01	2.631E-01	3.735E+01
1.500E+00	4.018E-01	1.771E-01	4.408E+01	1.439E-03	5.921E-04	4.815E+01	7.087E-01	3.554E-01	5.015E+01
2.000E+00	1.872E-01	9.779E-02	5.225E+01	3.451E-04	1.718E-04	4.980E+01	2.696E-01	1.072E-01	3.975E+01
2.500E+00	5.512E-01	2.309E-01	4.189E+01	9.121E-04	4.109E-04	4.504E+01	3.948E-01	1.455E-01	3.685E+01
2.999E+00	2.516E-01	1.489E-01	5.920E+01	8.036E-04	5.944E-04	7.396E+01	3.094E-01	2.191E-01	7.084E+01
3.000E+00	5.441E+00	7.265E-01	1.128E+01	5.830E-03	6.575E-04	1.128E+01	2.196E+00	2.465E-01	1.128E+01
TOTALS	1.093E+01	1.295E+00	1.184E+01	1.519E-02	2.540E-03	1.738E+01	7.742E+00	1.286E+0	1.661E+01

UPPER ENEGY BDS(MEV)	REGION NUMBER 4 FLUX	STD DEV	PC DEV	5 FLUX	STD DEV	PC DEV	6 FLUX	STD DEV	PC DEV
4.000E-01	1.001E-03	3.481E-04	3.478E+01	1.883E+00	5.209E-01	2.766E+01	1.254E-04	9.950E-05	7.869E+01
6.000E-01	6.284E-04	1.813E-04	2.885E+01	1.058E+00	2.595E-01	2.547E+01	2.698E-05	9.012E-06	3.340E+01
1.000E+00	2.984E-04	1.303E-04	4.365E+01	3.936E-01	1.327E-01	3.372E+01	1.941E-05	6.572E-06	3.386E+01
1.500E+00	3.338E-04	1.386E-04	4.153E+01	2.743E-01	9.505E-02	3.502E+01	1.310E-05	3.452E-06	2.634E+01
2.000E+00	1.912E-04	9.395E-05	4.914E+01	3.993E-01	1.594E-01	3.991E+01	3.024E-05	1.249E-05	4.130E+01
2.500E+00	2.175E-04	8.838E-05	4.064E+01	4.885E-01	2.338E-01	4.785E+01	3.409E-05	1.777E-05	5.215E+01
2.999E+00	1.471E-04	9.946E-05	6.760E+01	1.743E-01	1.080E-01	6.198E+01	1.025E-05	6.168E-06	6.016E+01
3.000E+00	1.022E-03	1.153E-04	1.128E+01	1.147E+00	1.294E-01	1.128E+01	5.893E-05	7.771E-06	1.128E+01
TOTALS	3.839E-03	6.165E-04	1.605E+01	5.818E+00	1.238E+00	2.128E+01	3.294E-04	1.102E-04	3.344E+01

UPPER ENEGY BDS(MEV)	REGION NUMBER 7 FLUX	STD DEV	PC DEV	8 FLUX	STD DEV	PC DEV
4.000E-01	1.374E-01	1.284E-01	9.347E+01	0.	0.	0.
6.000E-01	1.701E-03	1.701E-03	1.000E+02	0.	0.	0.
1.000E+00	0.	0.	0.	0.	0.	0.
1.500E+00	0.	0.	0.	0.	0.	0.
2.000E+00	0.	0.	0.	0.	0.	0.
2.500E+00	0.	0.	0.	0.	0.	0.
2.999E+00	0.	0.	0.	0.	0.	0.
3.000E+00	0.	0.	0.	0.	0.	0.
TOTALS	1.391E-01	1.284E-01	9.228E+01	0.	0.	0.

GAMMA DOSE RATE (R/HR PER PHOTON/CM2-SEC)
LOWER ENERGY = 2.000E-01

REGION NUMBER

UPPER ENEGY BDS(MEV)	1 FLUX	STD DEV	PC DEV	2 FLUX	STD DEV	PC DEV	3 FLUX	STD DEV	PC DEV
4.000E-01	9.397E-07	2.100E-07	2.234E+01	1.584E-09	6.555E-10	4.140E+01	1.199E-06	2.702E-07	2.254E+01
6.000E-01	1.154E-06	2.909E-07	2.522E+01	2.463E-09	1.055E-09	4.288E+01	1.254E-06	2.776E-07	2.214E+01
1.000E+00	7.329E-07	3.075E-07	4.195E+01	1.470E-09	6.920E-10	4.709E+01	1.136E-06	4.243E-07	3.735E+01
1.500E+00	9.132E-07	4.025E-07	4.408E+01	3.270E-09	1.573E-09	4.810E+01	1.511E-06	8.078E-07	5.345E+01
2.000E+00	5.425E-07	2.835E-07	5.225E+01	1.000E-09	4.981E-10	4.980E+01	7.815E-07	3.106E-07	3.975E+01
2.500E+00	1.934E-06	8.101E-07	4.189E+01	3.200E-09	1.442E-09	4.504E+01	1.385E-06	5.105E-07	3.685E+01
2.999E+00	1.027E-06	6.078E-07	5.920E+01	3.280E-09	2.426E-09	7.396E+01	1.253E-06	8.945E-07	7.084E+01
3.000E+00	2.825E-05	3.187E-06	1.128E+01	2.557E-08	2.884E-09	1.128E+01	9.587E-06	1.081E-06	1.128E+01
TOTALS	3.549E-05	4.202E-06	1.184E+01	4.184E-08	7.270E-09	1.738E+01	1.822E-05	3.027E-06	1.661E+01

REGION NUMBER

UPPER ENEGY BDS(MEV)	4 FLUX	STD DEV	PC DEV	5 FLUX	STD DEV	PC DEV	6 FLUX	STD DEV	PC DEV
4.000E-01	6.064E-10	2.109E-10	3.478E+01	1.141E-06	3.157E-07	2.766E+01	7.662E-11	5.030E-11	7.869E+01
6.000E-01	6.614E-10	1.908E-10	2.885E+01	1.114E-06	2.835E-07	2.547E+01	2.840E-11	9.486E-12	3.340E+01
1.000E+00	4.812E-10	2.101E-10	4.366E+01	6.348E-07	2.140E-07	3.372E+01	3.131E-11	1.060E-11	3.385E+01
1.500E+00	7.587E-10	3.149E-10	4.150E+01	6.233E-07	2.183E-07	3.502E+01	2.978E-11	7.345E-12	2.634E+01
2.000E+00	5.542E-10	2.723E-10	4.914E+01	1.157E-06	4.519E-07	3.991E+01	8.766E-11	3.620E-11	4.130E+01
2.500E+00	7.631E-10	3.101E-10	4.064E+01	1.714E-06	8.202E-07	4.785E+01	1.196E-10	6.237E-11	5.215E+01
2.999E+00	6.006E-10	4.060E-10	6.760E+01	7.115E-07	4.410E-07	6.198E+01	4.185E-11	2.517E-11	6.016E+01
3.000E+00	4.482E-09	5.055E-10	1.128E+01	5.031E-06	5.674E-07	1.128E+01	3.922E-10	3.408E-11	1.128E+01
TOTALS	8.907E-09	1.430E-09	1.605E+01	1.213E-05	2.580E-06	2.128E+01	7.174E-10	2.399E-10	3.344E+01

REGION NUMBER

UPPER ENEGY BDS(MEV)	7 FLUX	STD DEV	PC DEV	8 FLUX	STD DEV	PC DEV
4.000E-01	8.328E-08	7.784E-08	9.347E+01	0.	0.	0.
6.000E-01	1.790E-09	1.790E-09	1.000E+02	0.	0.	0.
1.000E+00	0.	0.	0.	0.	0.	0.
1.500E+00	0.	0.	0.	0.	0.	0.
2.000E+00	0.	0.	0.	0.	0.	0.
2.500E+00	0.	0.	0.	0.	0.	0.
2.999E+00	0.	0.	0.	0.	0.	0.
3.000E+00	0.	0.	0.	0.	0.	0.
TOTALS	8.507E-08	7.850E-08	9.228E+01	0.	0.	0.

DETECTOR NUMBER 1
COORDINATES X = 0. Y = 0. Z = 1.0500E+01 LOWER ENERGY = 2.000E-01 MEV

UPPER ENEGY BDS(MEV)	UFLUX	STD DEV	PC DEV	SFLUX	STD DEV	PC DEV	TFLUX	STD DEV	PC DEV
4.000E-01	0.	0.	0.	6.967E-05	1.283E-05	1.842E+01	6.967E-05	1.283E-05	1.842E+01
6.000E-01	0.	0.	0.	7.742E-05	2.188E-05	2.827E+01	7.742E-05	2.188E-05	2.827E+01
1.000E+00	0.	0.	0.	3.796E-05	6.869E-06	1.810E+01	3.796E-05	6.869E-06	1.810E+01
1.500E+00	0.	0.	0.	3.476E-05	5.353E-06	1.540E+01	3.476E-05	5.353E-06	1.540E+01
2.000E+00	0.	0.	0.	3.028E-05	2.972E-06	9.815E+00	3.028E-05	2.972E-06	9.815E+00
2.500E+00	0.	0.	0.	3.438E-05	5.629E-06	1.637E+01	3.438E-05	5.629E-06	1.637E+01
2.999E+00	0.	0.	0.	2.935E-05	3.306E-06	1.126E+01	2.935E-05	3.306E-06	1.126E+01
3.000E+00	2.649E-04	2.988E-05	1.128E+01	3.445E-08	1.398E-08	3.186E+01	2.650E-04	2.988E-05	1.128E+01
TOTALS	2.649E-04	2.988E-05	1.128E+01	3.139E-04	2.547E-05	8.435E+00	5.788E-04	3.992E-05	6.898E+00

GAMMA DOSE RATE (R/HR PER PHOTON/CM2-SEC)

UPPER ENEGY BDS(MEV)		STD DEV	PC DEV		STD DEV	PC DEV		STD DEV	PC DEV
4.000E-01	0.	0.	0.	4.222E-11	7.777E-12	1.842E+01	4.222E-11	7.777E-12	1.842E+01
6.000E-01	0.	0.	0.	8.149E-11	2.303E-11	2.827E+01	8.149E-11	2.303E-11	2.827E+01
1.000E+00	0.	0.	0.	6.122E-11	1.108E-11	1.810E+01	6.122E-11	1.108E-11	1.810E+01
1.500E+00	0.	0.	0.	7.901E-11	1.217E-11	1.540E+01	7.901E-11	1.217E-11	1.540E+01
2.000E+00	0.	0.	0.	8.777E-11	8.614E-12	9.815E+00	8.777E-11	8.614E-12	9.815E+00
2.500E+00	0.	0.	0.	1.206E-10	1.975E-11	1.637E+01	1.206E-10	1.975E-11	1.637E+01
2.999E+00	0.	0.	0.	1.198E-10	1.350E-11	1.126E+01	1.198E-10	1.350E-11	1.126E+01
3.000E+00	1.162E-09	1.311E-10	1.128E+01	1.511E-13	4.815E-14	3.185E+01	1.162E-09	1.311E-10	1.128E+01
TOTALS	1.162E-09	1.311E-10	1.128E+01	5.923E-10	4.996E-11	8.435E+00	1.754E-09	1.210E-10	6.898E+00

DETECTOR NUMBER 2
COORDINATES X = 0. Y = 0. Z = 2.10000E+01 LOWER ENERGY = 2.000E-01 MEV

UPPER ENEGY BDS(MEV)	UFLUX	STD DEV	PC DEV	SFLUX	STD DEV	PC DEV	TFLUX	STD DEV	PC DEV
4.000E-01	0.	0.	0.	1.478E-05	3.758E-06	2.542E+01	1.478E-05	3.758E-06	2.542E+01
6.000E-01	0.	0.	0.	5.700E-06	1.069E-06	1.875E+01	5.700E-06	1.069E-06	1.875E+01
1.000E+00	0.	0.	0.	1.572E-05	8.154E-06	5.187E+01	1.572E-05	8.154E-06	5.187E+01
1.500E+00	0.	0.	0.	4.839E-06	8.416E-07	1.739E+01	4.839E-06	8.416E-07	1.739E+01
2.000E+00	0.	0.	0.	6.283E-06	1.944E-06	3.095E+01	6.283E-06	1.944E-06	3.095E+01
2.500E+00	0.	0.	0.	5.497E-06	7.808E-07	1.421E+01	5.497E-06	7.808E-07	1.421E+01
2.999E+00	0.	0.	0.	5.868E-06	6.354E-07	1.083E+01	5.868E-06	6.354E-07	1.083E+01
3.000E+00	2.432E-05	2.743E-06	1.128E+01	6.193E-09	1.903E-09	3.073E+01	2.433E-05	2.743E-06	1.128E+01
TOTALS	2.432E-05	2.743E-06	1.128E+01	5.870E-05	1.010E-05	1.721E+01	8.302E-05	1.047E-05	1.261E+01

GAMMA DOSE RATE (R/HR PER PHOTON/CM2-SEC)

UPPER ENEGY BDS(MEV)		STD DEV	PC DEV		STD DEV	PC DEV		STD DEV	PC DEV
4.000E-01	0.	0.	0.	8.959E-12	2.278E-12	2.542E+01	8.959E-12	2.278E-12	2.542E+01
6.000E-01	0.	0.	0.	6.000E-12	1.125E-12	1.875E+01	6.000E-12	1.125E-12	1.875E+01
1.000E+00	0.	0.	0.	2.535E-11	1.315E-11	5.187E+01	2.535E-11	1.315E-11	5.187E+01
1.500E+00	0.	0.	0.	1.100E-11	1.913E-12	1.739E+01	1.100E-11	1.913E-12	1.739E+01
2.000E+00	0.	0.	0.	1.821E-11	5.636E-12	3.095E+01	1.821E-11	5.636E-12	3.095E+01
2.500E+00	0.	0.	0.	1.929E-11	2.740E-12	1.421E+01	1.929E-11	2.740E-12	1.421E+01
2.999E+00	0.	0.	0.	2.395E-11	2.593E-12	1.083E+01	2.395E-11	2.593E-12	1.083E+01
3.000E+00	1.067E-10	1.203E-11	1.128E+01	2.716E-14	8.347E-15	3.073E+01	1.067E-10	1.203E-11	1.128E+01
TOTALS	1.067E-10	1.203E-11	1.128E+01	1.128E-10	1.941E-11	1.721E+01	2.195E-10	2.757E-11	1.261E+01

DETECTOR NUMBER 3
COORDINATES X = 0. Y = 0. Z = 4.2000DE+01 LOWER ENERGY = 2.000F-01 MEV

UPPER ENEGY BDS(MEV)	JFLUX	STD DEV	PC DEV	SFLUX	STD DEV	PC DEV	TFLUX	STD DEV	PC DEV
4.000E-01	0.	0.	0.	1.978E-06	1.577E-06	7.972E+01	1.978E-06	1.577E-06	7.972E+01
6.000E-01	0.	0.	0.	2.391E-07	9.935E-08	4.155E+01	2.391E-07	9.93 -08	4.156E+01
1.000E+00	0.	0.	0.	4.788E-07	1.573E-07	3.284E+01	4.788E-07	1.573 -07	3.284E+01
1.500E+00	0.	0.	0.	2.147E-07	3.952E-08	1.841E+01	2.147E-07	3.95 E-08	1.841E+01
2.000E+00	0.	0.	0.	1.808E-07	3.844E-08	2.127E+01	1.808E-07	3.84 E-08	2.127E+01
2.500E+00	0.	0.	0.	5.772E-07	2.322E-07	4.023E+01	5.772E-07	2.322E-07	4.023E+01
2.999E+00	0.	0.	0.	4.458E-07	1.352E-07	3.055E+01	4.458E-07	1.36 E-07	3.055E+01
3.000E+00	8.200E-07	9.249E-08	1.128E+01	5.873E-10	3.410E-10	4.961E+01	8.207E-07	9.249E-08	1.127E+01
TOTALS	8.200E-07	9.249E-08	1.128E+01	4.115E-06	1.555E-06	3.782E+01	4.935E-06	1.559 -06	3.159E+01

GAMMA DOSE RATE (R/HR PER PHOTON/CM2-SEC)

UPPER ENEGY BDS(MEV)		STD DEV	PC DEV		STD DEV	PC DEV		STD DEV	PC DEV
4.000E-01	0.	0.	0.	1.199E-12	9.556E-13	7.972E+01	1.199E-12	9.556E-13	7.972E+01
6.000E-01	0.	0.	0.	2.515E-13	1.045E-13	4.155E+01	2.516E-13	1.046E-13	4.156E+01
1.000E+00	0.	0.	0.	7.722E-13	2.536E-13	3.284E+01	7.722E-13	2.536E-13	3.284E+01
1.500E+00	0.	0.	0.	4.879E-13	8.982E-14	1.841E+01	4.879E-13	8.982E-14	1.841E+01
2.000E+00	0.	0.	0.	5.239E-13	1.114E-13	2.127E+01	5.239E-13	1.114E-13	2.127E+01
2.500E+00	0.	0.	0.	2.025E-12	8.149E-13	4.023E+01	2.025E-12	8.149E-13	4.023E+01
2.999E+00	0.	0.	0.	1.820E-12	5.550E-13	3.055E+01	1.820E-12	5.56 E-13	3.055E+01
3.000E+00	3.597E-12	4.057E-13	1.128E+01	3.014E-15	1.495E-15	4.961E+01	3.600E-12	4.057E-13	1.127E+01
TOTALS	3.597E-12	4.057E-13	1.128E+01	7.082E-12	2.579E-12	3.782E+01	1.068E-11	3.374E-12	3.159E+01

END OF PROBLEM 20

FINAL RANDOM NUMBER
056055355315

01 EXIT IN EXECT

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1. Collins, D. G.; and DeVries, T. W.: Monte Carlo Calculations of Energy Deposition and Radiation Transport. Vol. I - Validation of COHORT Codes; Vol. II - Utilization of COHORT Codes. Rep. FZK-176-1 and 2, General Dynamics/Fort Worth, Dec. 21, 1963.

2. Collins, D. G.; and Wells, M. B.: COHORT - A Monte Carlo Program for Calculation of Radiation Heating Transport. Rep. RRA-T62, Vols. I to IV, Radiation Research Assoc., Sept. 1966.

3. Byrn, N. R.: CAVEAT, A Revised Version of the General Purpose Monte Carlo Program, COHORT. Rep. SE-290, Vols. I and II, Brown Eng. Co., Inc., Oct. 1969 (Rev. 1970).

4. Malenfant, Richard E.: QAD: A series of Point-Kernel General-Purpose Shielding Programs. Rep. LA-3573, Los Alamos Scientific Lab., Oct. 1966.

5. Kahn, Herman: Application of Monte Carlo. Rep. RM-1237-AEC, Rand Corp., Apr. 27, 1956.

6. Spielberg, D.: ATHENA - A system of Fortran Programs for Radiation Transport and Heating Calculations in Complex Reactor Geometries. Rep. UNC-5148, United Nuclear Corp. (NASA CR-54905), Mar. 1966.

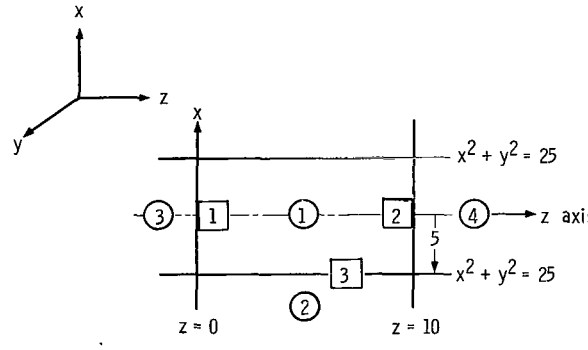

Figure 1. - Geometry illustration.

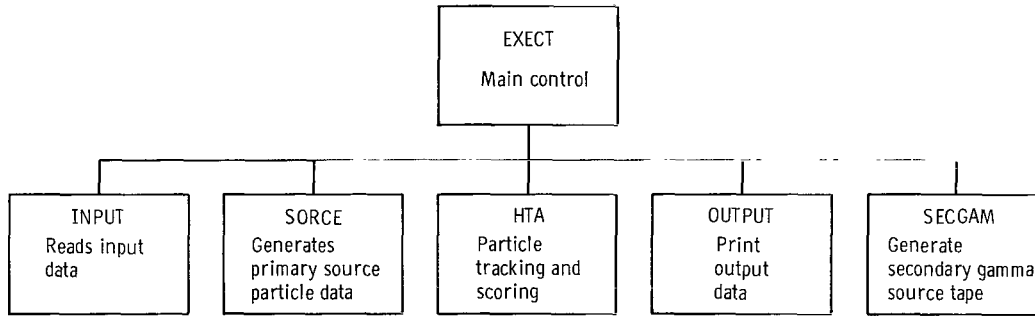

Figure 2. - COHORT-II major subdivisions and functions.

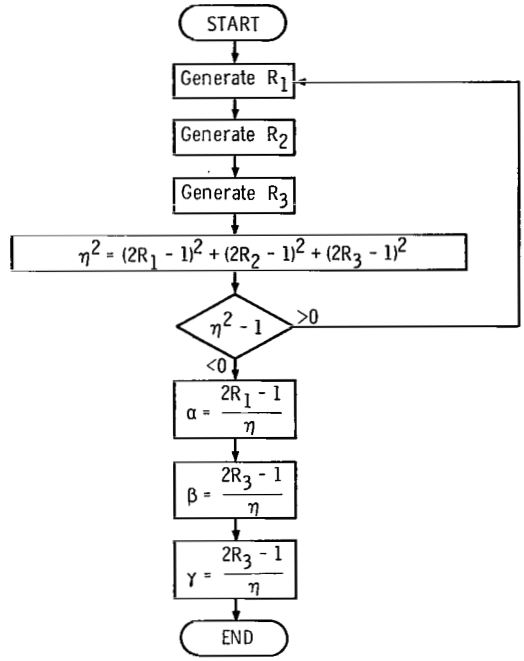

Figure 3. - Selection of random direction cosine in the laboratory system.

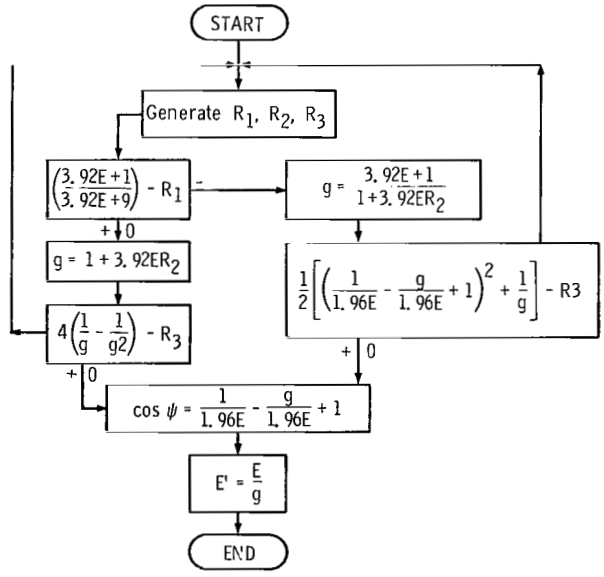

Figure 4. - Rejection technique for selection of scattering angles and scattered energies for compton collisions.

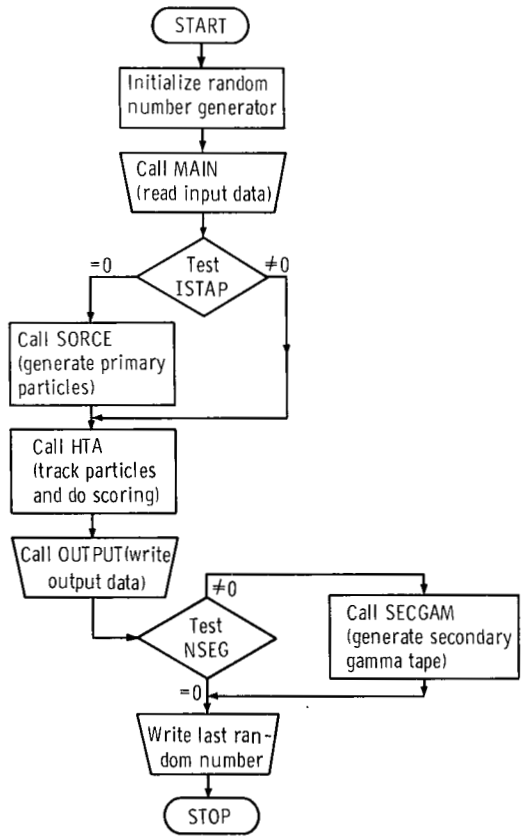

Figure 5. - Subroutine EXECT. Acts as executive routine for entire code.

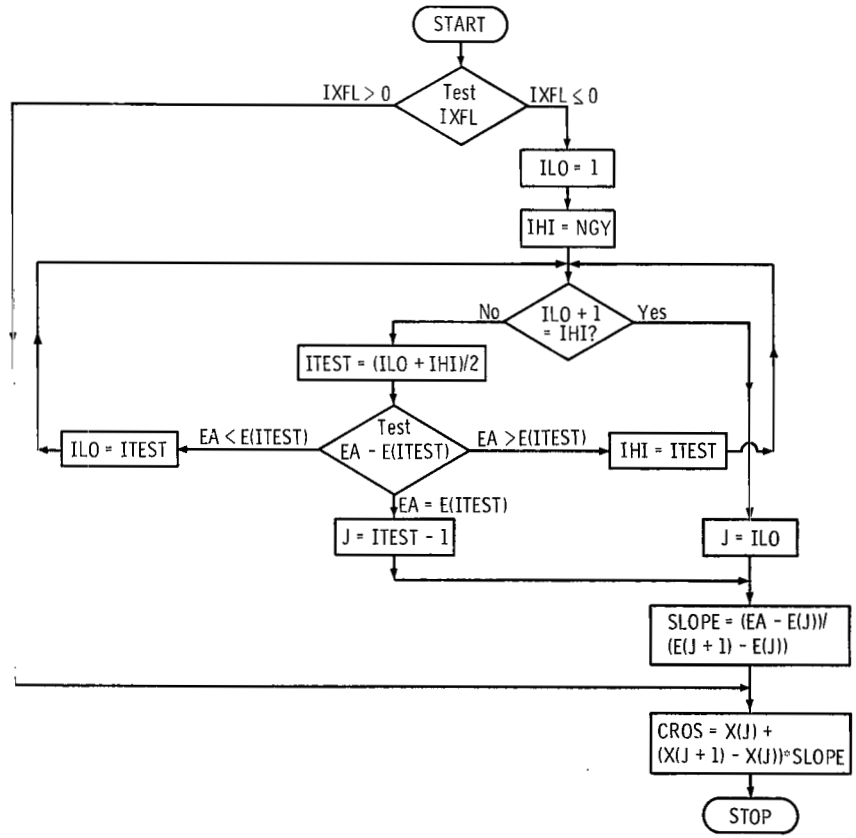

Figure 6. - Subroutine XSEC. Given the particle energy (EA), performs linear interpolation to obtain a cross-section value at that energy.

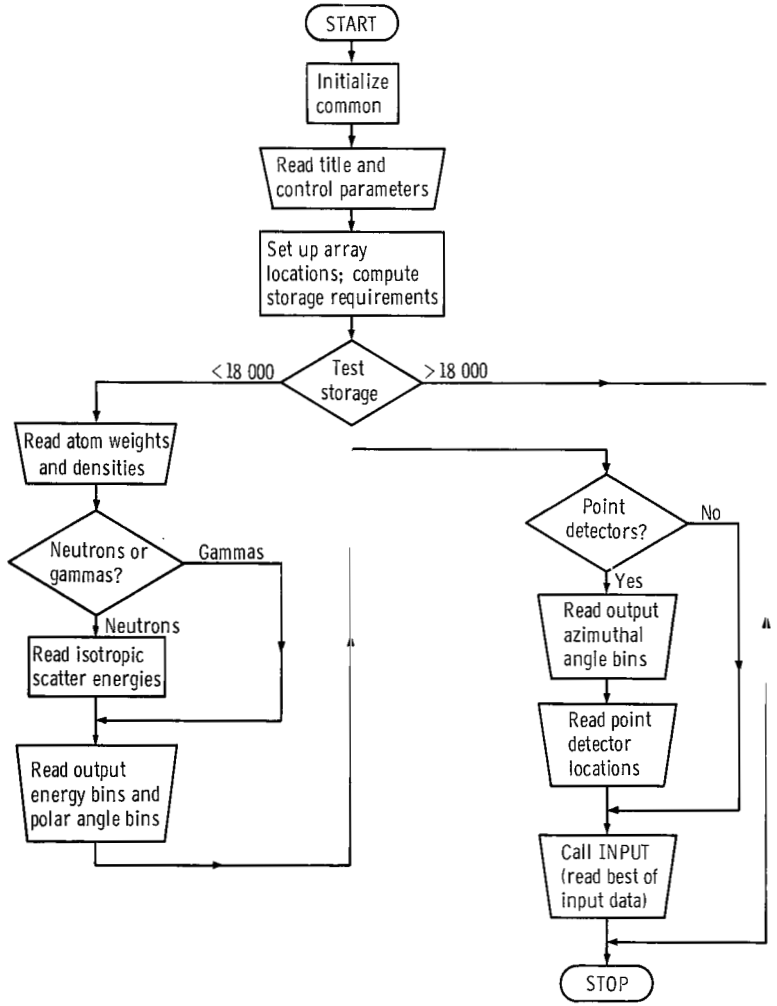

Figure 7. - Subroutine MAIN. Computes storage requirements of problem and reads in part of input data.

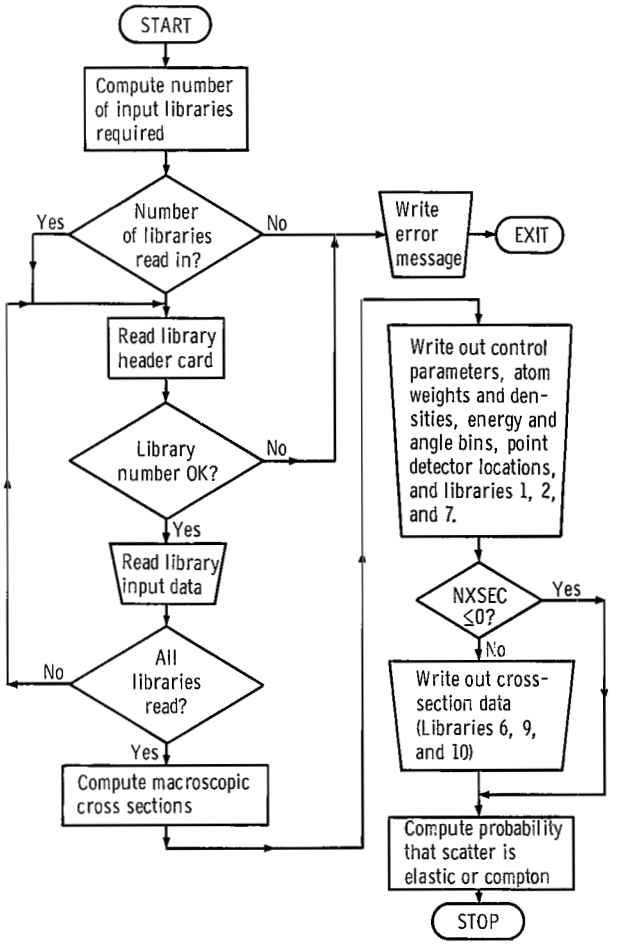

Figure 8. - Subroutine INPUT. Reads and prints out remaining input data.

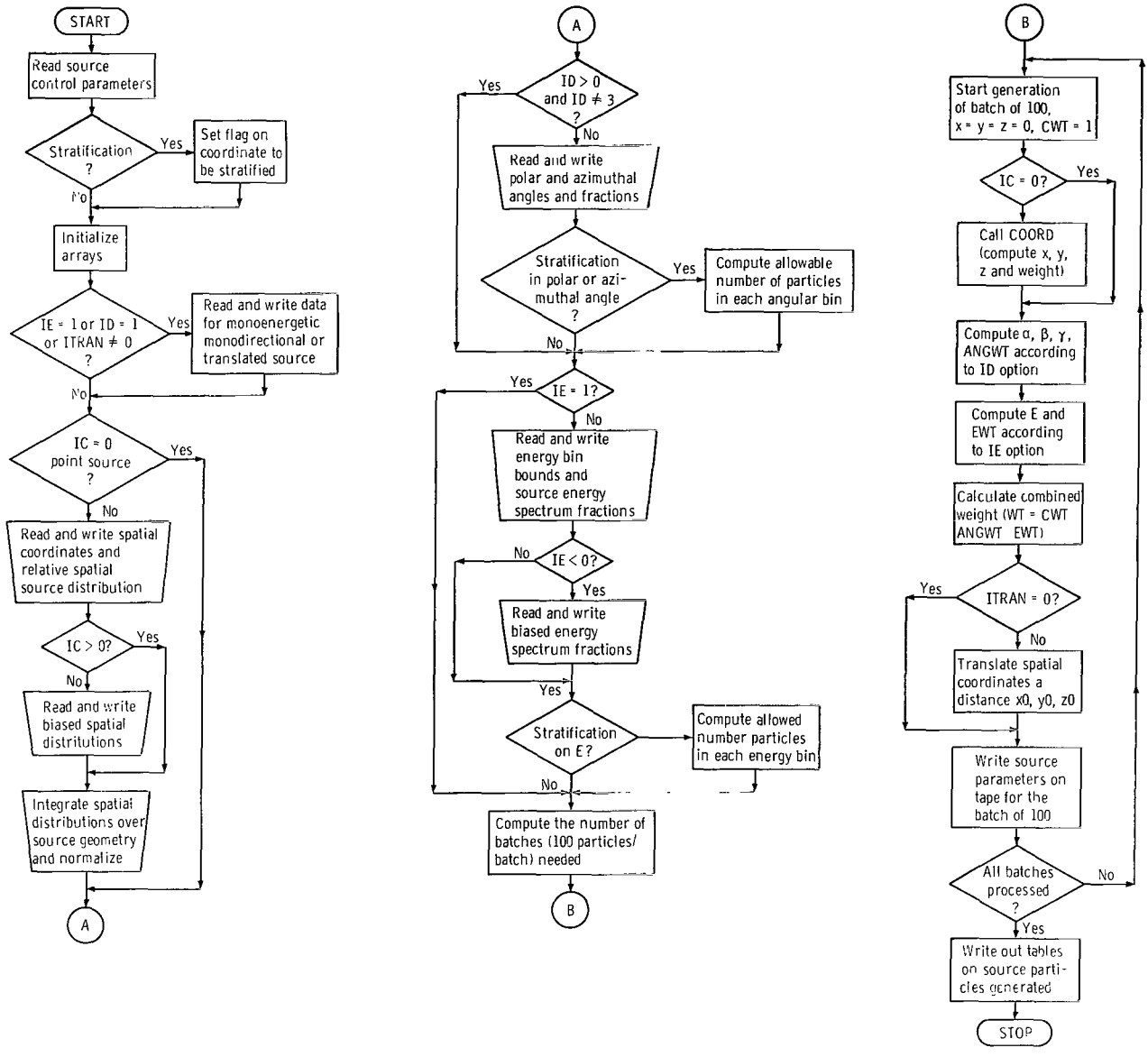

Figure 9. - Subroutine SORCE. Main routine for primary particle source generator.

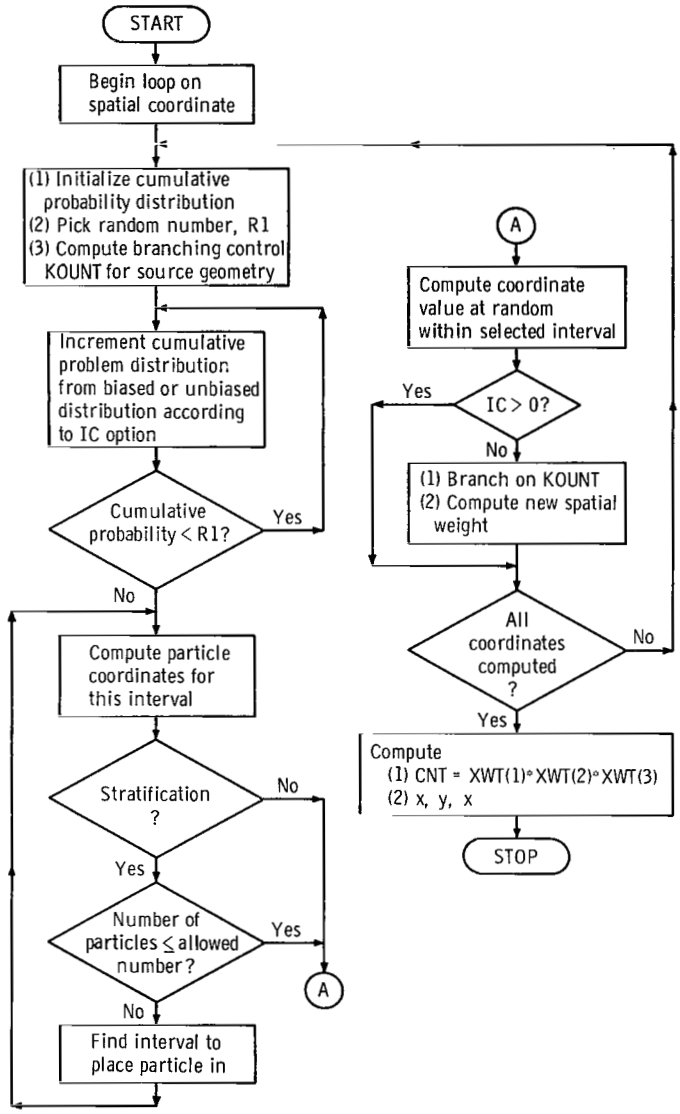

Figure 10. - Subroutine COORD. Selects spatial coordinates of primary source particles according to input spatial distributions.

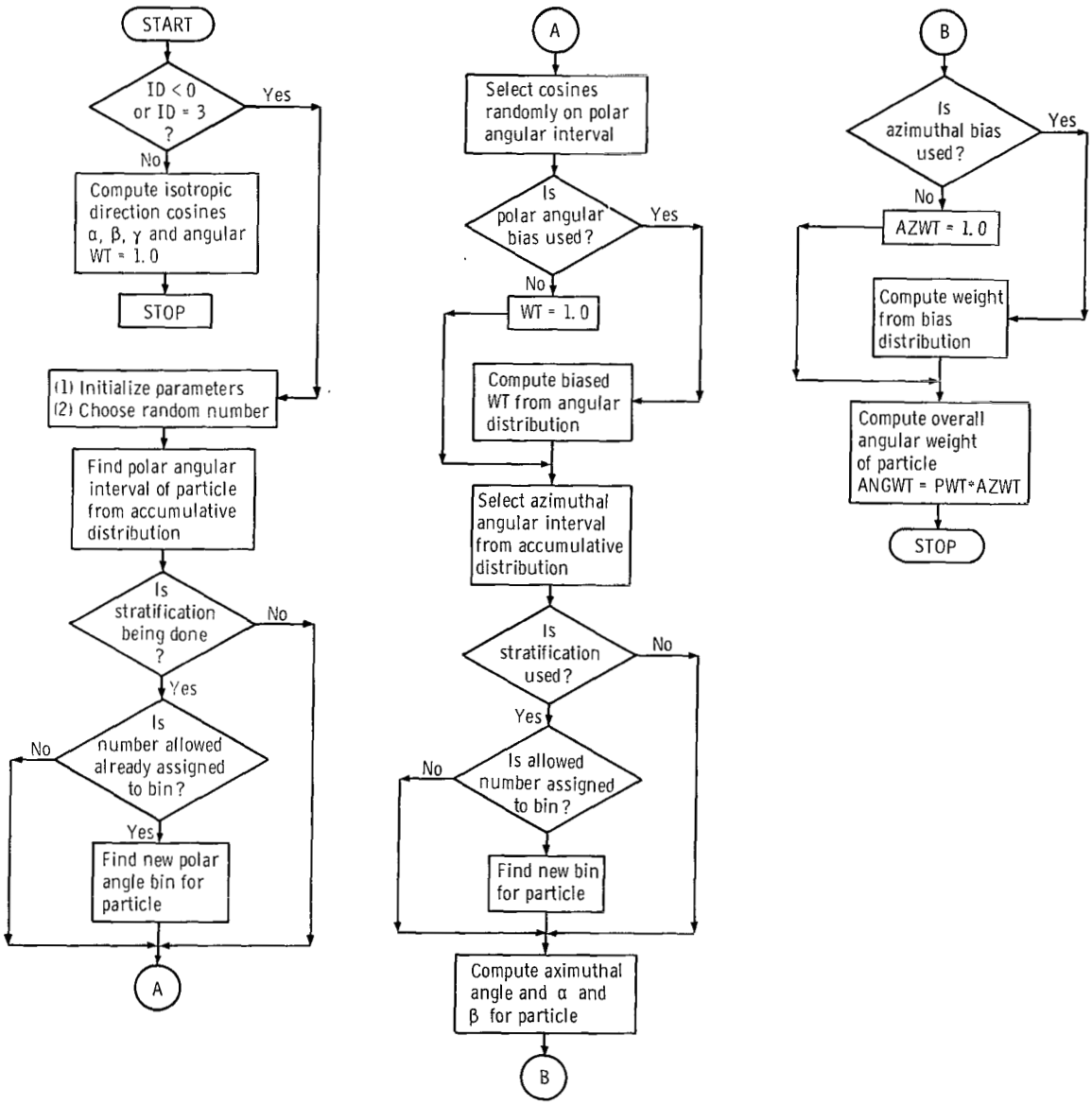

Figure 11. - Subroutine DIRCOS. Generates direction cosine for source particles according to option.

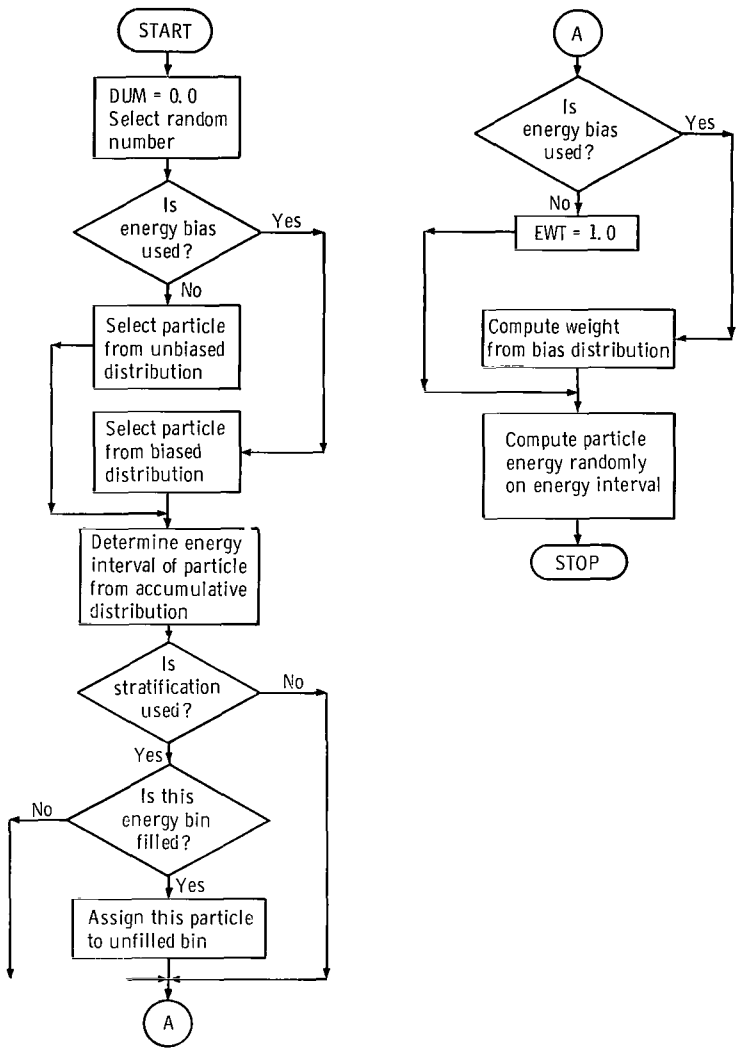

Figure 12. - Subroutine ENERGY. Selects source particle energy from energy spectrum.

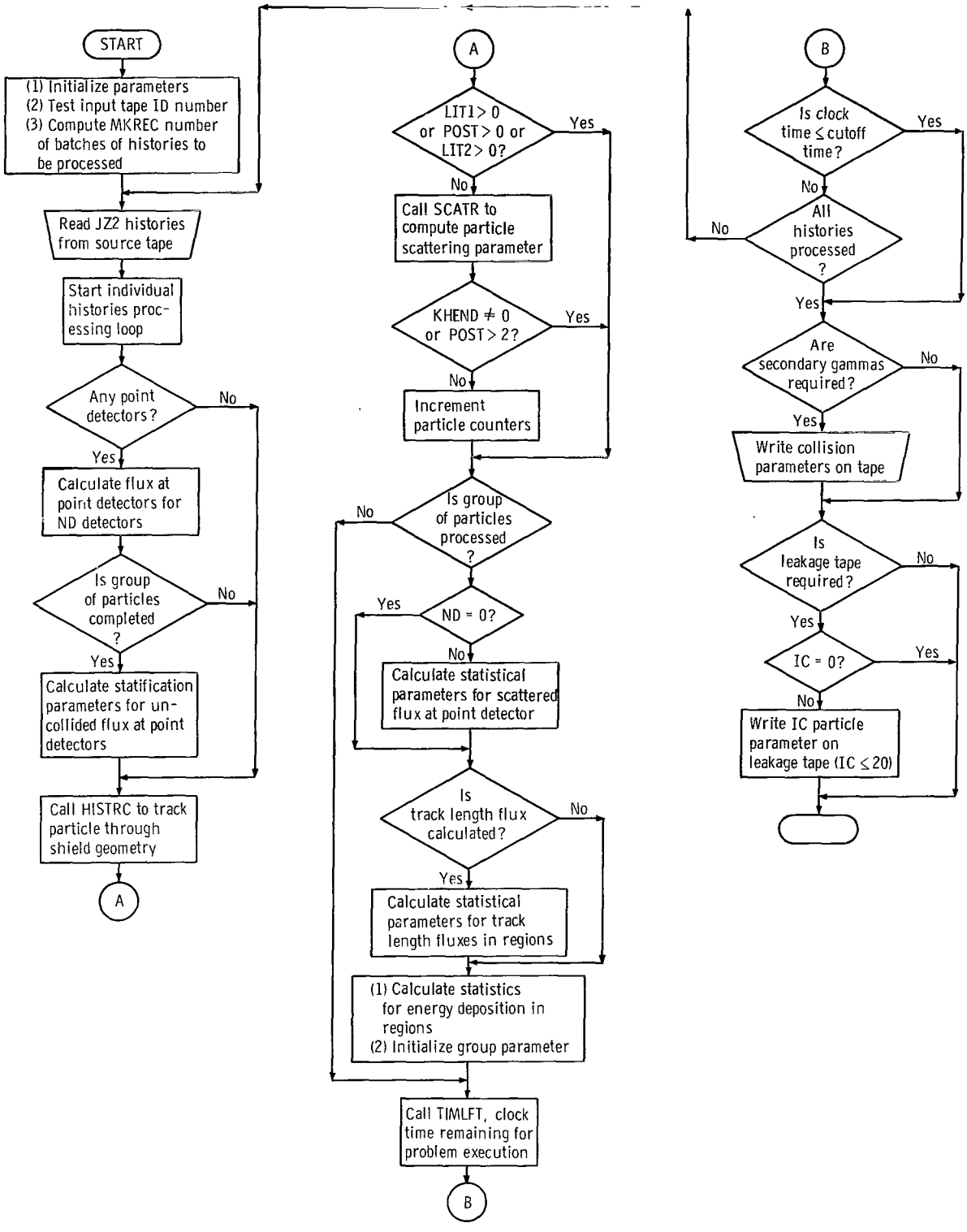

Figure 13. - Subroutine HTA. Executive routine for particle tracking and scoring part of the code.

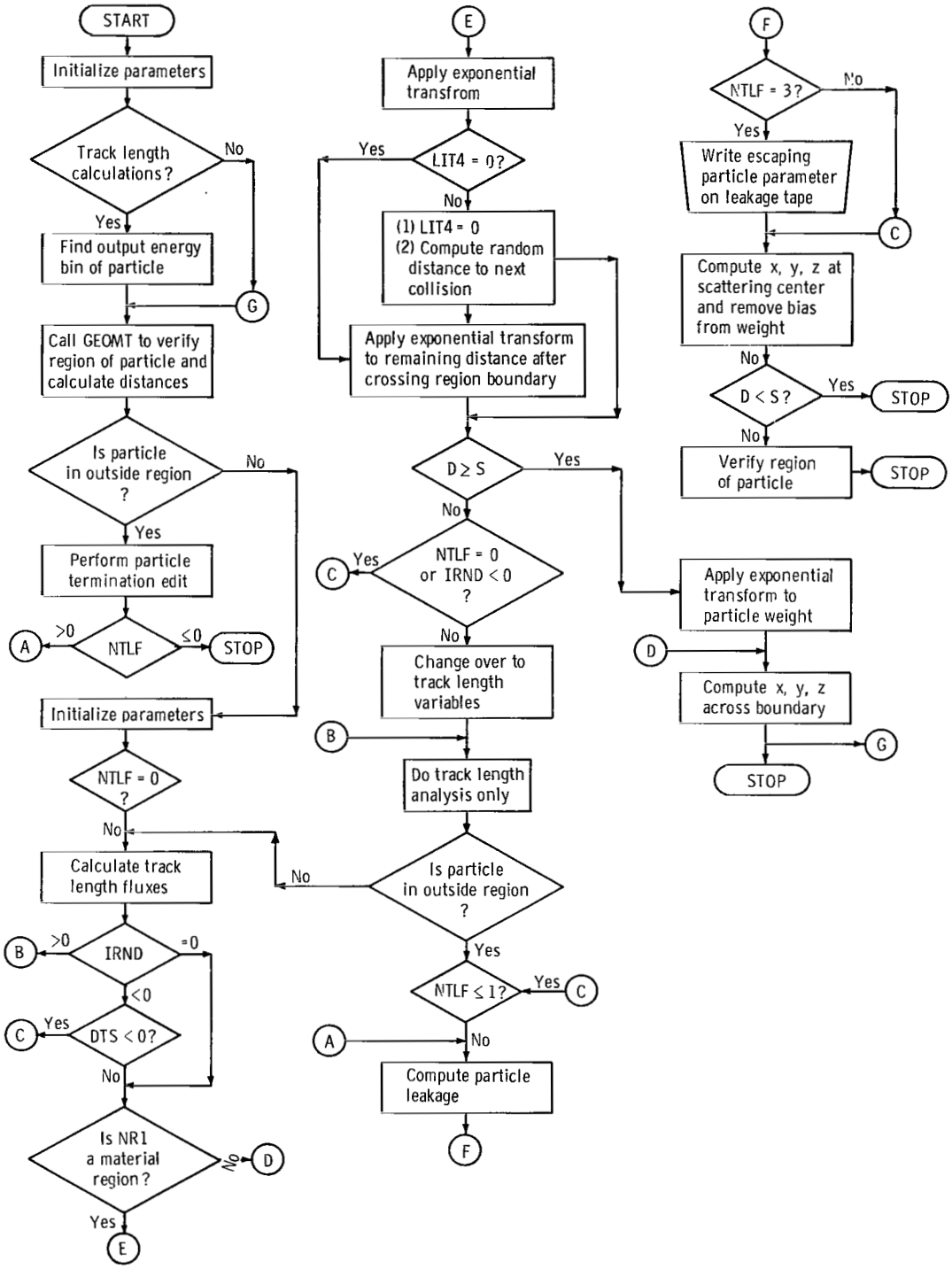

Figure 14. - Subroutine HISTRC. Performs particle tracking through reactor shield geometry.

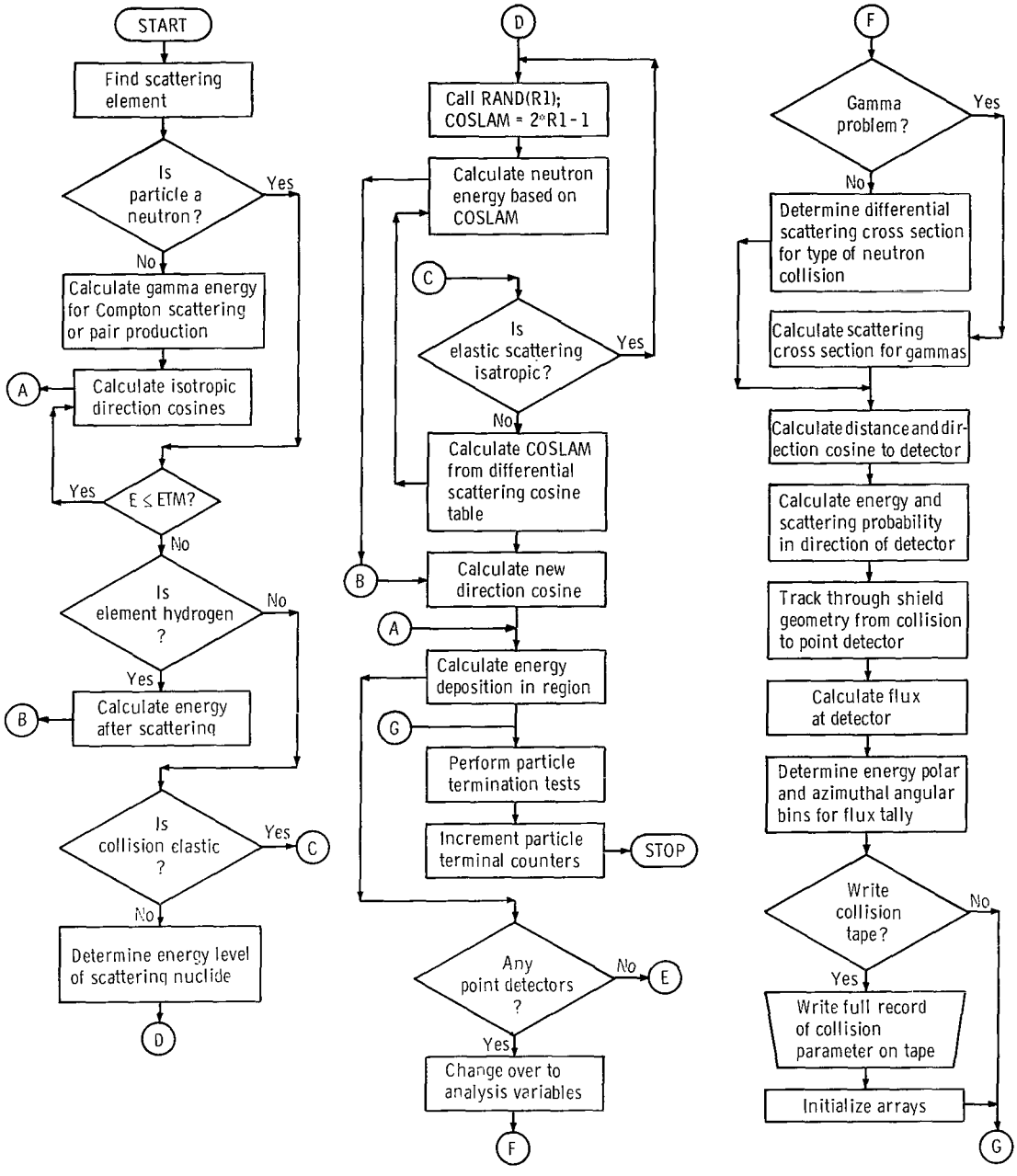

Figure 15. - Subroutine SCATR. Performs particle collision mechanics and calculates scattered flux at point detectors.

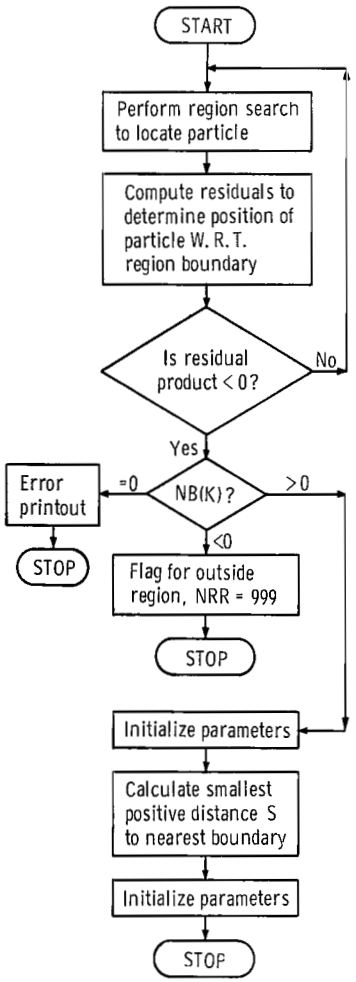

Figure 16. - Subroutine GEOMT. Performs geometry calculations.

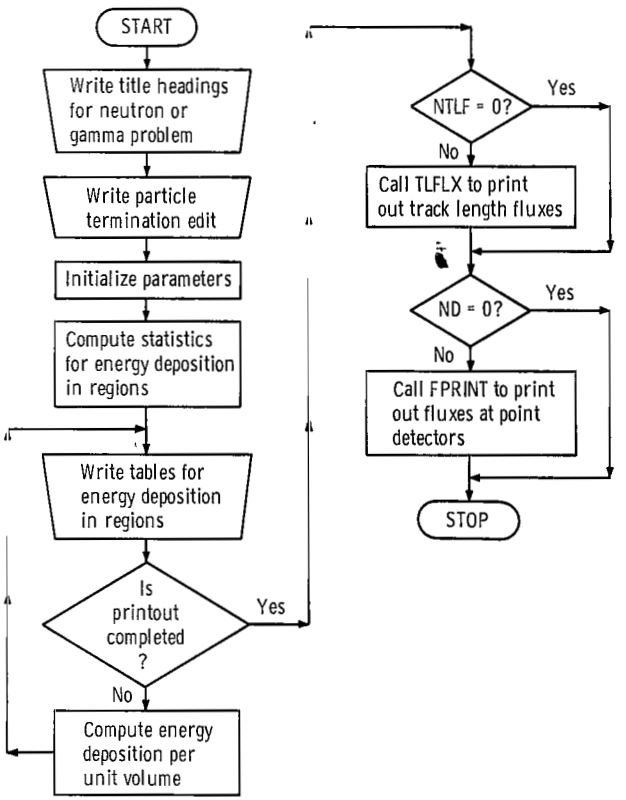

Figure 17. - Subroutine OUTPUT. Writes out tables for energy deposition in regions.

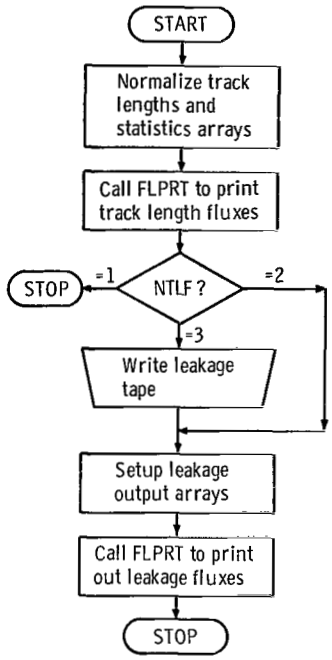

Figure 18. - Subroutine TLFLX. Normalizes track length fluxes and writes leakage tape.

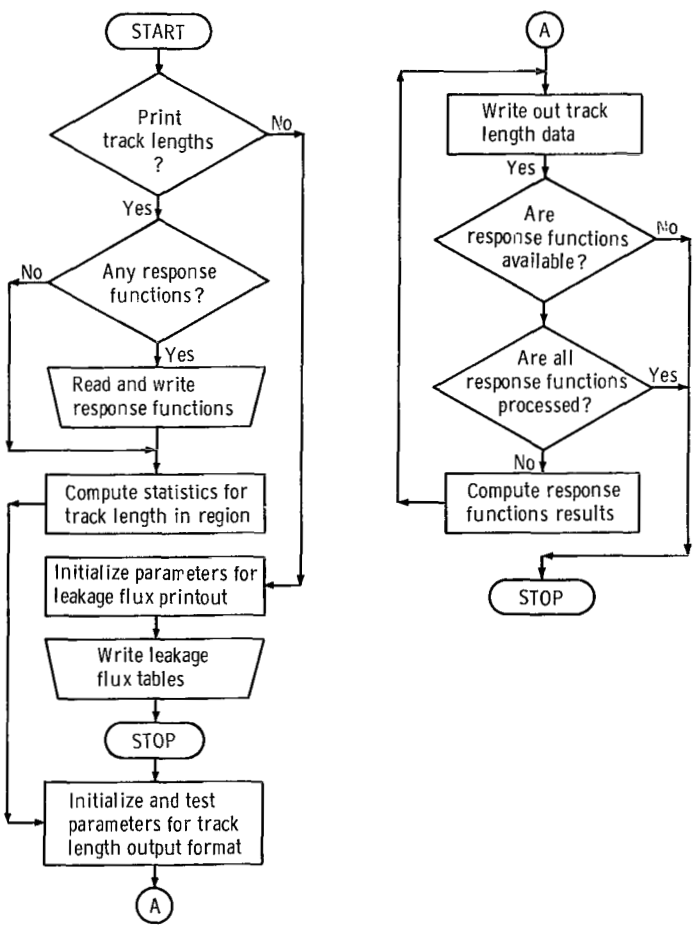

Figure 19. - Subroutine FLPRT. Writes out region fluxes and particle currents leaking from shield geometry.

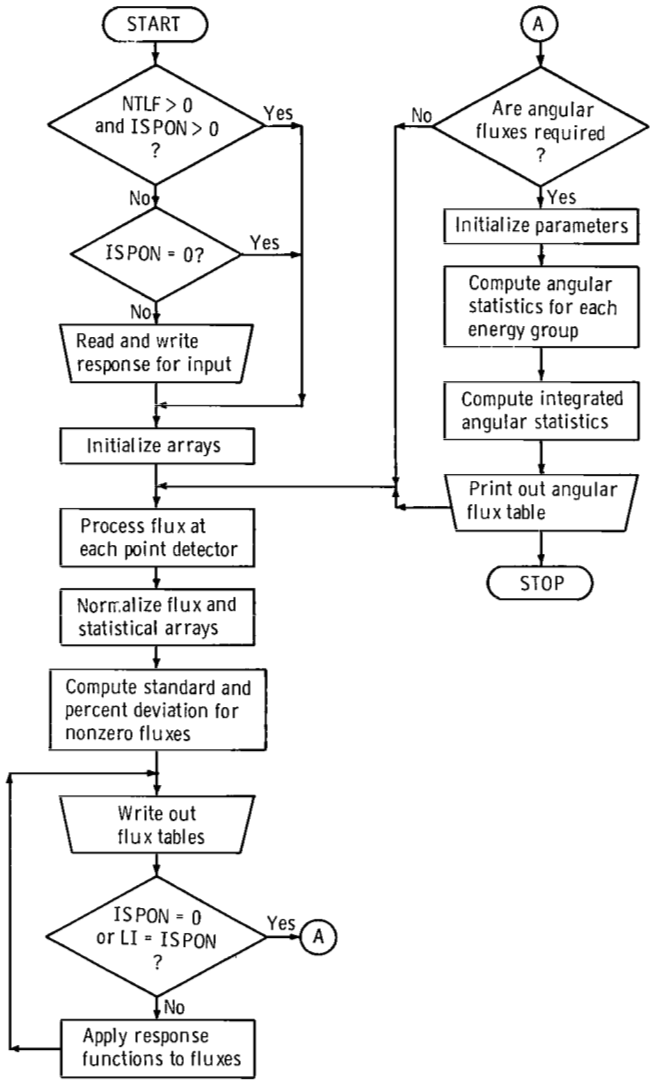

Figure 20. - Subroutine FPRINT. Prints out point detector fluxes.

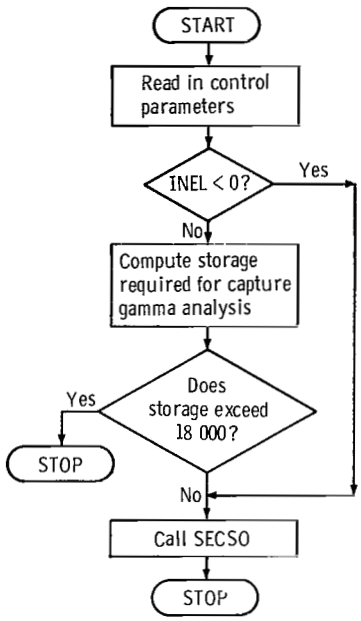

Figure 21. - Subroutine SECGAM. Computes and allocates storage required for secondary gamma problem.

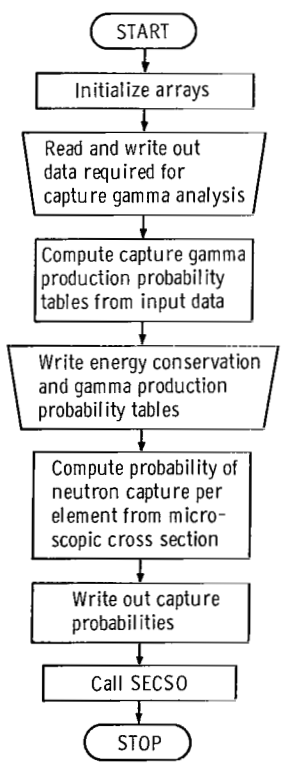

Figure 22. - Subroutine SECRED. Reads in secondary gamma input data.

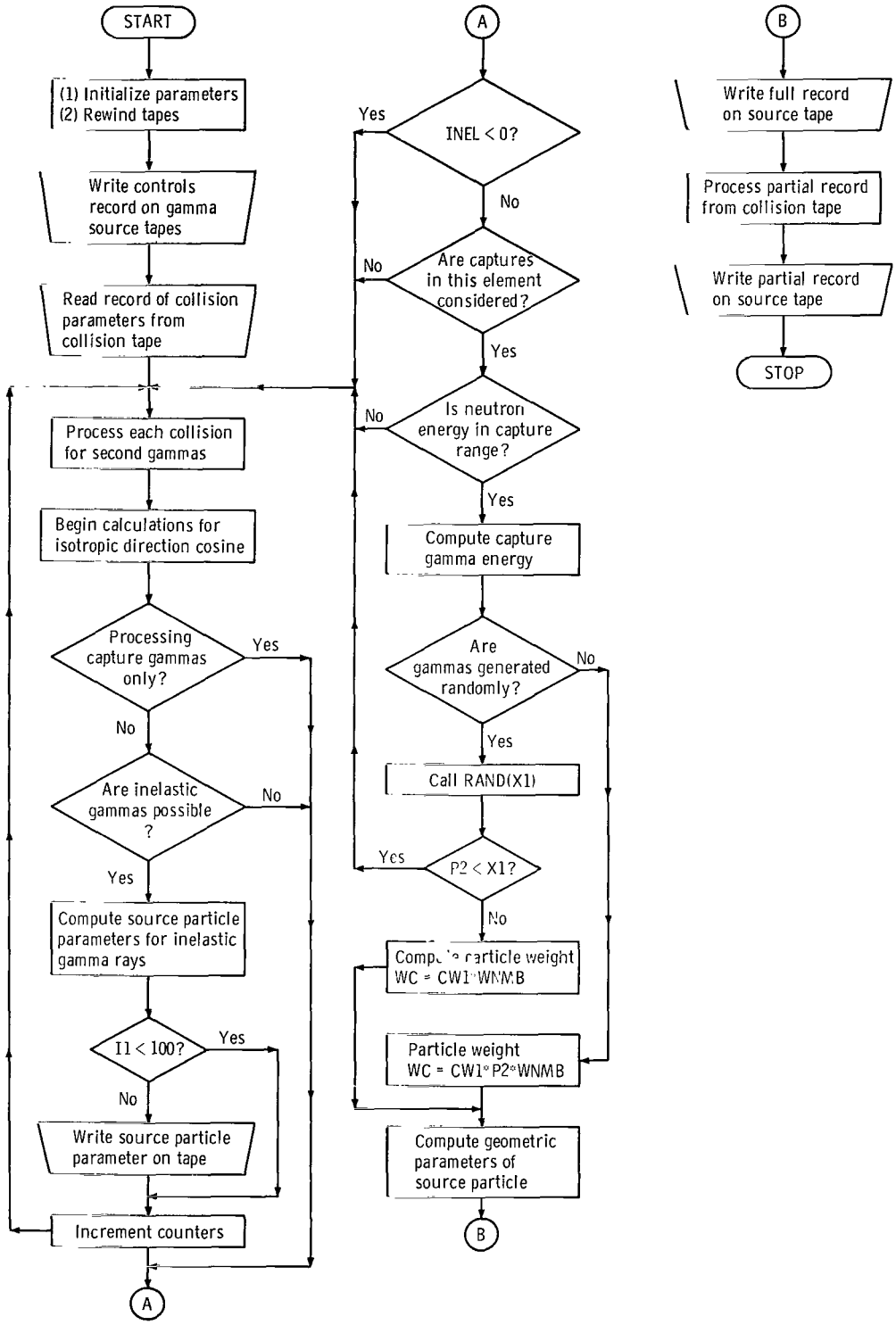

Figure 23. - Subroutine SECSO. Computes secondary gamma and writes source tape.