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**RCPO1 - A Monte Carlo Program for
Solving Neutron and Photon Transport Problems in
Three Dimensional Geometry with Detailed Energy
Description and Depletion Capability**

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RCP01 - A MONTE CARLO PROGRAM FOR SOLVING NEUTRON AND PHOTON
TRANSPORT PROBLEMS IN THREE DIMENSIONAL GEOMETRY WITH DETAILED ENERGY
DESCRIPTION AND DEPLETION CAPABILITY

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1 INTRODUCTION

1.1 General Outline of RCP01

The RCP01 Monte Carlo program is used to analyze many geometries of interest in nuclear design and analysis of light water moderated reactors such as the core in its pressure vessel with complex piping arrangements, fuel storage arrays, shipping container arrangements, and neutron detector configurations. Written in FORTRAN and in use on a variety of computers, it is capable of estimating steady state neutron or photon reaction rates and neutron multiplication factors. The energy range covered in neutron calculations is that relevant to the fission process and subsequent slowing-down and thermalization, i.e., 20 MeV to 0 eV. The same energy range is covered for photon calculations.

This document is updated from Reference 7 which was issued as part of the final phase of the Shippingport LWBR reactor program. It includes descriptions of many new features such as a depletion capability, a flux-at-a-point option, expanded plotting features, new source spectrum, and new scattering models. Additionally, many program limits have been expanded.

RCP01 was initially based on the RECAP program (Reference 1).

The neutron Monte Carlo calculational procedure used in RCP01 may be summarized as follows (throughout this report we will refer only to neutron calculations with the exception of Chapter 8 which describes the photon calculations in terms of modifications to the neutron procedures): Individual neutron reactions are determined using the probabilities of occurrence of the possible reactions. To start a neutron, its initial position and velocity are determined. To stop the neutron, a specified terminating event, such as absorption or slowing down below some energy, must occur. The set of calculations for a neutron from birth to termination is called a neutron history. To determine the average properties of all neutrons in a system, a large number of neutron histories are processed and the average values of certain reaction rates as well as statistical statements of the accuracy of each are calculated. The number of histories which must be processed depends on accuracy requirements. (Normally one desires to approximate the continuous transport equation. In analog Monte Carlo, the statistical fluctuations associated with a given number of histories represent the physical fluctuations resulting from a finite neutron density.)

Only nuclide identifications and atom densities are input to RCP01 along with a description of geometrical arrangements. In order to determine the probabilities of the possible neutron reactions, the RCP01 program needs microscopic cross section data. The program accesses microscopic cross section data from a job library previously generated by RCPL1

(Reference 2). The data contained in this library are the Doppler broadened resonance cross sections, i.e., some combination in non-overlapping energy ranges of multilevel, single level, and unresolved cross sections for each resonance nuclide; smooth cross sections; inelastic transfer matrices; fast range differential cross sections; and thermal range double differential cross sections. The details of the job library generation are contained in the RCPL1 report.

The total energy range covered by a given job library from RCPL1 is sub-divided into at most 200 large energy intervals called RCP (throughout this report, RCP is frequently used to refer to RCP01) groups. (See Figure 3-1). Many subgroups are permitted per RCP group so that a “continuous” energy solution is possible.

There are four types of RCP groups permitted; these are summarized in Section 1.2. Each type of RCP group is subdivided into finer energy intervals to describe cross section detail. The RCP groups control the RCP01 calculation in two ways. First, the RCP group type determines the type of calculation for the group (a possible exception occurs in the energy range of epithermal binding; this is discussed later). Second, all neutron histories are processed for a given RCP group before proceeding to the group next lower in energy. This latter process is carried out within the computer as described in the following paragraph.

For group g , the cross section data are obtained and stored in core memory. All types of events in group g (birth, scattering, absorption, and length of free flight) are then determined using pseudo-random number sequences until the energy of each neutron falls below the lower cutoff of group g (on total absorption, the neutron’s energy is set to 0). This condition terminates the history for group g . The group g emergent parameters for all neutrons are retained. For group $g + 1$, cross sections are obtained and stored in core memory. The calculation for this group is then performed by reading the emergent parameters previously retained and continuing the tracking process until all neutrons degrade in energy below the lower cutoff of group $g + 1$. The calculation of subsequent groups is similar.

Neutron reaction rates in any given RCP group are calculated with a collision scoring methodology using either the $\frac{\Sigma_a}{\Sigma_T}$ terminating, $\frac{\Sigma_a}{\Sigma_T}$ non-terminating, or the binomial estimator.

Basic edits consist of absorption and neutron production per nuclide, per composition, per few group. RCP01 permits an arbitrary number of compositions; the only limit is available machine storage. The uncertainty is computed on an iteration by iteration basis for each quantity tallied. RCP groups above thermal may be coalesced into as many few groups as desired.

RCP01 has several plotting capabilities for generating various views of the three-dimensional reactors being analyzed. These include black and white or color plots of geometric components in several levels of detail, black and white perspective plots of three dimensional layouts, as well as two-dimensional slice plots perpendicular to each coordinate axis. Users can select the colors used for each material. Color plots can be displayed on workstations or printed.

1.2 Outline of the RCP01 Collision Treatments

There are four types of collision treatments permitted in RCP01 which are, in general, in one to one correspondence with the four types of RCP groups mentioned in Section 1.1. Each RCP group type may be outlined as described below.

1.2.1 Inelastic Groups

These groups collectively extend from 20 MeV to 5.53 keV. No inelastic group can exist below 5.53 keV in energy. In each of these groups, explicit resolved or unresolved resonance structure is permitted over at most 500 uniform energy subintervals. Additionally, multigroup smooth cross sections are used (20 MeV to 5.53 keV normally covers 28 MUFT multigroups, Reference 3). For each nuclide, a 28 x 28 multigroup inelastic matrix for isotropic inelastic scattering in the lab system is permitted. The use of an inelastic scattering weight makes it possible to account for $(n, 2n)$, $(n, 3n)$ type reactions. Also, for each nuclide, the first four Legendre components (for the first 28 multigroups) of the differential cross section in the center-of-mass system are used in the elastic scattering process. Optionally, a collection of energy dependent histograms may be used for elastic scattering.

1.2.2 Resonance Groups

These groups collectively cover the unresolved and resolved resonance ranges down to an energy where bound proton scattering starts to be important, i.e., an energy range normally extending from 5.53 keV to about 10 eV. Each of these groups may be uniformly subdivided into a maximum of 1000 energy subintervals to describe the Doppler-broadened resonance cross sections. The selection of the energy cut points of the RCP groups, the number of subdivisions per group, and the type of calculation per group used to obtain resonance cross sections are all made when using RCPL1 to construct the job library. In these groups, the bound hydrogen target is treated as a free proton at rest. Only isotropic elastic scattering in the center of mass system is permitted. No inelastic scattering is permitted.

1.2.3 Epithermal Binding Range

This range normally covers the energy range 10 eV to 0.625 eV. Up to 1000 energy subintervals are permitted to describe the Doppler broadened resonance cross sections. This range is treated the same as a resonance group with the following exception: In the neutron collision process, a bound hydrogen target is not treated as a free proton target at rest. Instead, in a manner suggested by the work of Corngold (Reference 4), neutron down-scattering with the bound hydrogen target is treated kinematically as a free proton target with a Maxwellian distribution of velocities corresponding to the effective source temperature. As is shown in Reference 15, this collision process produces a good estimate of the epithermal flux and a good estimate of the space-energy-angle-dependent thermal source in water. (The epithermal binding group is

taken, by default, to be the last epithermal RCP group; however the user may specify an arbitrary energy, E_{eh} , below which the bound hydrogen kinematics are applied; thus, if E_{eh} is larger than the upper energy cutpoints of several resonance groups, then in effect we have several epithermal binding groups).

1.2.4 Thermal Group

This group covers the energy range 0.625 eV to 0 eV. In this group, for light nuclides for which upscattering in the thermal range is important, such as Hydrogen, Deuterium, Beryllium, and Carbon, we use P-3, double differential, thermal kernels in the lab system expressed as, at most, 25 x 25 transfer matrices. The matrix energy transfer is treated as a histogram, i.e., a continuum of exit energies from the collision process is available. Up to 299 energy sub-intervals are permitted in this group to describe thermal Doppler-broadened resonance cross sections. Nuclides other than those treated by kernels are treated by a P-1 lab system scattering pattern without neutron energy exchange.

1.3 Outline of RCP01 Geometry Capability

The basic three-dimensional geometry unit in RCP01 is an initial assembly. Its x - y exterior boundary is either a rectangle or a 60° parallelogram as developed for the Shippingport LWBR program. Its interior domain is subdivided into basic regions by lines parallel to the x - y exterior boundaries and each basic region may be further divided by doubly repetitive subcells. Each subcell may be subdivided into an arbitrary number of regions by the use of elliptical cylinders with axes parallel to z (straight line boundaries may be defined by making the major axis of an elliptical cylinder large). This formulation as ellipses is useful primarily as a method of representing circles and straight lines. A double truncation occurs when subcells are used. First, the elliptical cylinders are truncated by the x - y subcell boundaries, and second, the subcells are truncated by the x - y basic region boundaries. The definition of z -zones in all regions is performed by defining a sequence of planes perpendicular to the z -axis.

The next level of geometry capability in RCP01 results from using the initial assemblies in a final assembly laydown (the collection of final assemblies in a final assembly laydown is called an initial module). A final assembly is an initial assembly which has been translated and/or rotated to locate the initial assembly within an initial module coordinate system. A mirror image of the initial assembly may also be used in defining a final assembly, and there is a geometry variation that will convert a 60° parallelogram exterior boundary into an equilateral triangle or a trapezoid. In a final assembly laydown the requestor must ensure, with the aid of automatic input checks, that the final assemblies are properly located such that neither internal gaps nor overlaps exist between final assemblies of an initial module. A set of three 60° rhombic final assemblies, for example, is used to create a hexagon.

The geometry definition of initial and final assemblies is sufficiently flexible to permit detailed description of various designs such as the LWBR hexagonal core and the LWBR rectangular fuel storage arrangement. Maximum geometry capability in RCP01, however, is

attained when final modules and module 0 are specified. A final module is an initial module which has been translated and oriented in space relative to an absolute coordinate system. Final modules may not intersect, but there may be arbitrary gaps between them. Module 0 specifies the geometry of the intermodule regions by use of concentric cylinders or spheres, and a set of axial zones. The definitions of initial and final modules are sufficiently flexible to permit detailed three-dimensional representations of, for example, the LWBR pressure vessel, complex piping arrangements, complex shipping container configurations, and explicit LWBR neutron detector orientations.

Additional geometry flexibility is available in RCP01 through the use of composite final assemblies. A composite final assembly comprises a primary initial assembly together with one to seven secondary assemblies. Each secondary assembly is totally within the primary initial assembly, may be arbitrarily oriented relative to the primary initial assembly, overrides the primary over the domain of the secondary, and must not intersect with any other secondary. Composite final assemblies are useful in describing LWBR structural regions with transverse coolant holes, that is, a final assembly laydown with subregions in which the axes of cylinders in a subcell are oriented at right angles to the z-axis of the primary initial assembly.

1.4 Outline of the Remainder of the Report

An outline of the remainder of this report follows. Chapter 2 presents the various types of energy and angular treatments available for the neutron start. These include an isotropic slowing-down source, an isotropic fission (or other spectrum) source, a monodirectional or conical source with an arbitrary spectrum, a monodirectional monoenergetic source, and a source constructed from slab P-3 flux components with an arbitrary spectrum. This last source can be used to splice Monte Carlo to deterministic P-3 deep penetration calculations. Chapter 3 presents the details of the four types of collision treatments outlined in Section 1.2. Chapter 4 presents methods of treating the spatial dependence of the neutron start and geometry tracking. Chapter 5 presents splitting procedures. Chapter 6 presents the automatic iteration strategy used to obtain eigenfunctions and multiplication factors. Chapter 7 describes the fixed source and eigenfunction uncertainties. Chapter 8 describes photon transport, gamma energy deposition, and neutron heating. Chapter 9 describes subcritical calculations. Chapter 10 describes the input to the program. Chapter 11 describes the program output. Chapter 12 describes the File Manager Files. Chapter 13 describes the nuclide depletion option, and Chapter 14 describes the plotting capabilities. Chapter 15 contains the references.

Appendix A describes the slowing down start. Appendix B and Appendix C describe techniques for selecting source energies and scattering angles from probability density functions comprising connected line segments and equiprobability interval histograms. Appendix D proves that a neutron conserving Russian roulette used in RCP01 in the thermal group is a fair game. Appendix E gives the details of determining final assemblies in contact in an initial module. Appendix F gives the details of the final module input checks. Appendix G gives the details of the composite final assembly input checks. Appendix H gives the details of initial assembly volume calculations. Appendix I gives the details of the module zero volume calcu-

lation. Appendix J describes a perturbation calculation available in RCP01. Appendix K describes the variance calculation for a variable number of histories per iteration. Appendix L describes the correlated sampling used in RCP01. Appendix M describes the equilibrium xenon poisoning calculation available in RCP01. Appendix N describes the RCP01 trapping surface capability, and Appendix O describes the RCP01 splice to a cylindrical discrete-ordinate two-dimensional transport solution (References 12 and 13). Appendix P describes a flux-at-a-point estimator to provide improvements in efficiency for shielding applications.

2 ENERGY AND ANGULAR TREATMENTS OF SOURCE

2.1 General Discussion of Neutron Starts

This chapter describes the energy and angular treatments of the most commonly used neutron starts available in RCP01. The less frequently used slowing-down start is described in Appendix A. The energy and angular part of the neutron start involves determination of the following quantities per starting neutron in a given initial assembly:

1. j - the composition in which the neutron is located. A composition is identified in RCP01 by an integer and consists of a set of nuclide identification numbers and corresponding atom densities (in atoms/barn-cm),
2. E - the neutron energy,
3. w - the neutron weight (set to unity for most start options),
4. n, m - region indices of the initial assembly basic region in which the neutron is located,
5. l - axial zone index. The parameters n, m, l denote a three-dimensional region in an initial assembly. If that region is homogeneous, there is one composition assigned to n, m, l . If that region contains subcells and if each subcell contains G elliptical cylinders, then there are $G + 1$ compositions assigned to n, m, l ,
6. μ, γ, η - the direction cosines of the neutron velocity vector measured relative to the Cartesian x, y , and z axes respectively.

This completes the list of parameters considered to be the energy and angular portion of the neutron start. The determination of the final module, FM, which refers to an initial module, IM; the determination of final assembly, FA, which refers to an initial assembly, IA; and the determination of spatial coordinates (x, y, z) in Chapter 4 will complete the description of the neutron start. The collection of parameters, FM, FA, $j, E, w, n, m, l, \mu, \gamma, \eta, x, y, z$, involved in the neutron start play a fundamental role throughout RCP01. It is precisely this

collection of parameters per neutron that is recorded as the neutron degrades in energy below the lower cutpoint of a given RCP group. These parameters then serve to define a “source” neutron for the next lower RCP group as outlined in Chapter 1. The methods for determining the parameters j , E , W , n , m , l , μ , γ , η for each of the most commonly used neutron starts available in RCP01 are given below. Note: Throughout the following sections, we make use of the initial assembly region volumes and total volumes per composition j which are calculated during the input processing as described in Appendix H.

2.2 Isotropic Fission Start

The isotropic fission start is the most commonly used neutron start in RCP01. It is used in RCP01 if the RCP01 starting group is an inelastic group. For such a case, the starting group must have an upper energy cutpoint greater than the highest energy of the spectrum. The composition source densities must be specified in the input. The source spectrum is obtained from the RCPLI job library. This start is described below.

2.2.1 Determination of the Composition, j

For an isotropic fission start, with specified source densities, S_j , by composition in the problem input, let Q_j be the integrated source density for composition j . Then,

$$Q_j = S_j V_j$$

where V_j is the total volume for composition j .

The starting composition, j , is then sampled randomly using the values $P_j = Q_j$ as a discrete probability set, as described below.

2.2.1.1 Random Sampling from a Discrete Probability Set

Using P_j as a discrete probability set (unnormalized, in general) and using a random number ρ uniformly distributed between 0 and 1, a sample j is obtained by solving for j in the following inequality:

Let

$$P_{\text{tot}} = \sum_i P_i, \text{ then}$$

$$\left(\sum_{i=1}^{j-1} P_i \right) / P_{\text{tot}} < \rho \leq \left(\sum_{i=1}^j P_i \right) / P_{\text{tot}}.$$

2.2.2 Determination of the Energy, E

For the isotropic fission start, energies are determined from the fission spectrum in the RCPL1 job library. There are two forms for the fission spectrum: multigroup histogram and pointwise linear. Their use is described below.

2.2.2.1 Multigroup Histogram Fission Spectrum

A multigroup histogram fission spectrum in RCPL1 contains a selected fission spectrum over M non-thermal multigroups ($M \leq 57$). This data is treated as a discrete energy probability set by multigroup. When this spectrum is used in the isotropic fission start for the determination of neutron starting energies, the spectrum, χ^m , is put into cumulative, normalized form as follows:

$$\chi^m = \frac{\sum_{i=1}^m \bar{\chi}^i \Delta u^i}{\sum_{i=1}^M \bar{\chi}^i \Delta u^i}, \text{ for } m = 1, \dots, M$$

where $\bar{\chi}^i$ is the source density per unit lethargy in multigroup i and Δu^i is the lethargy width of group i .

The multigroup i which contains the neutron starting energy E is selected by random sampling from the discrete probability set defined by χ^i (see Section 2.2.1.1).

After a multigroup is selected, the starting energy is sampled uniformly within the selected multigroup. Note: Even if this starting energy falls in the epithermal binding range, the velocity of the neutron is **not** altered by the vectorial addition of a hydrogen velocity vector (as is normally done for neutrons which slow down to such energies as the result of scattering with bound hydrogen atoms).

2.2.2.2 Pointwise Linear Fission Spectrum

A pointwise linear fission spectrum contains the probability density, $f(E)$, specified at a set of N specific energy points, E_i . The density function between these points is the linear function connecting the values at the points. Using this probability density function, the discrete probability for each energy interval between points is calculated analytically by integrating over the interval. Then, discrete random sampling is used to select an interval followed by random linear sampling within the selected interval to select an energy (see Appendix B for description of random linear sampling over an interval.)

2.2.3 “Correction” Sampling

A form of semi-systematic sampling called “correction sampling”, is used to augment the energy sampling described above. This method aims to adjust the present sample to balance prior samples. In this method, χ^i is used as above only for the 0th and 1st iterations (or only for the 0th experiment in a fixed source problem). For other iterations a correction source spectrum, $S^{m,k}$, is used,

$$S^{i,k} = \frac{N^k \chi^i - N^{k-1} \overline{TS}^{i,k-1}}{N^k - N^{k-1}},$$

where N^k is the total number of histories in iterations 1 through k (or 0 through k for fixed source problems) and where $\overline{TS}^{i,k-1}$ are the normalized cumulative values of the actual number of neutrons drawn for multigroup i through and including the $k-1$ st iteration. The multigroup index is selected by discrete random sampling using the corrected $S^{i,k}$ (fixed k) values instead of the original χ^i values. This method works similarly for both multigroup histogram fission spectrum and pointwise linear spectrum data.

2.2.4 Determination of the Starting Weight, W

The neutron starting weight is set to unity.

2.2.5 Determination of the Basic Region Indices, n,m

The basic region indices are determined as follows: Assuming that the axial zone index, l , is known, denote the total volume of region n,m,l , which may be subdivided by subcells, as $V_{n,m,l}$. Let $f_{(n,m),j}^s$ ($s = 1, \dots, G+1$) each be a volume fraction of one of the possible $G+1$ compositions in n,m,l , assigned to one of the $G+1$ subcell regions s if the composition is j , and let each $f_{(n,m),j}^s = 0$ if the composition is not j .

Note: Due to the use of cylindrical surfaces with axes parallel to the z -axis, the RCP01 volume fractions are independent of l . See Appendix H for description of initial assembly volumes.

In general, $V_{n,m,l}(f_{(n,m),j}^1 + \dots + f_{(n,m),j}^{G+1})$ is the volume of composition j in n,m,l . An ordering index i is assigned to each basic region n,m . The total volume of composition j in axial zone l , $V_{l,j}$, is

$$V_{l,j} = \sum_{t=1}^T [V_{n,m,l}(f_{(n,m),j}^1 + \dots + f_{(n,m),j}^{G+1})]_t.$$

The desired value of t , and thus (n, m) , is determined by use of random sampling with discrete probabilities equal to the volume of composition j by t over the total volume of composition j for all t .

2.2.6 Determination of the Axial Zone Index, l

The axial zone index is determined by use of random sampling with discrete probabilities equal to $v_{l,j}$ (fixed j). We use a random number ρ and solve the inequality

$$\sum_{l'=1}^{l-1} v_{l',j} < \rho \cdot v_j \leq \sum_{l'=1}^l v_{l',j} \text{ for } l.$$

2.2.7 Determination of the Direction Cosines, μ, γ, η

The direction cosines of the neutron velocity vector relative to the cartesian x , y , and z axes, respectively, are determined to be those for an isotropic source as follows (the possible addition to the neutron velocity vector of a randomly drawn hydrogen velocity vector with an isotropic angular distribution as discussed in Section A.1.2 of Appendix A does not alter the isotropic nature of the source): First observe that $d\mu d\theta$ represents a constant elementary area on the surface of a unit sphere where μ is the projection of a sphere radius on the x -axis and θ is the azimuthal angle of the sphere radius projected on the y - z plane. Thus we choose both μ and θ from flat distributions, That is,

$$\theta = \rho\pi,$$

$$\mu = 2\rho - 1.$$

γ and η are then determined by

$$\gamma = \sqrt{1 - \mu^2} \cos \theta,$$

and

$$\eta = \frac{2\rho - 1}{|2\rho^* - 1|} \sqrt{|1 - \mu^2 - \gamma^2|},$$

Observe that θ was drawn from only its half range, but this is sufficient to determine γ . Knowing μ and γ , the magnitude of η is given by $|\eta| = \sqrt{|1 - \mu^2 - \gamma^2|}$. Since the sign of η is equally

likely to be positive or negative, the term $(2\rho - 1)/|2\rho^* - 1|$ determines its sign. The absolute value under the square root in the expression for η is to avoid possible round-off difficulties.

Note: Throughout this report, any ρ without an asterisk is a different random number than the ρ previously used. The asterisk on the random number ρ^* indicates that the same random number is reused.

2.3 Special Source Options

Several special source options are available in RCP01. They can be used only in fixed source calculations.

One option provides a link from a one-dimensional analytic calculation to a three-dimensional RCP01 Monte Carlo calculation.

The others provide combinations of energy and angular options. Energy options include: a) a monoenergetic source; b) a source flat over a selected energy range; and c) an arbitrary multigroup spectrum including thermal subgroups. Angular options include: a) monodirectional; and b) selection from a conical shell. They all can be relative to the initial assembly x , y , or z axis or a specified arbitrary direction.

The available options are discussed in the following sections. Input for these options is described in Section 10.9.

2.4 Slab P-3 Source for Analytic to Monte Carlo Splice

This option can be used to make a deterministic P-3 to Monte Carlo splice at some location corresponding to some deep penetration in a neutron shielding type of calculation. The deterministic P-3 calculation will be one-dimensional, and it is assumed that this is sufficient for deep penetration to some splicing plane. Beyond this plane, there may exist a complicated shielding arrangement, e.g., a cylindrical hole through the shield, that requires a two or three-dimensional description. At the same time, the amount of neutron attenuation that occurs over the distance from the splicing plane to where the geometrical complication occurs is small. The deterministic Monte Carlo splice is made at the splicing plane. The deterministic calculation, performed with some representation of material to the right and left of the splicing plane, will yield the first four Legendre components of the vector flux at this location. Suppose we desire to continue the penetration to the right of the splicing plane by Monte Carlo. This may be done by use of a thin source region at the position of the splicing plane with a source strength over this region given by J_+ (i.e., the current in the right hemisphere), and by use of a black region to the left of the source region. This black region is required since the deterministic calculation has a representation of actual material to the right and left of the splicing plane. Thus, neutrons crossing this plane from right to left, and subsequently re-entering the right portion again, have already been accounted for. Therefore, the procedure for arriving at the Monte Carlo source will be to construct a vector source to the right from the input determinis-

tic P-3 components and to use J_+ groupwise as the source spectrum. Automatic normalization of the splice is provided by using the integrated value of J_+ as a neutron weight.

The mathematical details of the above procedure are as follows: Let $\phi_l, l = 0, \dots, 3$, be the Legendre components of the slab vector flux at the splicing plane integrated over multigroup m . Here the thermal group is considered as multigroup $M+1$ and the input $\phi_l^{M+1}, l = 0, 1, \dots, 3$ is the thermal group integrated flux; the input $\phi_l^m(u), l = 0, \dots, 3, m = 1, \dots, M$ is the flux per unit lethargy and is subsequently multiplied by the lethargy width of multigroup $m, \Delta u_m$, to form $\phi_l^m, m = 1, \dots, M$.

Thus

$$\phi^m(\mu) = \sum_{l=0}^3 \frac{2l+1}{2} \phi_l^m P_l(\mu).$$

The relationship between a slab source $S^m(\mu)$ at the position of the splicing plane and the vector flux $\phi^m(\mu)$ immediately to the right or left of the splicing plane in multigroup m is

$$\phi^m(\mu) = \frac{S^m(\mu)}{|\mu|}.$$

Thus, the source we desire to work with is given by

$$S^m(\mu) = \sum_{l=0}^3 \frac{2l+1}{2} |\mu| \phi_l^m P_l(\mu).$$

Since we desire only the right directed source, we may write

$$S^m(\mu) = \sum_{l=0}^3 \frac{2l+1}{2} \phi_l^m \mu P_l(\mu), \quad 0 \leq \mu \leq 1.$$

Let J^{+m} be the current to the right in multigroup m , then

$$J^{+m} = \int_0^1 S^m(\mu) d\mu = \frac{\phi_0^m}{4} + \frac{\phi_1^m}{2} + \frac{5}{16} \phi_2^m.$$

The total number of neutrons starting to the right, J_+ , is given by

$$J^+ = \sum_{m=1}^{M+1} J^{+m}.$$

For this option, a selection of source axis must be made, i.e., $\mu = 1$, $\gamma = 1$, or $\eta = 1$. External source spectra must be supplied which give multigroup P-3 vector flux components per unit lethargy and one set of energy integrated thermal P-3 vector flux components. If the energy of the upper cutpoint of the starting RCP group falls within multigroup m , then the vector flux components in multigroup m , and those in all multigroups at higher energies, must be zero. The composition source densities must be specified.

2.4.1 Determination of the Composition, j

The composition is determined in the manner of that for the isotropic fission start with composition source densities specified.

2.4.2 Determination of the Energy, E

The neutron energy is determined by use of the following considerations:

The multigroup m , containing the neutron starting energy, E , is obtained by random sampling with discrete probabilities given by J^{+m} .

The spectrum is treated as a histogram in energy, thus E is sampled uniformly between E^m , the upper energy cutpoint, and E^{m+1} , the lower energy cutpoint, of selected multigroup m .

2.4.3 Determination of Neutron Properties $W, n, m, l, \mu, \gamma, \eta$

w - the neutron starting weight for all histories is given by $w = J^+$.

n, m - the basic region indices are determined as for the isotropic fission start.

l - the axial zone index is determined as for the isotropic fission start.

μ, γ, η - the direction cosines of a source neutron velocity vector are determined as follows: If the source has $\mu = 1$ as an axis of rotational symmetry, then the value of μ in multigroup m is obtained from a distribution function constructed from $S^m(\mu)$. First $S^m(\mu)$ is put in a histogram form with eleven uniform blocks from $\mu = 0$ to $\mu = 1$. That is

$$S_i^m = \frac{1}{10} S^m(\mu_i) = \frac{1}{10} \sum_{l=0}^3 \frac{2l+1}{2} \Phi_l^m \mu_i P_l(\mu_i), \quad i = 1, \dots, 9,$$

while for the two values $i = 0$ and 10

$$S_i^m = \frac{1}{20} S^m(\mu_i).$$

where

$$\mu_i = (i/10) \text{ in both cases.}$$

The block index, i , is determined by random sampling with discrete probabilities S_i^m . The starting value of μ is then drawn flat over block i , that is

$$\mu = \frac{\mu_{i-1} + \mu_i}{2} + \rho \left(\frac{\mu_{i+1} - \mu_{i-1}}{2} \right)$$

where $\mu_{-1} = 0$ and $\mu_{11} = 1$.

The values of γ and η are determined as for the isotropic fission start, i.e.,

$$\begin{aligned} \theta &= \rho\pi \\ \gamma &= \sqrt{1 - \mu^2} \cos \theta, \\ \eta &= \frac{2\rho - 1}{|2\rho^* - 1|} \sqrt{|1 - \mu^2 - \gamma^2|} \end{aligned}$$

If the source angular pattern has $\gamma = 1$ as an axis of rotational symmetry then the above μ, γ, η undergo the permutation $\mu = \eta$, $\gamma = \mu$, $\eta = \gamma$. If the source angular pattern has $\eta = 1$ as an axis of rotational symmetry, then the original μ, γ, η undergo the permutation $\mu = \gamma$, $\gamma = \eta$, $\eta = \mu$.

2.5 Conical Source with an Arbitrary Spectrum

In this case, a selection of source axis must be made, i.e., $\mu = 1$, $\gamma = 1$, or $\eta = 1$. The cosines of the angles between the source axis and the surfaces of two cones must be supplied, i.e., μ_0 and μ_1 (if μ_1 is not supplied by the requestor, then μ_1 is taken as 1). An external source spectrum must be supplied which consists of one entry per multigroup. The entry for multigroup m , $1 \leq m \leq M$, is the source strength per unit lethargy; for $m = M + 1$, the entry is the thermal energy integrated source strength. If the energy of the upper cutpoint of the starting RCP group falls within multigroup m then the source strength in multigroup m and in all multigroups at higher energies, must be zero. The composition source densities must be specified.

2.5.1 Determination of the Composition, j

The composition j is determined in the manner of that for the isotropic fission start with composition source densities specified.

2.5.2 Determination of the Energy, E

The neutron energy, E , is determined as follows. Let s^m be the integrated source spectrum in multigroup m as interpreted in Section 2.4 (again the thermal group will be considered as multigroup $M+1$). The multigroup m containing the neutron starting energy, E , is obtained by random sampling with discrete probabilities s^m .

The source spectrum is treated as a histogram in energy. Thus, E is sampled uniformly between E^m , the upper energy cutpoint, and E^{m+1} , the lower energy cutpoint, of multigroup m .

A thermal spectrum is treated as a histogram in energy over the thermal multigroups (maximum of 25). Given such a spectrum, the total thermal group integrated source strength is equal to s^{M+1} . The input values of the spectrum determine only the relative probability of a neutron starting in a particular thermal multigroup.

If $i = M+1$ is selected, then a sampling process, identical to that used to determine m , determines the thermal multigroup.

2.5.3 Determination of Neutron Properties $W, n, m, l, \mu, \gamma, \eta$

The neutron starting weight, w , for all histories is unity.

The basic region indices, n, m , are determined as for the isotropic fission start.

The axial zone index, l , is determined as for the isotropic fission start.

The direction cosines of each source neutron velocity vector, μ, γ, η , are set as follows:

If the cone axis is $\mu = 1$, set

$$\begin{aligned}\mu &= \mu_0 + \rho(\mu_1 - \mu_0) \\ \theta &= \rho\pi, \\ \gamma &= \sqrt{1 - \mu^2} \cos \theta, \\ \eta &= \sqrt{|1 - \mu^2 - \gamma^2|}, \\ \text{if } \eta &= 0, \text{ set } \eta = 10^{-8}, \\ \eta &= \frac{2\rho - 1}{|2\rho^* - 1|} \eta.\end{aligned}$$

Note: 10^{-8} is used to prevent division by zero during particle tracking.

The permutation required if the cone axis is $\gamma = 1$ is $\mu = \eta, \gamma = \mu, \eta = \gamma$. The permutation required if the cone axis is $\eta = 1$ is $\mu = \gamma, \gamma = \eta, \eta = \mu$.

2.6 Conical Monoenergetic Source

For a conical monoenergetic source, selection of cone axis must be made, i.e., $\mu = 1$, $\gamma = 1$, or $\eta = 1$. The energy of the source, E_0 , must be specified. The composition source densities must be specified.

The procedures for obtaining starting neutron parameters for this source are identical to those for Section 2.5 above, except that the energy, E , for all starting neutrons, is given simply by $E = E_0$.

3 REACTION RATE, EXIT ENERGY, EXIT WEIGHT, EXIT ANGLE DETERMINATION FOR A NEUTRON COLLISION

3.1 General Description of the RCP01 Collision Process

Starting with the birth of a source neutron as described in the preceding chapter, the next step in the Monte Carlo process is to determine the length of neutron free flight measured in mean free paths from the point of birth to the point of first collision. This is done through the use of a random number and the exponential distribution function for length of free flight. The spatial coordinates of this first collision point are then determined through the geometry tracking. That is, knowing the spatial coordinates, direction, and energy of the neutron at birth, it is successively moved to region boundaries intersected by the neutron path and finally moved along some fraction of the traversing distance of a final region such that the total number of mean free paths so traversed is the value desired. The following parameters are thus determined:

1. the final module and final assembly, FM and FA, that contain the first collision,
2. the associated initial assembly number, IA,
3. the initial assembly spatial coordinates, x, y, z , of the first collision point,
4. the indices n, m of the basic region that contains the first collision point,
5. the index l of the axial zone that contains the first collision point,
6. the composition j in which the first collision occurs.

The complete details of the geometry tracking as well as the details related to the determination of the above parameters are given in Chapter 4. The above parameters, together with

E, W, μ, γ, η , which are the energy, weight, and direction cosines of the source neutron, constitute the complete description of the incident neutron at the first collision point. It is these latter parameters that are involved in the energy and angular treatment of the first collision. That is, after first collision reaction rates are estimated and the exit neutron values for E, W, μ, γ, η are determined, then the free-flight to the second collision point may be performed. All exit parameters from the first collision become the incident parameters for the second collision. This process is continued from collision point to collision point until the neutron is terminated for that group. Termination occurs when the neutron leaves the energy range of the RCP group under consideration, is totally absorbed, or escapes from module 0.

The detailed treatment of a Monte Carlo collision process can conveniently be divided into two parts. The first is the estimation of absorption reaction rates and thereby the determination of the fraction of a neutron, remaining from the incident weight, which is scattered. The second is the determination of the parameters E, W, μ, γ, η of the exit neutron. The first part requires selection of some Monte Carlo estimator and knowledge of the absorption and scattering cross sections per nuclide at the neutron incident energy. The second part requires knowledge of detailed cross sections in differential form. Section 3.2, below, describes the various estimators available in RCP01 and their use in determining absorption and scattering reaction rates. Sections 3.3-3.6 describe the manner in which differential cross section data from an RCPL1 (Reference 2) job library are used to obtain E, W, μ, γ, η for an exit neutron in each of the four types of RCP groups respectively, i.e., the fast inelastic groups, the resonance groups, the epithermal binding range, and the thermal group.

3.2 Determination of Absorption and Scattering Reaction Rates

There are three Monte Carlo estimators available in RCP01 to determine estimates of absorption and scattering reaction rates at a collision point. The type of estimator together with the absorption and scattering cross sections per nuclide uniquely determine these rates.

In the first three types of RCP groups, i.e., the fast inelastic groups, the resonance groups, and the epithermal binding range, one can use the binomial estimator, the Σ_a/Σ_T non-terminating estimator, or a group controlled selection which uses Σ_a/Σ_T non-terminating from the starting group down to some selected group, say g' , and a binomial estimator from group $g' + 1$ down to the thermal group, where g' is input by the user. In these groups, choosing the Σ_a/Σ_T non-terminating estimator is preferable if the probability of a neutron reaching the thermal group is large. If this probability is small, the choice of the binomial estimator is preferable. For problems where the choice is not evident, the user should run a few thousand histories with each estimator, compare the size of reaction rate uncertainties per unit machine time, and choose the estimator that yields the lower uncertainties per unit machine time for compositions of interest.

The binomial estimator and the Σ_a/Σ_T non-terminating estimator are neutron conserving estimators. That is, in any RCP group where these estimators are used, the sum of the slowing-

down density at the bottom of the RCP group integrated over all space, the group absorption integrated over all space, and leakage in that group is equal to the group source integrated over all space (this assumes no $n \rightarrow 2n$ or $n \rightarrow 3n$ reactions).

In the thermal group, the estimator is either the binomial estimator or the Σ_a/Σ_T terminating estimator. For this group, the requestor has only limited control of estimator selection. Here, the binomial estimator is used automatically for any composition which has one or more fissionable nuclides with atom densities greater than or equal to 10^{-20} (a fissionable nuclide is any nuclide for which ν 's are provided in the RCPL1 library). The Σ_a/Σ_T terminating estimator is used in all other compositions.

As will be seen later, the neutron scattering weights and the absorption probability that results in a scattering weight of zero are determined in the same manner for both thermal estimators. Thus, reaction rates determined by the neutron conserving binomial estimator in fissionable compositions will be the same whether there was a neutron conserving binomial estimator used everywhere or whether there was a non-neutron conserving Σ_a/Σ_T terminating estimator used in all non-fissionable compositions. The above use of the two thermal estimators in RCP01 is an attempt to obtain multiplication factors and eigenfunctions as though neutron conserving estimators are used everywhere while at the same time acquiring the smaller standard deviation per unit machine time by use of the Σ_a/Σ_T terminating estimator in compositions which may have a large scattering to absorption ratio such as H_2O .

The three RCP01 estimators are described in Sections 3.2.1, 3.2.2, and 3.2.3 below. We also describe, in Section 3.2.4, a neutron conserving Russian roulette using the binomial estimator and the Σ_a/Σ_T terminating estimator that is available in the thermal group.

3.2.1 Binomial Estimator

Let the neutron incident weight be w at the collision point in composition j . Let the macroscopic absorption and scattering cross sections for nuclide i in composition j at the incident energy E be Σ_{aj}^i and Σ_{sj}^i . When the collision occurs, a check is made to see if

$$\rho \leq \frac{\sum_i \Sigma_{aj}^i}{\sum_i (\Sigma_{aj}^i + \Sigma_{sj}^i)}.$$

If this check is met, then the incident weight, w , is totally absorbed at this collision point, and for each nuclide i in composition j , an absorption rate estimate given by

$$w \frac{\Sigma_{aj}^i}{\sum_i \Sigma_{aj}^i}$$

is tallied. The exit energy and the exit weight are set to zero in this case, thus assuring that every neutron history will have a complete set of parameters to be picked up in subsequent RCP groups even though no additional transport will occur. If the above check fails, then no absorptions are tallied, and the full incident weight w is scattered.

3.2.2 Σ_a/Σ_T Non-Terminating Estimator

For this estimate, when a collision occurs, the fraction

$$\frac{\sum_i \Sigma_{aj}^i}{\sum_i (\Sigma_{aj}^i + \Sigma_{sj}^i)}$$

of the incident weight is absorbed, and the fraction

$$\frac{\sum_i \Sigma_{sj}^i}{\sum_i (\Sigma_{aj}^i + \Sigma_{sj}^i)}$$

is scattered. Thus, an absorption rate estimate for each nuclide i in composition j given by

$$w \frac{\Sigma_{aj}^i}{\sum_i (\Sigma_{aj}^i + \Sigma_{sj}^i)}$$

is tallied, and the exit weight given by

$$w \frac{\sum_i \Sigma_{sj}^i}{\sum_i (\Sigma_{aj}^i + \Sigma_{sj}^i)}$$

is scattered.

3.2.3 Σ_a/Σ_T Terminating Estimator

For this estimate, when a collision occurs in composition j in an analog neutron tracking process, a contribution may be made to the integrated collision density in composition j . This contribution is, of course, the incident neutron weight. Since the integrated collision density in

composition j is equal to the integrated neutron flux density in composition j times the total cross section of composition j , $\sum_i (\Sigma_{aj}^i + \Sigma_{sj}^i)$, then it follows that

$$w \frac{1}{\sum_i (\Sigma_{aj}^i + \Sigma_{sj}^i)}$$

is the contribution to the integrated neutron flux density in composition j resulting from the collision. Thus,

$$w \frac{\Sigma_{aj}^i}{\sum_i (\Sigma_{aj}^i + \Sigma_{sj}^i)}$$

is tallied as the absorption rate estimate for each nuclide i in composition j . The proper estimate of the integrated collision density requires that the neutron be terminated in the identical manner to the binomial estimator (i.e., an analog process). Thus, following the above tally, a check is made to see if

$$\rho \leq \frac{\sum_i \Sigma_{aj}^i}{\sum_i (\Sigma_{aj}^i + \Sigma_{sj}^i)}.$$

If this check is met, then the history is terminated without further tallies. If this test fails, then the neutron is scattered with its exit weight equal to w , its incident weight.

3.2.4 Neutron Conserving Russian Roulette

A special form of Russian roulette may be used with either the binomial or the Σ_a/Σ_T terminating estimator in the thermal group in compositions selected by the user. Russian roulette is desirable in some types of problems, for example, a multiplication factor calculation of an assembly with a large reflector. Here the method could be applied over a portion of the reflector to reduce the time spent following thermal neutrons that are unlikely to return to the core and contribute to the multiplication factor.

It should be emphasized that Russian roulette is a fair game, i.e., no approximations are involved, and the Monte Carlo solution will converge to the true solution as the number of histories becomes large. Conventional Russian roulette, however, is not neutron conserving for a finite number of histories, a particularly disturbing feature when used in multiplication factor calculations. Thus, a special form of Russian roulette has been devised which is very nearly neutron conserving (see Appendix D for a proof that it is a fair game). This special form is applied only once per neutron history. The details of the procedure are as follows: The compositions which are to use Russian roulette in the thermal group, say j_{RR} , together with their

respective Russian roulette kill-off probabilities, say $K_{j_{RR}}$, are specified by the requestor. On a neutron free flight just prior to a collision in composition j in the thermal group, Russian roulette is played if the following conditions are satisfied:

1. j must be one of the j_{RR} 's specified,
2. Russian roulette must not have been played previously in this history. Let a quantity δ be set to zero at the beginning of each history in the thermal group and set to 1 when Russian roulette is applied for the first time; then this condition is $\delta = 0$.

If we have a collision such that $j = j_{RR}$ and $\delta = 0$, then the following operations are performed in sequence:

1. Set $\delta = 1$.
2. Determine if kill-off should occur by use of a cumulative weight defect counter for composition j , say w_d^j . The w_d^j are initialized to zero at the beginning of a RCP01 problem. If $w_d^j > 0$, then

$$w_d^j = w_d^j - W$$

and the history is terminated.

3. The neutron has survived if $w_d^j \leq 0$. Set

$$w_d^j = w_d^j + \left[\frac{K_{j_{RR}}}{1 - K_{j_{RR}}} \right] W$$

and continue the history with new incident weight given by

$$W = W \left[\frac{1}{1 - K_{j_{RR}}} \right].$$

Here w is the new incident weight for the collision which is to be used in the usual manner with the binomial or Σ_a/Σ_T terminating estimator (for a more detailed discussion of this form of Russian roulette, see Appendix D).

3.3 Determination of Exit Neutron Parameters in the Fast Inelastic Groups

This section provides the details of the determination of the exit energy, E , the exit weight, w , and the exit direction cosines, μ, γ, η , for a neutron undergoing scattering in a fast inelastic

RCP group. We first consider the nature of the microscopic differential cross section data obtained from the job library and stored in memory at the beginning of the calculations for each such group. This is followed by a detailed description of the determination of neutron exit parameters. Throughout, we denote the incident parameters by $E_0, w_0, \mu_0, \gamma_0, \eta_0$. Here it is understood that w_0 is the weight of the neutron to be scattered, i.e., the weight surviving absorption.

3.3.1 Form of the Differential Cross Section Data in the Job Library

The following data are contained in the job library for each nuclide i :

1. Multigroup smooth absorption cross sections, $\sigma_a^i(\text{sm})$, for each nuclide i in multigroup n . For resonance nuclides, they are used as background corrections to explicit resolved or unresolved Doppler broadened resonance absorption cross sections. For nuclides without resonance detail, they are used as the total absorption cross sections.
2. Explicit Doppler broadened resolved or unresolved resonance absorption cross section, $\sigma_a^i(\text{res})$, tabulated at up to 500 uniform energy points spanning each fast inelastic group under consideration. If fission rates are desired, then the two nuclide method must be used.

As explained in the RCPL1 report (Reference 2) fissile nuclides are represented by two RCP nuclides, the first having the nuclide's capture cross section as σ_a and its scattering cross section as σ_s , and the second having the nuclide's fission cross section as σ_a and zero as the σ_s . v_s are defined only for the second nuclide. Users must include the nuclide's concentration for both RCP nuclides.

3. Explicit Doppler broadened resolved or unresolved elastic scattering resonance cross sections, σ_s^i , including interference scattering, superimposed with the multigroup smooth scattering as a background correction, or as a total scattering for nuclides without resonance detail, and tabulated over the same fine energy structure as used for the absorption cross sections.
4. The first four Legendre components of elastic scattering in the center of mass system, $B_0^i, B_1^i, B_2^i, B_3^i$, tabulated over multigroups n , $1 \leq n \leq 28$. The lower cutpoint of a fast inelastic group is not permitted to be lower than the lower cutpoint of multigroup 28.
5. Data for energy dependent equiprobability interval histogram elastic scattering. These data comprise:
 - (a) N energies E_p , $i = 1, 2, \dots, N$.
 - (b) $N \cdot (n + 1)$ cosines of scattering angles μ_{ij} ($j = 0, 1, \dots, n$, $i = 1, 2, \dots, N$).

6. The isotropic component of the inelastic scattering cross section combined with the isotropic component of $(n, 2n)$, $(n, 3n)$ cross sections, σ_{in}^i , and tabulated over multigroups 1 to 28 inclusive.
7. An inelastic scattering matrix, superimposed with the matrices for $(n, 2n)$, $(n, 3n)$ reactions, tabulated over multigroups 1 to 28 inclusive. Usually, the incident and exit energies for inelastic scattering are in the range 20 MeV to 5.53 keV. This matrix is obtained in the following form from the RCPL1 job library. If $p^{n \rightarrow m, i}$ is the probability of neutron energy transfer from multigroup n to multigroup m for nuclide i , then matrix $\sigma_{in}^i p^{n \rightarrow m, i}$ is the input to RCPL1. Observe that

$$\sum_{m \geq n} p^{n \rightarrow m, i} = 1$$

if $(n, 2n)$ or $(n, 3n)$ reactions are not present. Otherwise, this quantity is greater than 1. RCPL1 transforms the above matrix to a cumulative matrix, say $\bar{a}^{nm, i}$, by the operation

$$\bar{a}^{nm, i} = \sum_{m' = n}^m \frac{\sigma_{in}^i p^{n \rightarrow m', i}}{\sigma_{in}^i}$$

This cumulative matrix is stored in the RCPL1 job library.

8. The nuclide mass, A^i , measured in units of neutron mass.

3.3.2 Construction of Macroscopic Cross Sections at Neutron Incident Energy

In all RCP groups, there is a coarse and a fine set of subintervals over which microscopic cross sections are held. The coarse structure consists of the whole and partial multigroups contained within the RCP group. Knowing E_0 , then, for nuclide i in composition j , microscopic values of $\sigma_a'(sm)$, B_0' , B_1' , B_2' , B_3' , σ_{in}' , and $\bar{a}^{nm, i}$ are found by simply determining the multigroup n that contains E_0 . This is done by finding multigroup cutpoints such that

$$E^{n+1} < E_0 \leq E^n$$

which defines multigroup n .

The fine subintervals are an integral number of uniform energy intervals spanning the RCP group. These fine energy intervals are numbered in RCP, as are all energy intervals, by starting with the highest energy and working down. In general, values of $\sigma_a^i(res)$ and σ_s^i are obtained at E_0 by linearly interpolating the fine mesh values. The cross sections are tabulated at the cut-

points of intervals. Thus, if E^k and E^{k+1} are upper and lower cutpoints of the RCP group g and if N intervals were used when performing the job library construction by RCPL1, then the fine interval number containing E_0 is given by the integral part of

$$\frac{(E^k - E_0)}{(E^k - E^{k+1})/N} + 1.$$

The fractional part of this same number then provides the weighting function to interpolate the cross section between the upper and lower cutpoints of the interval.

It was stated above that, in general, values of $\sigma_a^i(res)$ and σ_s^i are obtained by linear interpolation. An exception occurs if these cross sections are unresolved. In this case, RCP01 uses the nearest value. The reason for this is described in detail in an Appendix of the RCPL1 report (Reference 2). In this case, the program uses the fractional part of the quantity above to decide whether to use the cross section at the upper or lower cutpoint of the fine interval, according to which cutpoint is closer.

After obtaining the microscopic data described above, the input atom densities for each nuclide i in composition j are used to form the following macroscopic cross sections:

1. Smooth absorption, $\Sigma_a^i(sm)$,
2. Resonance absorption, $\Sigma_a^i(res)$,
3. Elastic scattering, Σ_s^i ,
4. Inelastic scattering, Σ_{in}^i .

Note that $\bar{a}^{nm,i}$ does not require atom densities. The B_l components of elastic scattering do, but they are used in RCP01 only as ratios, hence the atom densities may be omitted.

3.3.3 Determination of Type of Scattering

The total scattering cross section for nuclide i in composition j , say Σ_{Ts}^i , is given by

$$\Sigma_{Ts}^i = \Sigma_s^i + \Sigma_{in}^i.$$

DETAILED CROSS SECTIONS

RCP ENERGY ($\sigma(E)$ VS E) DATA
GROUPS BKPTS
 $2 \leq G \leq 200$
 $1 \leq \text{NFG} \leq 57$
GROUPWISE CONSTANT
DATA

I - NUMBER OF INELASTIC GROUPS
 G - TOTAL NUMBER OF RCP GROUPS
 NFG - NUMBER OF MULTIGROUPS

Figure 3-1 RCP Energy Group Structure

The nuclides contained in composition j may be ordered with an index, say i . A value of i , and thus the identification of the nuclide i with which the neutron scatters, is obtained by solving the inequality

$$\sum_{i'=1}^{i-1} \Sigma_{Ts}^{i'} < \rho \Sigma_{Ts} \leq \sum_{i'=1}^i \Sigma_{Ts}^{i'}$$

where

$$\Sigma_{Ts} = \sum_i \Sigma_{Ts}^i.$$

Knowing the scattering nuclide i , another random number is used to decide whether the scattering is elastic or inelastic. If $\rho < \Sigma_s^i / \Sigma_{Ts}^i$, then the scattering is elastic. Otherwise, it is inelastic.

3.3.4 Treatment of Elastic Scattering

If the scattering is elastic, then the direction cosine, μ_c , of the scattering angle relative to the incident neutron direction in the center of mass system is obtained using either of two methods as determined by user option.

The first method selects from the P-3 Legendre polynomial distribution specified by B_0^i , B_1^i , B_2^i , and B_3^i . The second method selects from the equiprobability interval histograms specified by the E_i and μ_{ij} data.

3.3.4.1 Summary of Selection of Scattering Angle From the Legendre Polynomial Scattering Pattern

First, ratios of the B 's to B_0^i are formed to define

$$f_1^i = (B_1^i / B_0^i),$$

$$f_2^i = (B_2^i / B_0^i),$$

$$f_3^i = (B_3^i / B_0^i).$$

Then, the scattering pattern in the center-of-mass system, $f^i(\mu_c)$, is given by

$$f^i(\mu_c) = \frac{1}{2} + \frac{3}{2}\mu_c f_1^i + \frac{5}{4}(3\mu_c^2 - 1)f_2^i + \frac{7}{4}(5\mu_c^3 - 3\mu_c)f_3^i.$$

The scattering pattern is put into a discrete ordinate form using 4 Gaussian ordinates. This procedure is a natural consequence of the equivalence between spherical harmonics and discrete ordinates discussed in Reference 5. The discrete ordinate scattering pattern preserves the value of the P-3 components when 4 ordinates are used.

The discrete ordinate pattern can have negative ordinates. When this occurs in RCP01, the pattern is altered by starting with the most forward negative ordinate and moving it to the adjacent ordinate toward $\mu_c = -1$ and adding. If the result is still negative then this combined

ordinate is further moved to the next adjacent ordinate toward $\mu_c = -1$ and added. The process is continued until all ordinates are positive or all are positive except the last. In this latter case this last negative ordinate is moved to the next adjacent ordinate toward $\mu_c = +1$ and added. If this result is still negative, then this combined ordinate is further moved to the next adjacent ordinate toward $\mu_c = +1$ and added. This process is continued until all ordinates are positive. The resulting discrete ordinate pattern is the one used by RCP01.

The end result of so moving the negative ordinates is to construct a reasonable block histogram of the scattering pattern in discrete ordinate form, although only the P_0 component is now, in general, rigorously preserved. The discrete ordinate pattern is converted to a four block histogram so that a continuum of μ_c will exist.

3.3.4.2 Details of Selection of Scattering Angle From the Legendre Polynomial Elastic Scattering Pattern

Starting with the P-3 scattering pattern $f^i(\mu_c)$, one may re-obtain the individual P-components by

$$P_l^i = \int_{-1}^1 f^i(\mu_c) P_l(\mu_c) d\mu_c, \quad l = 0, 1, 2, 3.$$

Since the polynomial in the integrand is, at most, of degree 6, and since a Gaussian quadrature with m ordinates will integrate rigorously a polynomial of degree $2m-1$, or degree 7 if $m = 4$, then we may write the following:

$$P_l^i = \sum_{k=1}^m H_k f^i(\mu_k) P_l(\mu_k), \quad l = 0, 1, 2, 3.$$

where H_k are Gaussian weights, μ_k are Gaussian abscissas, and $m = 4$. It is clear that the same P_l^i components would result if the continuous scattering pattern, $f^i(\mu_c)$, were assumed to be δ - functions of strength $H_k f^i(\mu_k)$ at the locations μ_k . Thus the discrete ordinate pattern, say F_k , is the following:

$$F_k^i = H_k f^i(\mu_k), \quad k = 1, \dots, m.$$

These F_k are normalized, such that

$$\sum_{k=1}^m F_k = 1$$

and furthermore, some F_k 's may be negative. We may write

$$F_k^i = A_0^k + A_1^k f_1^i + A_2^k f_2^i + A_3^k f_3^i$$

where

$$A_0^k = \frac{1}{2} H_k$$

$$A_1^k = \frac{3}{2} \mu_k H_k$$

$$A_2^k = \frac{5}{4} (3\mu_k^2 - 1) H_k$$

$$A_3^k = \frac{7}{4} (5\mu_k^3 - 3\mu_k) H_k \text{ and}$$

where k takes on the values 1,..., 4. $k = 1$ is the most forward ordinate, i.e., toward $\mu = +1$.

The values of μ_k , H_k , A_0^k , A_1^k , A_2^k , and A_3^k are given in Table 3-1. The values of μ_k and the A 's are stored permanently in RCP01. Thus, from f_1^i , f_2^i , and f_3^i , each desired ordinate F_k^i is obtained with 3 multiplications and 3 additions.

Table 3-1 Scattering Ordinates and Weights

Four Ordinate Option						
k	μ_k	H_k	A_0^k	A_1^k	A_2^k	A_3^k
1	0.861136	0.347855	0.173927	0.449326	0.532507	0.371023
2	0.339981	0.652145	0.326072	0.332575	-0.532507	-0.939774
3	-0.339981	0.652145	0.326072	-0.332575	-0.532507	0.939774
4	-0.861136	0.347855	0.173927	-0.449326	0.532507	-0.371023

Given the values defined above, a random number ρ is used to select a scattering angle ordinate, k , in the following way:

If $\rho \leq F_1^i$, then $k = 1$;

if $\rho^* \leq F_1^i + F_2^i$, then $k = 2$;

if $\rho^* \leq F_1^i + F_2^i + F_3^i$, then $k = 3$;

otherwise, $k = 4$.

Once the value of k , and hence μ_k , is known, the value of the direction cosine of the scattering angle, μ_c , in the center-of-mass system is drawn flat over a range enclosing μ_k , so that the 4 possible ranges define a block histogram from $\mu_c = -1$ to $\mu_c = +1$. These ranges are defined by requiring that an isotropic pattern be treated rigorously; thus the magnitude of the range associated with μ_k is $2A_0^k$. The cutpoints of the ranges are the following: $1, 1 - 2A_0^1, 0, -1 + 2A_0^1, -1$.

A random number determines the center-of-mass μ_c scattering angle drawn flat from the k^{th} range.

3.3.4.3 Selection of Scattering Angle Using Equiprobability Interval Histograms

In this option, the incident energy E_0 is used to select a histogram and a random number is used to select an interval $\mu_{ij} \leq \mu \leq \mu_{i,j+1}$, and μ_c from the interval. Details of this treatment can be found in Appendix C.

3.3.4.4 Determination of E, W, μ, γ, η

The azimuthal angle ϕ in, radians, i.e., the angle measured in a plane perpendicular to the incident neutron direction, and hence the same in the center-of-mass or lab system (see Figure 3-2), is given by $\phi = \pi(2\rho - 1)$.

For elastic scattering, the exit energy of the neutron is determined by the cosine of the scattering angle, μ_c , and the inverse mass of the scattering nuclide i , $\gamma^i = 1/A^i$ (mass A^i is measured in units of neutron mass). Given these values,

$$E = E_0 \left[1 - (1 - \mu_c) \frac{2\gamma^i}{(1 + \gamma^i)^2} \right].$$

The exit neutron weight is not altered by elastic scattering and hence equals the neutron weight surviving absorption, i.e., $W = W_0$.

The scattering angle in the lab system, say μ' , relative to the incident neutron direction is given by

$$\mu' = \frac{\gamma^i + \mu_c}{[(\gamma^i + \mu_c)^2 + (1 - \mu_c^2)]^{1/2}}.$$

Finally, the exit direction cosines, μ, γ, η , in the lab system are obtained, see Figure 3-2, as

$$\begin{aligned}\mu &= \mu' \mu_0 - \sqrt{(1 - \mu_0^2)(1 - \mu'^2)} \cos \varphi, \\ \gamma &= \mu' \gamma_0 + \sqrt{\frac{1 - \mu'^2}{1 - \mu_0^2}} [\mu_0 \gamma_0 \cos \varphi - \eta_0 \sin \varphi], \\ \eta &= \mu' \eta_0 + \sqrt{\frac{1 - \mu'^2}{1 - \mu_0^2}} [\mu_0 \eta_0 \cos \varphi + \gamma_0 \sin \varphi].\end{aligned}$$

where absolute values are used in the above expressions to avoid problems caused by machine round-off errors.

Should the exit neutron energy E lie in the epithermal binding range or the thermal group, then the exit energy and exit direction cosines μ, γ, η may be further altered. The complete description of this process is given in Reference 15. This process is briefly discussed in Section 3.5.2.

This completes the determination of the exit parameters, E, W, μ, γ, η , for elastic scattering in the fast inelastic groups.

3.3.5 Treatment of Inelastic Scattering

When a scattering event is determined to be inelastic, by the technique described in Section 3.3.3, the following procedure is used to determine the exit parameters:

1. If E_0 is in multigroup n , then the multigroup m containing the exit energy is obtained by random sampling by finding m such that

$$\bar{a}^{nm-1,i} \leq \rho \bar{a}^{nM,i} < \bar{a}^{nm,i}$$

where the $\bar{a}^{nm,i}$ are defined in Section 3.3.1.

2. Given m , selected in step 1, with E_m and E_{m+1} the upper and lower cutpoints of the multigroup, the exit energy, E , for inelastic scattering is randomly sampled as follows:

$$E = E_{m+1} + (E_m - E_{m+1}) \frac{\bar{a}^{nm,i} - \rho \bar{a}^{nM,i}}{\bar{a}^{nm,i} - \bar{a}^{nm-1,i}}$$

where $\bar{a}^{n0,i} \equiv 0$. Note: In order to preclude upscattering, E_0 replaces E_m in this formula whenever in-group scattering occurs (i.e., $m = n$).

The sum of the projections of the vector μ' , and the three orthogonal vectors, $\sqrt{1-\mu'^2} \sin \theta$, $\sqrt{(1-\mu_0^2)(1-\mu'^2)} \cos \theta$, and $\mu_0 \sqrt{1-\mu'^2} \cos \theta$ on the x -axis yields μ ; on the y -axis yields γ ; and on the z -axis yields η .

Figure 3-2 Exit Direction Cosines in Lab System

3. The exit weight of the neutron, adjusted for $(n, 2n)$ and $(n, 3n)$ reactions, is given by

$$W = \bar{a}^{nM,i} W_0,$$

where M is the number of inelastic multigroups ($M \leq 28$).

4. The exit direction cosines, μ, γ, η , in the lab system are obtained as in Section 3.3.3.4 using

$$\begin{aligned}\mu_c &= 2\rho - 1 \\ \theta &= \pi \cdot (2\rho - 1)\end{aligned}$$

$$\text{and } \mu' = \frac{x + \mu_c}{[(x + \mu_c)^2 + (1 - \mu_c^2)]^{\frac{1}{2}}}$$

$$\text{where } x = \sqrt{\frac{E_0}{E}} \left(\frac{\gamma^i}{1 + \gamma^i} \right).$$

This completes the determination of exit parameters E, W, μ, γ, η for inelastic scattering in the fast inelastic groups.

If $E < E_b[1 + 2\rho]$, the epithermal binding adjustment is applied as discussed in Section 3.5.2.

3.4 Determination of Exit Neutron Parameters in the Resonance Groups

This section provides the details of the determination of E, W, μ, γ , and η for a neutron scattered in a resonance group.

3.4.1 Form of the Differential Cross Section Data in the Job Library

The form of the differential cross section data on the job library for a resonance group is identical to that for a fast inelastic group with the following exceptions:

1. In these groups, the differential scattering cross section is treated as isotropic for all nuclides. Therefore, the data specifying the elastic scattering cross section in the center of mass system are not present in the library.
2. No inelastic scattering is treated in these groups. Therefore, inelastic cross sections and matrices are not present in the library.
3. The fine energy structure for tabulating resonance cross section detail may consist of up to 1000 uniform energy intervals per resonance RCP group rather than the maximum of 500 permitted in fast inelastic groups.

3.4.2 Construction of Macroscopic Cross Sections at Incident Neutron Energy

The manner of obtaining macroscopic cross sections at an incident neutron energy in composition j , is identical to that used in the fast inelastic groups.

3.4.3 Determination of Type of Scattering

This step is not needed since the only type of scattering treated is elastic scattering.

3.4.4 Treatment of Elastic Scattering

The treatment is identical to that in the fast inelastic groups except that the cosine of the scattering angle in the center of mass system, μ_c , is sampled uniformly using the equation:

$$\mu_c = 2p - 1.$$

3.5 Determination of Exit Neutron Parameters in the Epithermal Binding Range

3.5.1 Scattering Treatment

The scattering process in the epithermal binding range is identical to that used in resonance groups, except that bound proton targets are not assumed to be at rest. The only additional nuclear data required is the effective “source” temperature, T_i^* , of each nuclide.

A value of T^* is available from the job library. However, T^* is not strongly medium-temperature dependent for a given material, thus a compromise T^* may be supplied by the RCP01 user if bound protons with more than one value of T^* appear in the same problem. Binding effects in water are quite important at energies above 0.625 eV, a commonly used thermal cut-point. Furthermore, an accounting of such binding effects is essential to obtain an accurate slowing-in-source to the thermal group.

The epithermal binding range defaults to the last RCP group before the thermal group, with an energy range from E_{G-1} to E_G , where E_G normally equals 0.625 eV. However, on user option the explicit treatment of bound proton scattering may start at a user supplied energy of E_{eb} rather than E_{G-1} . This optional input energy E_{eb} controls only bound proton scattering. The last epithermal group for defining cross sections, and other tasks, still has the range E_{G-1} to E_G . For discussion purposes we will assume that E_{eb} has not been supplied, but when giving RCP calculational steps both approaches will be covered.

The procedure used in the RCP01 epithermal binding range to determine the exit parameters from scattering is summarized as follows:

RCP01 has separate treatments for epithermal binding for light, hydrogen and deuterium, and other (“heavy”) nuclides. The treatments also vary by energy range and are described in Reference 15.

1. Given that a bound proton scattering event has occurred, using bound proton cross-sections, a candidate target velocity vector is drawn randomly from a Maxwellian distribution at the effective "source" temperature T^* .
2. Since the probability that the scattering involves a particular target velocity vector is proportional to the magnitude of the relative velocity, a rejection technique is applied to decide whether to accept or reject each candidate target velocity. (Note: This assumes that the scattering cross section is energy independent so that the number of scattering reactions resulting from a neutron beam incident on a moving thin target sample is proportional to the volume of the beam "swept" by the sample per unit time, i.e., proportional to the relative velocity.)
3. Once a target velocity vector is accepted, the usual center-of-mass kinematics is employed provided the neutron downscatters. Upscattering is not permitted.

Note: Theoretical justification for this method of treating bound proton scattering above 0.625 eV is given in Reference 15.

In addition to the procedure described above for the epithermal binding range, another procedure is used within the fast inelastic and resonance groups whenever the exit energy falls within the epithermal or thermal groups to correctly account for bound proton scattering at higher energies. This is described next.

3.5.2 Epithermal Binding

If the scattering nuclide i is one for which epithermal binding is to be treated, then if $E < E_{eh}[1 + 2\rho]$, the exit energy E is adjusted as described in Reference 15. E_{eh} , normally about 10eV, is the nominal energy below which epithermal binding is to be accounted for and ρ is a random number. Detailed kinematics is used for light nuclides ($A < 2.5$) and an effective α treatment is used for heavy nuclides ($A \geq 2.5$).

3.6 Determination of Exit Neutron Parameters in the Thermal Group

This section provides the details of the determination of E, w, μ, γ, η for a neutron scattered in the thermal group.

3.6.1 Form of the Cross Section Data in the Job Library.

The job library contains the following information for the thermal group:

1. Thermal energy coarse mesh points, $E^1, \dots, E^N$ where E^1 is the upper cutpoint of the thermal group and $E^N > 0$. The maximum value of N is 25. These points are used to

indirectly determine the size and range of N thermal coarse groups (or “multigroups”) by defining the n^{th} group as extending from $(E^n + E^{n+1})/2$ to $(E^n + E^{n-1})/2$, where $E^0 = E^1$ and $E^{N+1} = 0$.

2. The smooth absorption cross sections for all nuclides as well as the smooth scattering cross sections for non-resonance nuclides are defined as a histogram in energy over the above coarse thermal groups with the exception that the smooth cross section in group N extends to $E = 0$.
3. The absorption cross sections for resonance nuclides are defined on a uniform fine energy mesh of up to 299 points in the RCP thermal group extending from E^1 to 0 eV. (Note: cross sections at $E = 0$ are actually calculated at $E = 10^{-8}$ to avoid singularities that would occur in asymmetric resonance absorption cross sections).
4. The scattering cross section for a resonance nuclide in the RCP thermal group is tabulated over the fine energy mesh (299 points maximum) and is the superposition of the resonance scattering over the fine mesh and the smooth scattering in histogram form over the coarse mesh.
5. P-3 double differential thermal kernels are defined as histograms over the coarse thermal groups (the kernel nuclides cannot be resonance nuclides). The thermal kernels are “closed on themselves” in that a kernel energy transfer cannot occur above the upper energy cutpoint, E^1 , nor below the lower cutpoint of coarse group N , i.e., $E^N/2$. Of course, slowing down neutrons or source neutrons can exist down to $E = 0$. Each P-3 thermal kernel in the job library consists of four $N \times N$ matrices which are labeled $C_0^{nm}, C_1^{nm}, C_2^{nm}, C_3^{nm}$, where n is the incident group and m is the exit group ($1 \leq n \leq N, 1 \leq m \leq N$). These matrices are described below.

3.6.1.1 Description of C Matrices for Thermal Kernels

Let $\sigma(E_0 \rightarrow E, \mu')$ be a double differential thermal cross section in the lab system, such that

$$\frac{\sigma(E_0 \rightarrow E, \mu') dE d\mu'}{\iint \sigma(E_0 \rightarrow E, \mu') dE d\mu'}$$

is the probability that a neutron with incident energy E_0 and scattering angle cosine in the lab system in the interval $d\mu'$ about μ' will have, after a scattering event, an exit energy in the interval dE about E . (Note: $\mu' = 1$ is along the incident direction.)

Expanding $\sigma(E_0 \rightarrow E, \mu')$ in a P-3 Legendre polynomial expansion in μ' , we have:

$$\sigma(E_0 \rightarrow E, \mu') = \sum_{l=0}^3 \frac{2l+1}{2} \sigma_l(E_0 \rightarrow E) P_l(\mu').$$

The most detailed means of obtaining a histogram representation of the Legendre components $\sigma_l(E_0 \rightarrow E)$, say on $\sigma_l^{n \rightarrow m}$, is by an energy integration over exit group m and a flux averaging over incident group n , as follows:

$$\sigma_l^{n \rightarrow m} = \frac{\int_{\text{group } m} dE \int_{\text{group } n} dE_0 \varphi_l(E_0) \sigma_l(E_0 \rightarrow E)}{\int_{\text{group } n} dE_0 \varphi_l(E_0)}$$

where $\varphi_l(E_0)$ is an estimate of the l^{th} Legendre component of the thermal flux.

The simplest means of obtaining a histogram representation is to assume that the quantity $\sigma(E_0 \rightarrow E)$ is a constant, $\sigma(E^n \rightarrow E^m)$, for any E_0 in group n and any E in group m . Using the coarse energy mesh and coarse group description, this then results in the following:

$$\sigma_l^{n \rightarrow m} = \sigma_l(E^n \rightarrow E^m) \cdot \frac{1}{2}(E^{m-1} - E^{m+1}).$$

The thermal kernel matrices for RCP are normally defined by this latter equation. However, the thermal matrices are often used for calculations where it is more convenient to use C-matrices defined as follows:

$$C_l^{nm} = \sigma_l(E^n \rightarrow E^m) \cdot \frac{1}{2}(E^{n-1} - E^{n+1}).$$

It is the set of matrices C_l^{nm} , $l = 0, \dots, 3$ which constitutes a thermal kernel in the RCP job library. The probability of a neutron energy transfer from group n to m is given by

$$\frac{\sigma_0^{n \rightarrow m}}{\sum_{m=1}^N \sigma_0^{n \rightarrow m}}$$

The C_0^{nm} matrix, upon being read into RCP01, is transformed into a convenient cumulative form, $\bar{P}_0^{nm}$, for obtaining energy transfer probabilities as follows:

$$\bar{P}_0^{nm} = \sum_{m=1}^n C_0^{nm} \frac{(E^{m-1} - E^{m+1})}{(E^{n-1} - E^{n+1})}.$$

Note that $\bar{P}_0^{nN}$ could be used as the scattering cross section for group n for the kernel nuclide. However, this is not done in RCP01. Instead, the scattering cross section appears separately in the job library over the coarse group, and does not in general exactly equal $\bar{P}_0^{nN}$.

The other C-matrices, upon being read into RCP01, are transformed into the following convenient normalized forms:

$$\begin{aligned} f_1^{nm} &= C_1^{nm} / C_0^{nm}, \\ f_2^{nm} &= C_2^{nm} / C_0^{nm}, \\ f_3^{nm} &= C_3^{nm} / C_0^{nm}. \end{aligned}$$

3.6.2 Construction of Macroscopic Cross Sections at Incident Neutron Energy

The microscopic smooth absorption for all nuclides and the microscopic smooth scattering for non-resonance nuclides are defined at the incident neutron energy, E_0 , once the incident group index n is determined. This index is determined by finding the smallest n such that

$$\frac{1}{2}(E^n + E^{n+1}) < E_0$$

If this condition is still not satisfied when $n = N$, then set $n = N$; this extends the smooth cross sections to $E = 0$. The group index n is also the incident group index required for a neutron collision with a nuclide with an energy transfer matrix.

The microscopic cross sections for resonance absorption as well as the scattering cross sections for resonance nuclides are obtained by linear interpolation over the fine energy mesh of the job library data in exactly the same way as in the fast energy range.

After obtaining the microscopic data described above, the input atom densities for each nuclide i in composition j are used to compute the following macroscopic cross sections:

1. Smooth absorption, $\Sigma_a^i(sm)$,
2. Resonance absorption, $\Sigma_a^i(res)$, and
3. Total scattering, Σ_s^i .

As already discussed, for each kernel nuclide the matrices $\bar{P}_0^{nm}, f_1^{nm}, f_2^{nm}, f_3^{nm}$ are also available. The only additional datum from the job library used in the thermal group is the nuclide mass, A' , measured in neutron mass units for each non-kernel nuclide.

3.6.3 Determination of Type of Scattering

The nuclides contained in composition j are ordered with an index, say i . A value of i , and thus the identification of the nuclide i with which the incident neutron scattered is obtained by solving the following equation for i :

$$\sum_{i=1}^{i-1} \Sigma_s^i < \rho \Sigma_{Ts} \leq \sum_{i=1}^i \Sigma_s^i$$

where $\Sigma_{Ts} = \sum \Sigma_s^i$. The selected scattering nuclide i then determines the type of scattering. That is, the scattering nuclide i is identified as either a “kernel” nuclide or as a “non-kernel” nuclide.

3.6.4 Treatment of Kernel Nuclide Scattering

When a scattering event occurs with a kernel nuclide, we have available the neutron incident energy group, n , and the matrices, $\bar{P}_0^{nm}, f_1^{nm}, f_2^{nm}, f_3^{nm}$. Since integration over the cosine of the lab system scattering angle yields the lab system P_0 Legendre component of the scattering pattern, we may immediately obtain an exit neutron group, m , by using $\bar{P}_0^{nm}$ as a cumulative distribution function. That is, a value of m is obtained by solving for m , such that

$$\bar{P}_0^{nm-1} < \rho \bar{P}_0^{nN} \leq \bar{P}_0^{nm}.$$

A continuum of exit energies is obtained by drawing an exit energy from a flat distribution over the domain of exit group m . Thus,

$$E = \frac{1}{2} \left[E^m + E^{m+1} - \left(\frac{\rho \bar{P}_0^{nN} - \bar{P}_0^{nm}}{\bar{P}_0^{nm} - \bar{P}_0^{nm-1}} \right) (E^{m-1} - E^{m+1}) \right]$$

where it is understood that $\bar{P}_0^{n0} = 0, E^0 = E^1, E^{N+1} = 0$.

The exit neutron weight, w , is not altered by kernel nuclide scattering, and therefore equals the incident weight, provided that kill-off does not occur at the collision, as described in Section 3.2.4.

The incident group n and exit group m define the lab system P-3 scattering pattern, $f(\mu')$, as follows:

$$f(\mu') = \frac{1}{2} + \frac{3}{2} \mu' f_1^{nm} + \frac{5}{4} (3\mu'^2 - 1) f_2^{nm} + \frac{7}{4} (5\mu'^3 - 3\mu') f_3^{nm}.$$

The cosine of the lab system scattering angle, μ' , relative to the incident neutron direction is randomly obtained using this distribution function in exactly the same way as the center of mass scattering pattern was treated using the Legendre polynomial option in the fast inelastic group. That is, a value of μ' is obtained by the use of a four block histogram based on 4 Legendre-Gauss ordinates.

The azimuthal scattering angle, ϕ , in radians measured in a plane perpendicular to the incident neutron direction is given by $\phi = \pi(2\rho - 1)$. Knowing μ' , ϕ , and the incident neutron direction cosines μ_0, γ_0, η_0 , we may obtain the exit direction cosines μ, γ, η , as follows:

$$\begin{aligned}\mu &= \mu'\mu_0 - \sqrt{|(1 - \mu_0^2)(1 - \mu'^2)|} \cos \phi \\ \gamma &= \mu'\gamma_0 + \sqrt{\frac{1 - \mu'^2}{1 - \mu_0^2}} [\mu_0\gamma_0 \cos \phi - \eta_0 \sin \phi] \\ \eta &= \mu'\eta_0 + \sqrt{\frac{1 - \mu'^2}{1 - \mu_0^2}} [\mu_0\eta_0 \cos \phi + \gamma_0 \sin \phi]\end{aligned}$$

where absolute values are used in the above expressions to avoid round off difficulties. This completes determination of the exit parameters, E, W, μ, γ, η for kernel nuclide scattering in the thermal group.

3.6.5 Treatment of Non-kernel Nuclide Scattering

In RCP, non-kernel nuclide scattering in the thermal group does not result in energy exchange, therefore the exit neutron energy, E , equals the incident neutron energy, E_0 . The neutron weight, w , is also not altered by non-kernel nuclide scattering, and therefore the exit weight equals the incident weight, unless kill-off occurs at the collision, as described in Section 3.2.4.

The angular pattern and the determination of the exit direction cosines are treated exactly the same as for kernel nuclide scattering except that the lab system scattering pattern, $f(\mu')$, is taken to be the P-1 pattern consistent with isotropic scattering in the center of mass system for nuclide i . That is,

$$f(\mu') = \frac{1}{2} + \frac{3}{2}\mu'\bar{\mu}$$

where, $\bar{\mu} = 2/(3A')$, and A^i is the i^{th} nuclide mass measured in neutron mass units.

This completes determination of the exit neutron parameters E, W, μ, γ, η for non-kernel nuclide scattering in the thermal group.

4 GEOMETRY DESCRIPTION AND GEOMETRY OF SOURCE START

4.1 General Description of RCP01 Geometries

The buildup of a complex geometry in RCP01 starts with the definition of an initial assembly. An initial assembly is the simplest geometry level at which the neutron tracking may be treated as a problem unto itself. A more complex geometry results when initial assemblies are used in a final assembly laydown. Maximum generality in geometry is obtained with initial modules (collections of final assemblies which may include composite final assemblies), final modules, and module 0. A summary of each of the geometrical building blocks follows.

4.1.1 Initial Assembly

An initial assembly's exterior boundary is a parallelepiped with sides parallel to an x,y,z initial assembly coordinate system. The z -axis of this system is perpendicular to the plane formed by the x - y axes. The angle between the x and y axes may be either 90° or 60° depending on the option selected. The 60° capability exists due to RCP01's development for the LWBR program at Shippingport.

The interior domain of an initial assembly is subdivided into smaller parallelepipeds called basic regions by planes parallel to the x - z and y - z coordinate axes. Each basic region may itself be subdivided into a still smaller array of parallelepipeds called subcells, and finally, each subcell may be broken up into multiple regions by elliptical cylinders whose axes are parallel to the initial assembly z -axis. Thus, for example, within a subcell we may readily define a fuel rod with clad.

Additionally, slab regions may be represented within a subcell by making the major axis of an elliptical cylinder very large. A double truncation occurs when subcells are used. First, the elliptical cylinders are truncated by the x - y subcell boundaries; and second, the subcells are truncated by the x - y basic region boundaries. Axial zones are defined by z -planes which cut across the entire domain of an initial assembly, including all basic regions and subcells.

4.1.2 Final Assembly

A final assembly is an initial assembly which has been located relative to an initial module coordinate system (described below). A translation of the initial assembly is made in x and y (translation in z is not permitted at this stage). The initial assembly may then be rotated about its z -axis by a multiple of the angle between the x and y axes (90° or 60° , depending on the option selected). On option the initial assembly can also be converted by a reflection (mirror image) about its local x axis. As described below, in 60° geometry, the x - y exterior boundaries of the initial assembly may also be altered to form a triangle or a trapezoid. Finally, the compositions may be perturbed in a final assembly by a one-to-one conversion of selected compositions in the original initial assembly. The definitions of final and initial assemblies outlined above are sufficiently flexible to permit detailed three-dimensional full-core representations.

4.1.3 Composite Final Assembly

A composite final assembly may be used in place of any ordinary final assembly. It consists of up to eight initial assemblies such that all of the up to seven “secondary” (all but the first) initial assemblies are totally contained within the first (“primary”). The secondary initial assemblies override the primary over the domain of the secondaries. They may be arbitrarily oriented relative to the primary within the constraint of remaining totally contained within the primary and being mutually disjoint.

Composite final assemblies are especially useful when there are subregions in which it is desirable to have the axes of elliptical cylinders in a subcell oriented in a direction in space which differs from the z -axis of the primary initial assembly.

4.1.4 Initial Module

A collection of final assemblies, all of the same height in the z direction, are laid down together to define an initial module. After laydown the requestor must ensure that the final assemblies are located such that internal gaps or overlaps do not exist between final assemblies. Each side of each final assembly must either be totally uncovered (“free”) or totally covered by sides of other final assemblies.

Exterior boundaries of initial modules will become boundaries through which neutrons may enter module 0, i.e., the intermodule region. The coordinate system used to locate the final assemblies within an initial module is known as the initial module coordinate system.

4.1.5 Final Module

A final module is an initial module which has been located and oriented in space relative to the absolute (module 0) x,y,z coordinate system. This is done by specifying the location and orientation of the initial module coordinate system within the absolute coordinate system. (See Figure 10-8.) First the intersection of the initial module z axis with the absolute x - y plane

is identified. This may be followed by a translation in z of the initial module along the initial module z axis. (The intersection of the initial module z axis with the absolute x - y plane does not change in this translation). The z axis of the initial module is then oriented in space by specifying two angles. The initial module may be rotated about its z axis by specifying a third angle. Finally, the compositions may be perturbed in a final module by a one-to-one conversion of selected compositions in the initial module.

Arbitrary gaps may exist between final modules. However they may not touch or overlap one another. The definitions of initial and final modules are sufficiently flexible to permit detailed three-dimensional representations of very complex cores.

4.1.6 Module 0

Module 0 is the outermost geometric construct and consists of the collection of intermodule regions. It is divided by a concentric set of circular cylinders whose common axis is the absolute z -axis. Specification of z -planes permits axial zones for each cylinder. The outermost cylinder and the top and bottom z -planes define the external boundaries of the entire system (i.e., final modules must not protrude outside this region). The geometry of module 0 was constructed so as to permit convenient representations of core-associated structures such as a barrel and pressure vessel. Final modules override and replace module 0 over the final modules' domains. Module 0 acts thus as a background over which final modules are placed. For example, a properly defined final module which represents a pressure vessel nozzle would model a real penetration of the pressure vessel. (See Figure 10-11.)

The definitions of initial and final modules and module 0 are sufficiently flexible to permit detailed three-dimensional representations. On user option, the module zero set of concentric cylinders may be replaced by a set of concentric spheres whose centers are at the origin of the absolute coordinate system. In this case, module 0 z -zones are defined in the same way as in the cylindrical case, perpendicular to the z -axis.

The outermost cylinder or sphere has vacuum boundary conditions. The top and bottom z -planes normally also have vacuum boundary conditions, but on user option, they can be reflective to simulate infinite height.

4.2 Description of Expanded Input for an Initial Assembly

This section describes the list of original input parameters and the additional parameters which are calculated before geometry tracking begins. A combination of these additional parameters with some of the original parameters defines the expanded input. Computer input formats are described in detail in Chapter 10 of this report.

4.2.1 Basic Region Definition and C-List, P-List Assignment

The original input parameters define an x, y mesh for an initial assembly by lines parallel to the initial assembly x, y coordinate axes. This mesh is divided by lines parallel to the y axis at $x = X_0, X_1, \dots, X_N$, and lines parallel to the x axis at $y = Y_0, Y_1, \dots, Y_M$. The lines at X_0, X_N, Y_0 , and Y_M define exterior boundaries of the initial assembly. The input basic regions are defined by the indices, n, m , of their lower left points. For example basic region 0,0 is the lower left input basic region. Through an overlay process, described in the input section, a composition list (C-list) or a partial subcell list (P-list) is assigned to each of the input basic regions.

The **input** basic regions are converted to what we will call basic regions by eliminating y boundaries within each x slab across which the C-list or P-list number does not change, and also x boundaries across which all the C-list or P-list numbers do not change. In addition basic regions will be defined by the indices of their upper right points instead of their lower left points. Thus, part of the expanded input for an initial assembly consists of the x boundaries, $X_0, \dots, X_n, \dots, X_N$ (X_0 and Y_0 are understood to be 0) and a separate set of y boundaries for each slab n (defined by X_{n-1} to X_n), $Y_{n,0}, \dots, Y_{n,m}, \dots, Y_{n,M_n}$, where M_n is the number of y boundaries remaining in slab n after the removals described above. Note that Y_{n,M_n} for all values of n must be equal since edge values cannot be removed.

Users should note that redundant y boundaries are eliminated but locally redundant x boundaries are not. Therefore, it is advantageous in terms of computing speed to position an initial assembly such that more internal slab-type interfaces, if any exist, are parallel to the y -axis rather than oriented in any other direction, so that more y boundaries may be eliminated.

Indices n, m will be understood throughout the tracking description to be those for the basic regions, not the input basic regions. Thus for example, 1,1 is the lower left corner basic region and 1, M_n is the upper left corner basic region.

4.2.2 Composition Definition

RCP01 composition definitions are set up once per problem and then are used in all initial assemblies and in the composition variations that may be used in a final assembly laydown or a final module laydown. The RCP job library contains microscopic cross sections (barns). A composition definition is simply a sequence of nuclide identification numbers from the job library together with input atom densities in units of (atoms) / (barn-cm). Each composition is identified by an integer.

4.2.3 C-List Definition

Each basic region defines a single infinite parallelepiped in the z -direction which is subdivided into L z -zones by z -planes that uniformly cut across all basic regions. (Note that all initial assembly z -planes must be above 0.0 and an additional plane at 0.0 is assumed.) Then, a

C-list is simply a list of L composition identification numbers, $C_1, \dots, C_L$. In this list, C_1 is the composition in the bottom-most parallelepiped, i.e., the one from $z = 0.0$ to $z = Z_1$, and C_L is the composition in the top-most parallelepiped, i.e., the one from $z = Z_{L-1}$ to $z = Z_L$.

4.2.4 P-List Definition

A P-list defines an infinite, doubly repetitive array of subcells in the x - y plane. As in the case of basic regions, these planar subcell boundaries define infinite blocks. Each region of a subcell has a C-list assigned. Therefore, a P-list is a complete description of an infinite array of three-dimensional subcells with the exception that the z -zone boundary distances are not part of a P-list. For this reason the term partial subcell list was applied; hence P-list. P-lists are assigned to basic regions. When this happens, the infinite, doubly repetitive array of subcells defined by the P-list is truncated by the boundaries of the basic region.

In the x - y plane, the exterior boundary of each subcell is a quadrilateral with sides parallel to the initial assembly coordinate axes. The length of the sides is given by D_x and D_y . An infinite doubly repetitive array of subcells is thus obtained with repeat distances D_x and D_y . The lower left corner of the first subcell is specified by an anchor point x_a, y_a in the coordinate system of the initial assembly. (On option, the point x_a, y_a can be measured relative to the lower left corner of the basic region in which the P-list is assigned, defining a "portable" P-list. However, use of this option is not recommended.)

In addition, the interior x - y domain of a subcell may be subdivided by an arbitrary number of ellipses. The number of ellipses for a given P-list is specified by parameter G . All ellipses are truncated by the subcell exterior boundary. While RCP01 geometry tracking is formulated to properly treat a general overlay of ellipses in which later ellipses in a P-list overlay earlier ellipses in the P-list, the program's volume calculation (see Appendix H) does not permit intersecting ellipses within subcell boundaries and therefore the program will stop within input processing should this occur. Ellipses may however intersect outside the subcell boundary.

Exactly $G + 1$ C-lists are required in a P-list. The first C-list gives the composition description exterior to all ellipses. The parameters for the first ellipse are given followed by another C-list which is for the interior of this ellipse, and so forth for the remaining ellipses.

For each ellipse, i , the following parameters are input: x_{e_i}, y_{e_i} are coordinates of the center of ellipse i relative to the lower left corner of the subcell; μ_{e_i} is cosine of the angle between the semi-major axis of ellipse i and the x -axis of the initial assembly coordinate system; a_i, b_i are the semi-major and semi-minor axes of ellipse i .

The expanded form of a P-list consists of all the input P-list parameters with three additional derived parameters per ellipse whose use simplifies calculations in the geometry tracking. These additional parameters are functions of μ_{e_i} and the initial assembly geometry index, P/R ($P/R = 0$ for 60° and 1 for 90° geometry). We rename μ_{e_i} , and define for each ellipse i ,

$$\begin{aligned}
A_i &= \mu_{e_i} \\
B_i &= \frac{\mu_{e_i}}{2}(1 - P/R) + \sqrt{1 - \mu_{e_i}^2} \left(\frac{\sqrt{3}}{2}(1 - P/R) + P/R \right) \\
C_i &= \sqrt{1 - \mu_{e_i}^2} \\
D_i &= \mu_{e_i} \left(\frac{\sqrt{3}}{2}(1 - P/R) + P/R \right) - \sqrt{1 - \mu_{e_i}^2} (1 - P/R) \frac{1}{2}
\end{aligned}$$

In summary then, an expanded P-list for the general case of G ellipses consists of the following parameters:

$$\begin{aligned}
&x_a, y_a, D_x, D_y, G, C_{\text{List } 1}, x_{e_1}, y_{e_1}, A_1, B_1, C_1, D_1, a_1, b_1, C_{\text{List } 2}, \dots, \\
&x_{e_G}, y_{e_G}, A_G, B_G, C_G, D_G, a_G, b_G, C_{\text{List } G+1}.
\end{aligned}$$

4.2.5 Z-Zone Definition

The L z-zones for an initial assembly are specified simply by $L+1$ values of z : $Z_0, Z_1, \dots, Z_p, \dots, Z_L$ where it is required and assumed that $Z_0 = 0$.

4.2.6 Summary of Expanded Input for an Initial Assembly

We may summarize the expanded input for an initial assembly, IA, as:

1. Geometry Index: P/R
2. Basic Regions:

$$\begin{aligned}
&X_0, \dots, X_n, \dots, X_N; X_0 = 0 \\
&Y_{n,0}, \dots, Y_{n,m}, \dots, Y_{n,M_n}; n = 1, \dots, N; Y_{n,0} = 0
\end{aligned}$$

3. P/C List Assignment: A two-dimensional array giving P or C list numbers for basic region n, m .
4. C List: $C_1, \dots, C_L$
5. P List:

$$\begin{aligned}
&x_a, y_a, D_x, D_y, G, C_{\text{List } 1}, x_{e_1}, y_{e_1}, A_1, B_1, C_1, D_1, a_1, b_1, C_{\text{List } 2}, \dots, \\
&x_{e_G}, y_{e_G}, A_G, B_G, C_G, D_G, a_G, b_G, C_{\text{List } G+1}
\end{aligned}$$

6. Z-zones: $Z_0, \dots, Z_p, \dots, Z_L; Z_0 = 0$.

4.3 Description of Expanded Input for Final Assemblies

This describes the list of original input parameters and the additional parameters which are calculated before geometry tracking begins. A combination of these additional parameters with the original parameters defines the expanded input. Computer input formats are described in detail in Chapter 10 of this report.

4.3.1 Final Assembly Laydown: Initial Module

A complete final assembly laydown constitutes an initial module. A final assembly laydown is made in the initial module coordinate system. A final assembly is denoted by an integer, FA. It also refers to an initial assembly denoted by an integer, IA, and is specified in the initial module coordinate system as follows. First, we may take a mirror image of the initial assembly. This is indicated by a negative value of IA. In this case the y axis of the initial assembly coordinate system is reflected about the x - z coordinate plane of the initial assembly.

For the special case of 60° geometry, a geometry variation may be performed by setting parameter $v_g = 1$ (normally $v_g = 0$). In a geometry variation the line defining the top boundary of the initial assembly, $y = Y_{n,M_n}$, is rotated 60° clockwise around fixed point $(0, Y_{n,M_n})$ and defines a new external boundary. This rotation results in either a triangular or a trapezoidal initial assembly exterior shape.

A composition variation set may be selected by assigning the composition variation parameter v_c a non-zero integer value. For each different value of v_c a particular set of composition changes are specified by a sequence of pairs of composition numbers; the second composition in the pair replaces the first wherever it appears in the initial assembly. For no composition changes the parameter v_c is set to 0. Composition variations may be used in both final assemblies and final modules.

The origin of the initial assembly coordinate system is located in the initial module coordinate system by specifying x_{FA} , y_{FA} . Translations in z cannot be performed in a final assembly laydown; furthermore, all final assemblies in a given laydown, i.e., in a given initial module, must have the same height, i.e., the same value of z_L , and must have the same geometry index P/R .

The initial assembly coordinate axes are initially parallel to the absolute coordinate system. The initial assembly may be rotated counterclockwise about the initial assembly z -axis in integral multiples, A , of 90° for $P/R = 1$, or of 60° for $P/R = 0$.

Finally, a source strength per final assembly, s_{FA} , is input which gives the relative total final assembly source strength within the initial module. In summary, then a final assembly laydown, or one initial module, IM, consists of the following basic parameters:

$$IM : FA, \pm IA, V_g, V_c, x_{FA}, y_{FA}, A, S_{FA}, \dots, \\ FA, \pm IA, V_g, V_c, x_{FA}, y_{FA}, A, S_{FA}$$

4.3.2 Additional Final Assembly Parameters

The following additional parameters are calculated automatically for each final assembly FA. The sides of an initial assembly are numbered as: x -axis = 1, y -axis = 2, side opposite the x -axis = 3, and side opposite the y -axis = 4. For each side, SN , of final assembly FA, the number of final assemblies in contact with the side, C_{SN} , and identification numbers of the final assemblies in contact, $FA^1, FA^2, \dots, FA^{C_{SN}}$, are determined. This information may be used by the requestor to insure proper final assembly laydown, and is also used in the geometry tracking process. Recall that each side of each final assembly must be totally "free" or totally covered by sides of other final assemblies. RCP01 will detect violations of this rule during tracking. Two final assemblies are defined to be in contact if there is no more than a 10^{-4} cm gap or overlap between them. The detailed steps for determining which final assemblies are in contact are given in Appendix E.

The external size of FA is obtained from the corresponding IA dimensions, i.e., X_N, Y_N, M_n, Z_L . The four external corner points in the x - y plane of the final assembly are obtained in the initial module coordinate system. These points are retained as: $(X_1, Y_1), (X_2, Y_2), (X_3, Y_3), (X_4, Y_4)$. The process for obtaining these is also described in Appendix E.

Geometry tracking for a final assembly laydown requires frequent transfers of the neutron x, y coordinates in the initial assembly coordinate system, to the corresponding x', y' coordinates in the initial module coordinate system. Recall that the final assembly is an initial assembly whose origin has been translated in the initial module coordinate system by x_{FA}, y_{FA} , and rotated by an integral multiple, A , of 90° for $P/R = 1$ or 60° for $P/R = 0$. This transformation may be written as

$$x' = c_1 x + c_2 y + x_{FA}, \\ y' = d_1 x + d_2 y + y_{FA}.$$

Defining the rotation matrix as

$$\begin{pmatrix} c_1 & c_2 \\ d_1 & d_2 \end{pmatrix},$$

the elements, which are functions of A , P/R , and the sign of IA, are included in the expanded final assembly input. Let $\delta = 1$ if $IA > 0$, and $\delta = -1$ if $IA < 1$, and set

$$\begin{aligned} A' &= A \text{ if } A \neq 0, \text{ if } A = 0 \text{ set } A' = 6, \\ A'' &= A \text{ if } A \neq 0, \text{ if } A = 0 \text{ set } A'' = 4. \end{aligned}$$

Then the elements of the above rotation matrix become

$$\begin{aligned} c_1 &= \left(1 - \frac{P}{R}\right)[C_{7-A'}] + \frac{P}{R}[D_{5-A''}], \\ c_2 &= \left(1 - \frac{P}{R}\right)\left[\left(\frac{1+\delta}{2}\right)C_{6-A'} + \left(\frac{1+\delta}{2}\right)C_{8-A'}\right] + \frac{P}{R}[\delta D_{4-A''}], \\ d_1 &= \left(1 - \frac{P}{R}\right)[-C_{6-A'}] + \frac{P}{R}[-D_{4-A''}], \\ d_2 &= \left(1 - \frac{P}{R}\right)\left[\left(\frac{1+\delta}{2}\right)C_{8-A'} - \left(\frac{1+\delta}{2}\right)C_{7-A'}\right] + \frac{P}{R}[\delta D_{5-A''}]. \end{aligned}$$

The constants appearing in the above equations are defined by:

$$\begin{aligned} C_0 &= 0 & D_0 &= 0 \\ C_1 &= 1 & D_1 &= 1 \\ C_2 &= 1 & D_2 &= 0 \\ C_3 &= 0 & D_3 &= -1 \\ C_4 &= -1 & D_4 &= 0 \\ C_5 &= -1 & & \\ C_6 &= 0 & & \\ C_7 &= 1 & & \end{aligned}$$

The inverse of the above transformation also frequently occurs in geometry tracking. This transformation may be written as

$$\begin{aligned} x &= e_1(x' - x_{F_a}) + e_2(y' - y_{F_a}) \\ y &= f_1(x - x_{F_a}) + f_2(y' - y_{F_a}) \end{aligned}$$

In general the previous rotation matrix is not an orthogonal transformation, hence the reverse rotation matrix,

$$\begin{pmatrix} e_1 & e_2 \\ f_1 & f_2 \end{pmatrix}$$

is not simply the transpose of the previous matrix. For this reason the elements of this matrix are also part of the expanded final assembly input. These elements are given by

$$\begin{aligned}
e_1 &= \left(1 - \frac{P}{R}\right) \left[\left(\frac{1+\delta}{2}\right) C_{A+1} + \left(\frac{1-\delta}{2}\right) C_{A+2} \right] + \frac{P}{R} [D_{A+1}], \\
e_2 &= \left(1 - \frac{P}{R}\right) \left[\left(\frac{1+\delta}{2}\right) C_A + \left(\frac{1-\delta}{2}\right) C_{A+1} \right] + \frac{P}{R} [D_A], \\
f_1 &= \left(1 - \frac{P}{R}\right) [-\delta C_A] + \frac{P}{R} [-\delta D_A], \\
f_2 &= \left(1 - \frac{P}{R}\right) [\delta C_{A+2}] + \frac{P}{R} [\delta D_{A+1}].
\end{aligned}$$

A rotation matrix to transform the initial assembly direction cosines, μ, γ , to the initial module direction cosines, μ', γ' is also part of the expanded final assembly input. This transformation may be written as

$$\begin{aligned}
\mu' &= g_1 \mu + g_2 \gamma, \\
\gamma' &= h_1 \mu + h_2 \gamma,
\end{aligned}$$

where

$$\begin{aligned}
g_1 &= \left(1 - \frac{P}{R}\right) [B_{6-A'}] + \frac{P}{R} [D_{5-A''}], \\
g_2 &= \left(1 - \frac{P}{R}\right) \left[\delta \frac{\sqrt{3}}{2} C_{6-A'} \right] + \frac{P}{R} [\delta D_{4-A''}], \\
h_1 &= \left(1 - \frac{P}{R}\right) \left[-\frac{\sqrt{3}}{2} C_{6-A'} \right] + \frac{P}{R} [-D_{4-A''}], \\
h_2 &= \left(1 - \frac{P}{R}\right) [\delta B_{6-A'}] + \frac{P}{R} [\delta D_{5-A''}].
\end{aligned}$$

The additional constants appearing in the above equation are defined by:

$$\begin{aligned}
B_0 &= 1, \\
B_1 &= \frac{1}{2}, \\
B_2 &= -\frac{1}{2}, \\
B_3 &= -1, \\
B_4 &= -\frac{1}{2}, \\
B_5 &= \frac{1}{2}.
\end{aligned}$$

This rotation matrix is written

$$\begin{pmatrix} g_1 & g_2 \\ h_1 & h_2 \end{pmatrix}.$$

Since direction cosines are always measured in a right angled system regardless of the value of P/R , the matrix represents an orthogonal rotation hence the inverse transformation matrix is given by the transpose, i.e.,

$$\begin{aligned} \mu &= g_1\mu' + h_1\gamma' \\ \gamma &= g_2\mu' + h_2\gamma'. \end{aligned}$$

The parameter P/R is the geometry index associated with initial assembly IA.

Four additional parameters, C, x_c, y_c, r_a , used only for modular geometry tracking, are obtained as follows:

1. Set $C = 1$,
2. If $C_1 = 0$ or $C_2 = 0$, or $C_3 = 0$, or $C_4 = 0$, then set $C = 0$, but ignore $C_4 = 0$ if $v_g = 1$ and $X_N > Y_{N, M_n}$.

Thus the parameter $C = 0$ means that there are one or more free sides (a free side has no final assemblies in contact) for final assembly FA. The parameters x_c, y_c, r_a , define an infinite circular cylinder that totally contains FA with center at x_c, y_c and radius r_a . This cylinder is only used to reduce calculational steps in modular geometry tracking. These parameters are calculated using the four corner points of FA, $(X_n, Y_n), n = 1, \dots, 4$, as follows:

1. Define

$$\bar{X} = \frac{1}{4}(X_1 + X_2 + X_3 + X_4), \bar{Y} = \frac{1}{4}(Y_1 + Y_2 + Y_3 + Y_4).$$

2. Set $r_a^2 = 0$.

3. For 60° geometry:

$$(a) \text{ Set } r^2 = (X_n - \bar{X})^2 + (X_n - \bar{X})(Y_n - \bar{Y}) + (Y_n - \bar{Y})^2$$

$$(b) \text{ if } r^2 > r_a^2 \text{ set } r_a^2 = r^2; \text{ carry out process for } n = 1, \dots, 4.$$

$$(c) \text{ We then have } r_a = \sqrt{r_a^2} \text{ and set } X_c = \bar{X} + \bar{Y}/2, \quad Y_c = \bar{Y}(\sqrt{3}/2).$$

4. For 90° geometry:

(a) Set $r^2 = (X_n - \bar{X})^2 + (Y_n - \bar{Y})^2$

(b) if $r^2 > r_a^2$ set $r_a^2 = r^2$; carry out process for $n = 1, \dots, 4$.

(c) We then have $r_a = \sqrt{r_a^2}$ and set $X_c = \bar{X}$, $Y_c = \bar{Y}$.

4.3.3 Summary of Expanded Final Assembly Input

We may summarize the expanded input for each final assembly FA in initial module IM as:

$$FA, \pm IA, V_g, V_c, x_{FA}, y_{FA}, A, S_{FA}[C_1, FA^1, FA^2, \dots, FA^{C_1}, C_2, FA^1, FA^2, \dots, FA^{C_2}, C_3, FA^1,$$

$$FA^2, \dots, FA^{C_3}, C_4, FA^1, FA^2, \dots, FA^{C_4}], X_N, y_{n, M_n}, Z_L, (X_1, Y_1), (X_2, Y_2), (X_3, Y_3), (X_4, Y_4),$$

$$\begin{pmatrix} c_1 & c_2 \\ d_1 & d_2 \end{pmatrix}, \begin{pmatrix} e_1 & e_2 \\ f_1 & f_2 \end{pmatrix}, \begin{pmatrix} g_1 & g_2 \\ h_1 & h_2 \end{pmatrix}, P/R, c, x_c, y_c, r_a.$$

4.4 Description of Expanded Input for Composite Final Assemblies

This section describes the list of original input parameters and the additional parameters which are calculated before geometry tracking begins for composite final assemblies. A combination of these parameters defines the expanded input. Computer input formats are described in detail in Chapter 10 of this report.

4.4.1 Parameters for a Composite Final Assembly

The original input parameters required to lay down the primary initial assembly in a composite final assembly laydown consist of the same parameters as for a regular final assembly. To these are added the parameters required to lay down the secondary initial assemblies relative to the coordinate system of the primary initial assembly. Thus, the list of composite final assembly input parameters is:

$$FA, \pm IA, V_g^P, V_c^P, x_a^P, y_a^P, A^P, S_{FA}, (\pm IA^{s_1}, V_g^{s_1}, V_c^{s_1}, x_a^{s_1}, y_a^{s_1}, z^{s_1}, \theta_d^{s_1}, \theta_s^{s_1}, \theta_r^{s_1}, f^{s_1}); (\pm IA^{s_2}, V_g^{s_2}, V_c^{s_2}, \dots$$

where the superscript P denotes quantities used to lay down the primary initial assembly and the superscript s_i denotes quantities used to lay down the i^{th} secondary initial assembly. The source strength per composite final assembly, S_{FA} , gives the relative total final assembly source strength within the initial module. The secondary source fractions, f^{s_i} , give the fraction of the total source in each secondary initial assembly. Thus $1 - \sum_i f^{s_i}$ is the fraction of the total source in the primary initial assembly. The parameters $x_a^{s_i}, y_a^{s_i}, z_a^{s_i}$ are the coordinates of the origins of the secondary initial assembly coordinate systems in the coordinate system of the primary initial assembly. The angles $\theta_d^{s_i}, \theta_s^{s_i}, \theta_r^{s_i}$ are measured in right angled, right handed x, y, z coordinate systems whose origins are the origins of the secondary initial assembly coordinate systems. The x and z axes are initially parallel to the x and z axes of the primary initial assembly coordinate system. The angles $\theta_d^{s_i}, \theta_s^{s_i}, \theta_r^{s_i}$ have exactly the same interpretation as for a final module lay down, i.e., $\theta_d^{s_i}$ is counterclockwise rotation about the y -axis when looking toward the origin which alters the x and z axes, $\theta_s^{s_i}$ is a counterclockwise rotation about the x -axis when looking toward the origin which alters the z -axis, and $\theta_r^{s_i}$ is a counterclockwise rotation about the z -axis when looking toward the origin.

The additional parameters obtained for the primary initial assembly in a composite final assembly consist of all of those obtained for a regular final assembly. The additional parameters obtained for each secondary initial assembly in a composite final assembly consist of an orthogonal rotation matrix,

$$\begin{pmatrix} a_1^{s_i} & a_2^{s_i} & a_3^{s_i} \\ b_1^{s_i} & b_2^{s_i} & b_3^{s_i} \\ c_1^{s_i} & c_2^{s_i} & c_3^{s_i} \end{pmatrix}$$

where the elements are defined in terms of $\theta_d^{s_i}, \theta_s^{s_i}, \theta_r^{s_i}$ in exactly the same way as for a final module with $\theta_m = 0$. The parameters $X_N^{s_i}, Y_{n, M_n}^{s_i}, Z_L^{s_i}$ are the maximum extents of the secondary initial assemblies in their coordinate systems and are obtained from the initial assembly input. Finally, $(P/R)^{s_i}$ is the geometry index for the secondary initial assembly. This is permitted to differ from that of the primary initial assembly.

4.4.2 Summary of Expanded Composite Final Assembly Input

We summarize the expanded input for a composite final assembly, FA, as follows:

$$\begin{aligned}
& FA, \pm IA^P, V_g^P, V_c^P, x_a^P, y_a^P, A^P, S_{FA}, [C_1, FA^1, FA^2, \dots, FA^{C_1}, C_2, FA^1, FA^2, \dots, FA^{C_2}, C_3, FA^1, \\
& FA^2, \dots, FA^{C_3}, C_4, FA^1, FA^2, \dots, FA^{C_4}] \\
& X_N^P, Y_{n, M_n}^P, Z_L^P, (X_1, Y_1), (X_2, Y_2), (X_3, Y_3), (X_4, Y_4), \begin{pmatrix} c_1 & c_2 \\ d_1 & d_2 \end{pmatrix}, \begin{pmatrix} e_1 & e_2 \\ f_1 & f_2 \end{pmatrix}, \begin{pmatrix} g_1 & g_2 \\ h_1 & h_2 \end{pmatrix}, (P/R)^P, C, x_c, \\
& y_c, r_a, (\pm IA^{s_1}, V_g^{s_1}, V_c^{s_1}, x_a^{s_1}, y_a^{s_1}, z^{s_1}, \theta_d^{s_1}, \theta_s^{s_1}, \theta_r^{s_1}, f^{s_1}, \begin{pmatrix} a_1^{s_1} & a_2^{s_1} & a_3^{s_1} \\ b_1^{s_1} & b_2^{s_1} & b_3^{s_1} \\ c_1^{s_1} & c_2^{s_1} & c_3^{s_1} \end{pmatrix}, X_N^{s_1}, Y_{n, M_n}^{s_1}, Z_L^{s_1}, (P/R)^{s_1}); (\pm IA^{s_2}, V_g^{s_2}, V_c^{s_2}, \dots
\end{aligned}$$

4.5 Description of Expanded Input for Final Modules

This section describes the list of original input parameters and the additional parameters which are calculated before geometry tracking begins. A combination of these parameters defines the expanded input. Computer input formats are described in detail in Chapter 10 of this report.

4.5.1 Final Module Laydown

A final module laydown is accomplished by locating a series of initial modules in an absolute coordinate system which is always a right angled system regardless of the geometry index, P/R . The hierarchy of coordinate systems we will consider are: the initial assembly coordinate system, the initial module coordinate system, and the absolute coordinate system. There is one overall P/R index with the problem control parameters, but this may be overridden for any initial assembly. All primary initial assemblies referred to in an initial module through the final assemblies must have the same geometry index, but different initial modules may have different geometry indices.

Each final module FM refers to an initial module denoted by an integer, IM. Compositions may again be changed through use of a composition variation, v_c^m , as described for final assemblies. The sequence of composition changes occurs by performing the final assembly composition changes first, followed by changes of these compositions as indicated by the final module composition variation v_c^m . For the final module, the origin of the initial module coordinate system is translated in the absolute coordinate system to $x_m, y_m, 0$. An additional translation of the initial module by distance z_i along the z -axis of the initial module coordinate system is made after the angular orientation of the initial module coordinate system is set. Therefore, the z -axis of the initial module coordinate system always passes through the point $(x_m, y_m, 0)$ in the absolute coordinate system.

The initial module coordinate system is fixed in the initial module, thus to specify angular orientation of the final module, by specifying angular rotations about the x and z initial module axes and about an axis perpendicular to these, requires a hierarchy of angular rotations. Initially the x and z axes of the initial module are parallel to the x and z axes of the absolute coordinate system. The first angle in the hierarchy is an optional rotation about the initial module z -axis, θ_m , which results in the initial module positive x -axis pointing directly away from the absolute origin. This rotation, θ_m , is obtained automatically by the presence of a control card in the final module laydown. It is useful when setting up certain types of annular arrays of final modules. If the control card is not present then $\theta_m = 0^\circ$. The second angle in the hierarchy is θ_d . Rotation θ_d is about the initial module y -axis if the initial module geometry is 90° . For 60° geometry it is about an altered y -axis which is perpendicular to the x - z plane as in the case of 90° geometry. This angle in degrees is measured counterclockwise when looking toward the initial module origin. The third angle in the hierarchy is θ_s . This rotation is about the x -axis of the initial module **after** this axis has been moved by the θ_m and θ_d rotations. This angle in degrees is also measured counterclockwise when looking toward the initial module origin. The fourth angle in the hierarchy is θ_r . This rotation is about the z -axis of the initial module **after** this axis has been moved by the combination of θ_m , θ_d , and θ_s rotations. This angle in degrees is also measured counterclockwise when looking toward the initial module origin. (See Figure 10-11.)

A source strength, S_{FM} , is specified per final module in the same manner as for a final assembly. That is, S_{FM} gives the relative total final module source strength in the complete final module laydown.

In summary, the basic input parameters for final module FM consist of the following:

$$FM, IM, V_c^m, x_m, y_m, z_p, \theta_d, \theta_s, \theta_r, S_{FM}$$

Note that θ_m is determined directly from a particular card input option and is not listed above.

4.5.2 Additional Final Module Parameters

The following additional parameters are obtained for each final module FM. First, an orthogonal rotation matrix is computed:

$$\begin{pmatrix} a_1^m & a_2^m & a_3^m \\ b_1^m & b_2^m & b_3^m \\ c_1^m & c_2^m & c_3^m \end{pmatrix}$$

where the elements of the matrix are given as follows:

1. If automatic rotation is selected, set $\sin\theta_m = y_m/(\sqrt{x_m^2 + y_m^2})$, $\cos\theta_m = x_m/(\sqrt{x_m^2 + y_m^2})$, unless x_m and $y_m = 0$, in which case set $\theta_m = 0$, $\sin\theta_m = 0$, and $\cos\theta_m = 1$.
2. If automatic rotation option is not selected then set $\theta_m = 0$, $\sin\theta_m = 0$, and $\cos\theta_m = 1$.
3. Next, set:
 - (a) $a_1^m = (\sin\theta_d \cos\theta_m \sin\theta_s \sin\theta_r + \cos\theta_d \cos\theta_m \cos\theta_r - \sin\theta_m \cos\theta_s \sin\theta_r)$
 - (b) $a_2^m = (\sin\theta_d \cos\theta_m \sin\theta_s \cos\theta_r - \cos\theta_d \cos\theta_m \sin\theta_r - \sin\theta_m \cos\theta_s \sin\theta_r)$
 - (c) $a_3^m = (\sin\theta_d \cos\theta_m \cos\theta_s + \sin\theta_m \sin\theta_s)$
 - (d) $b_1^m = (\sin\theta_d \sin\theta_m \sin\theta_s \sin\theta_r + \cos\theta_d \sin\theta_m \cos\theta_r + \cos\theta_m \cos\theta_s \sin\theta_r)$
 - (e) $b_2^m = (\sin\theta_d \sin\theta_m \sin\theta_s \cos\theta_r - \cos\theta_d \sin\theta_m \sin\theta_r + \cos\theta_m \cos\theta_s \cos\theta_r)$
 - (f) $b_3^m = (\sin\theta_d \sin\theta_m \cos\theta_s - \cos\theta_m \sin\theta_s)$
 - (g) $c_1^m = (\cos\theta_d \sin\theta_s \sin\theta_r - \sin\theta_d \cos\theta_r)$
 - (h) $c_2^m = (\cos\theta_d \sin\theta_s \cos\theta_r + \sin\theta_d \sin\theta_r)$
 - (i) $c_3^m = (\cos\theta_d \cos\theta_s)$

Since the rotation is orthogonal, then as a check we should have:

$$(a_i^m)^2 + (b_i^m)^2 + (c_i^m)^2 = 1 \text{ for } i = 1, 2, 3.$$

Next, we obtain four parameters, r_o , R_0 , $z_{\max}$, and $z_{\min}$ which are used to reduce calculation times in modular geometry tracking. The parameter r_o is the radius of a circular cylinder whose axis is the initial module z-axis and which just contains the initial module. The value of r_o is obtained as follows:

1. Set $r_0^2 = 0$.
2. Starting with FA = 1 with corner point (X_n, Y_n) ; $n = 1, 2, 3, 4$.
3. For 60° geometry:
 - (a) Set $r^2 = X_n^2 + X_n Y_n + Y_n^2$, if $r^2 > r_0^2$ set $r_0^2 = r^2$

(b) Carry out the process for four corners ($n = 1, 2, 3, 4$), for each FA in IM. This defines

$$r_0 = \sqrt{r_0^2}.$$

4. For 90° geometry: Set $r^2 = x_n^2 + y_n^2$: otherwise same as 60° case.

The parameter R_0 is the radius of a circular cylinder whose axis is parallel to absolute z , passes through $(x_m, y_m, 0)$, and just contains the final module. The value of R_0 is obtained as follows:

$$\text{Let } \hat{z} = \text{Max}(|Z_L + z_t|, |z_t|) \text{ then } R_0 = r_0 |c_3^m| + \sqrt{\hat{z}^2 + r_0^2} \sqrt{1 - (c_3^m)^2}.$$

The parameters $z_{\max}$ and $z_{\min}$ are the upper and lower bounds of the r_0 cylinder in the absolute coordinate system. Their values are given as follows:

1. If $c_3^m \geq 0$

$$\begin{aligned} z_{\min} &= -r_0 \sqrt{1 - (c_3^m)^2} + z_t c_3^m \\ z_{\max} &= r_0 \sqrt{1 - (c_3^m)^2} + (Z_L + z_t) c_3^m \end{aligned}$$

2. If $c_3^m < 0$

$$\begin{aligned} z_{\min} &= -r_0 \sqrt{1 - (c_3^m)^2} + (Z_L + z_t) c_3^m \\ z_{\max} &= r_0 \sqrt{1 - (c_3^m)^2} + z_t c_3^m \end{aligned}$$

4.5.3 Summary of Expanded Final Module Input

We may summarize the expanded final module input for each final module, FM, as:

$$FM, IM, V_c^m, x_m, y_m, z_t, \theta_d, \theta_s, \theta_r, S_{FM}, \begin{pmatrix} a_1^m & a_2^m & a_3^m \\ b_1^m & b_2^m & b_3^m \\ c_1^m & c_2^m & c_3^m \end{pmatrix}, r_0, R_0, z_{\max}, z_{\min}$$

4.6 Description of Module 0 Input

As described in Section 4.1.6, module 0 is defined by a set of concentric circular cylinders whose axis is the absolute z -axis. On option, the concentric cylinders may be replaced by concentric spheres whose centers lie at the origin of the absolute coordinate system ($G_0 = 0$ for cylinders, $G_0 = 1$ for spheres). For both cylinders and spheres, a set of z -planes define axial zones perpendicular to the z -axis. In addition, as discussed in Section 4.1.6, each final module overrides and replaces module 0 regions over the domain of the final module. Computer input formats are described in detail in Chapter 10 of this report.

The input parameters consist of the following: A total of M radii are specified, $R_1, \dots, R_M$. A total of L z -zones are specified, $Z_0'', Z_1'', \dots, Z_L''$ where Z_0'' is the smallest and may be negative. A total of M C-lists are specified in the same way as described for initial assemblies. The first C-list gives the composition arrangement by z -zone interior to the first cylinder (or sphere); the second C-list gives the composition arrangement by z -zone to the domain laying between the first and second cylinders (or spheres); and so forth. Whenever modular geometry is used, module 0 data must be input. There are no additional parameters calculated for module 0 defining an expanded input.

We may summarize the basic input for module 0 as:

$$G_0, R_1, \dots, R_M, Z_0'', \dots, Z_L'', \{ \text{data defining } M \text{ C-lists} \}.$$

4.7 Summary of Total Geometry Expanded Input for RCP01

This section summarizes in one place the total geometry expanded input for RCP01 for convenience in following the details of the geometry tracking.

1. Initial Assembly, IA:

Geometry Index: P/R

Basic Regions: $X_0, \dots, X_n, \dots, X_N; X_0 = 0$

$$Y_{n,0}, \dots, Y_{n,m}, \dots, Y_{n,M_n}; n = 1, \dots, N; Y_{n,0} = 0.$$

P/C List Assignment: A two-dimensional array giving P or C List number for basic region n, m .

C List: $C_1, \dots, C_L$.

P List:

$$x_a, y_a, D_x, D_y, G, C_{List\ 1}, x_{e_1}, y_{e_1}, A_1, B_1, C_1, D_1, a_1, b_1, C_{List\ 2}, \dots, \\ x_{e_G}, y_{e_G}, A_G, B_G, C_G, D_G, a_G, b_G, C_{List\ G+1}$$

z-zones: $Z_0, \dots, Z_1, \dots, Z_L; Z_0 = 0$.

2. Final Assembly, FA, in Initial Module IM:

$$FA, \pm IA, V_g, V_c, x_{FA}, y_{FA}, A, S_{FA}, [C_1, FA^1, FA^2, \dots, FA^{C_1}, C_2, FA^1, FA^2, \dots, FA^{C_2}, C_3, \\ FA^1, FA^2, \dots, FA^{C_3}, C_4, FA^1, FA^2, \dots, FA^{C_4}]$$

$$X_N, Y_n, M_n, Z_L, (X_1, Y_1), (X_2, Y_2), (X_3, Y_3), (X_4, Y_4), \begin{pmatrix} c_1 & c_2 \\ d_1 & d_2 \end{pmatrix}, \begin{pmatrix} e_1 & e_2 \\ f_1 & f_2 \end{pmatrix}, \begin{pmatrix} g_1 & g_2 \\ h_1 & h_2 \end{pmatrix}, (P/R) . \\ C, x_c, y_c, r_a.$$

3. Composite Final Assembly, FA:

$$FA, \pm IA^P, V_g^P, V_c^P, x_a^P, y_a^P, A^P, S_{FA}, [C_1, FA^1, FA^2, \dots, FA^{C_1}, C_2, FA^1, FA^2, \dots, FA^{C_2}, C_3, FA^1, \\ FA^2, \dots, FA^{C_3}, C_4, FA^1, FA^2, \dots, FA^{C_4}]$$

$$X_N^P, Y_n^P, M_n^P, Z_L^P, (X_1, Y_1), (X_2, Y_2), (X_3, Y_3), (X_4, Y_4), \begin{pmatrix} c_1 & c_2 \\ d_1 & d_2 \end{pmatrix}, \begin{pmatrix} e_1 & e_2 \\ f_1 & f_2 \end{pmatrix}, \begin{pmatrix} g_1 & g_2 \\ h_1 & h_2 \end{pmatrix}, (P/R)^P, C, x_c$$

$$y_c, r_a, (\pm IA^{s_1}, V_g^{s_1}, V_c^{s_1}, x_a^{s_1}, y_a^{s_1}, z^{s_1}, \theta_d^{s_1}, \theta_s^{s_1}, \theta_r^{s_1}, f^{s_1}), \begin{pmatrix} a_1^{s_1} & a_2^{s_1} & a_3^{s_1} \\ b_1^{s_1} & b_2^{s_1} & b_3^{s_1} \\ c_1^{s_1} & c_2^{s_1} & c_3^{s_1} \end{pmatrix}, X_N^{s_1}, Y_n^{s_1}, M_n^{s_1}, Z_L^{s_1}, (P/R)^{s_1}; (\pm IA^{s_2}, V_g^{s_2}, V_c^{s_2}, \dots .$$

4. Final Module, FM:

$$FM, IM, V_c^m, x_m, y_m, z_l, \theta_d, \theta_s, \theta_r, S_{FM}, \begin{pmatrix} a_1^m & a_2^m & a_3^m \\ b_1^m & b_2^m & b_3^m \\ c_1^m & c_2^m & c_3^m \end{pmatrix}, r_0, R_0, z_{max}, z_{min}$$

5. Module 0:

$$G_0, R_1, \dots, R_M, Z_0^0, \dots, Z_L^0, \text{ and } M \text{ C-lists}$$

4.8 Boundary Condition Controls

The initial assembly boundary conditions, as well as final assembly boundary conditions and final assembly transfer, described below, are controlled by the values of the following six parameters, which are either geometry input data values or else properties of a particular neutron reaching a boundary:

1. N_{FM} - the number of final modules.
2. N_{FA} - the number of final assemblies, totalled over all initial modules.
3. δ_{IA} - a non-zero value indicates that the outer initial assembly boundary reached by a neutron is that of a secondary initial assembly in a composite final assembly, otherwise the value is normally 0.
4. SN - the side number of the boundary reached by a neutron in an initial assembly.
5. C_{SN} - the number of final assemblies in contact with side SN .
6. BC - boundary condition type number (Only applies in the case of a geometry model with a single initial module containing a single final assembly, such that $N_{FM} = 0$ and $N_{FA} = 1$.) The values of BC have the following meanings:
 - (a) $BC = 1$: reflective symmetry on all sides
 - (b) $BC = 2$: 120° periodicity on pairs of sides connected by 120° angles (for 60° geometry), or 90° periodicity on the upper left and lower right pairs of sides (for 90° geometry).
 - (c) $BC = 3$: reflective symmetry for upper left sides and 120° or 90° periodicity for lower right sides.
 - (d) $BC = -1$: 180° rotational symmetry on y_{max} surface, reflective symmetry on other three surfaces.

Reflective symmetry describes the mirror-like phenomenon where the neutron's direction changes such that its exit angle relative to the reflecting surface equals its incident angle. The neutron's location does not change.

Periodicity refers to the transfer of a neutron from one side of a pair to the other:

- (a) side 1 - $(x, 0)$ is transferred to $(x_{max}, y_{max} - x)$

(b) side 2 - $(0, y)$ is transferred to $(x_{\max} - y, y_{\max})$

(c) side 3 - $(x, y_{\max})$ is transferred to $(0, y_{\max} - x)$

(d) side 4 - $(x_{\max}, y)$ is transferred to $(x_{\max} - y, 0)$

Periodicity can be used only for a rhombus or a square.

180° rotational symmetry is the transfer of a neutron from $(x, y_{\max})$ to $(x_{\max} - x, y_{\max})$ with cosines (μ, γ) becoming $(-\mu, -\gamma)$.

We may describe the overall control process as follows:

1. If a neutron reaches the outer boundary of a secondary initial assembly, then the neutron coordinates and direction cosines are transformed to the primary initial assembly coordinate system and tracking continues in the primary initial assembly.
2. If a neutron reaches the outer boundary of a primary initial assembly, and the condition $N_{FM} = 0$ and $N_{FA} = 1$ holds, then the boundary condition specified by the value of BC at the boundary holds.
3. If a neutron reaches the outer boundary of a primary initial assembly, and the condition $N_{FM} = 0$ and $N_{FA} > 1$ holds, then if $C_{SN} = 0$ reflective symmetry is applied or else if $C_{SN} > 0$ then a final assembly transfer occurs and tracking resumes in the new final assembly.
4. If a neutron reaches the outer boundary of a primary initial assembly, and the condition $N_{FM} > 0$ holds, then if $C_{SN} = 0$ the neutron enters module 0 or else if $C_{SN} > 0$ then a final assembly transfer occurs and tracking resumes in the new final assembly.

In addition to these controls, one may also make use of special final assemblies to construct a large variety of boundary conditions for a final assembly laydown or for a final module laydown. This is described below.

4.8.1 Boundary Condition Final Assemblies

A large variety of boundary conditions are possible in a final assembly laydown or final module laydown by use of boundary condition final assemblies. For example, 60° or 90° rotational boundaries, reflective boundaries, and translational boundaries may be defined.

A boundary condition final assembly is designated on a special input card, separate from the usual final assembly input, and refers to a regular or composite final assembly, FA, which is to act as a boundary condition final assembly. This card also designates an associated final assembly, FA^a, and side number, SN^a, whose use is described next.

Whenever a neutron enters a new final assembly, either via a final assembly transfer or from module 0, if the final assembly is designated as a boundary condition final assembly then the program will, instead of tracking the neutron within the new final assembly, transfer the

neutron directly to side SN^a of final assembly FA^a as an **outgoing** neutron and resume tracking with either a final assembly transfer or module 0 tracking.

Three conditions must be met by such a boundary condition final assembly, and these are checked by the program during input checks. These conditions are the following:

1. Each pair of final assembly numbers, FA and FA^a , must refer to the same initial assembly, IA , although one or both of these may be a mirror image with code $-IA$.
2. Neither FA nor FA^a may have a geometry variation or source.
3. The number of final assemblies in contact with side SN^a must be greater than 0 if N_{FM} equals 0.

4.9 Geometry of Source Start

Regardless of RCP01 geometry, basic neutron tracking is performed in either an initial assembly or in module 0. In the former case, the neutron coordinates (x, y, z) are in the initial assembly coordinate system, and in the latter they are in the absolute coordinate system. However, an external source is not permitted in module 0, therefore the neutron geometry start procedure needs only to include determination of neutron start locations x, y, z in initial assemblies.

In Chapter 2, Energy and Angular Treatment of Source, detailed descriptions are given for the means of determining in initial assembly, IA , the start parameters, j, E, W, n, m, l , and μ, γ, η for a variety of source starts. Here j is the composition number, E is the neutron starting energy, W is the neutron starting weight, n, m are the basic region indices in the initial assembly, l is the z -zone index, and μ, γ, η are the neutron direction cosines in the initial assembly coordinate system (Note: the y -axis is perpendicular to x and z for describing direction cosines for 60° geometry but not for spatial location of neutrons).

The identification of a starting initial assembly results after identification of a starting final module, FM , identification of a starting final assembly, FA in FM , and, if FA is a composite final assembly, a further identification to indicate the primary or secondary initial assembly (this latter identification is made by a parameter δ_{IA} with $\delta_{IA} = 0$ for the primary initial assembly, and $\delta_{IA} = i$ for the i th secondary). Since the source strengths per final module, S_{FM} and per final assembly, S_{FA} , are not densities, the starting final module FM is obtained by solving the inequality for FM :

$$\sum_{FM'=1}^{FM-1} S_{FM'} < \rho \sum_{FM'=1}^{N_{FM}} S_{FM'} \leq \sum_{FM'=1}^{FM} S_{FM'}$$

where N_{FM} is the number of final modules.

Likewise, the starting final assembly, FA, is obtained by solving the inequality:

$$\sum_{FA'=1}^{FA-1} S_{FA'} < \rho \sum_{FA'=1}^{N_{FA}^m} S_{FA'} \leq \sum_{FA'=1}^{FA} S_{FA'}$$

where N_{FA}^m is the number of final assemblies in module m . If FA so determined is not composite, then we know the starting initial assembly, IA. If FA is composite, and

$$\sum_{j=1}^{i-1} f^{s_j} < \rho \leq \sum_{j=1}^i f^{s_j}$$

then the starting initial assembly is the i th secondary; if $\rho^* \geq \sum_{i=1}^n f^{s_i}$ where n is the number of secondaries, then the starting initial assembly is the primary.

If basic region n, m in initial assembly IA has an assigned C-list rather than a P-list, then the values of x, y are given by:

$$\begin{aligned} x &= X_{n-1} + \rho(X_n - X_{n-1}), \\ y &= Y_{n,m-1} + \rho(Y_{n,m} - Y_{n,m-1}), \end{aligned}$$

provided $y < -V_g x + Y_{n,Mn}$. Otherwise, new random draws of x and y are made until this condition is met.

If a P List is assigned to n, m , then a rejection technique is used to obtain x and y . The technique starts by drawing x and y as above, then calculations are performed to arrive at the subcell region index s and thus the composition at point x, y say j_{xy} . If $j_{xy} = j$, i.e., the composition already selected as described in Chapter 2, then the point x, y is accepted; if not then the process is repeated with a new draw of x and y and continued until an acceptable x and y are obtained.

Regardless of whether basic region n, m has a C-list or P-list assigned, the value of z is given by:

$$z = Z_{l-1} + \rho(Z_l - Z_{l-1}).$$

If FA is composite and $\delta_{la} = 0$ (i.e., the x and y are in the primary initial assembly), then we must insure that x, y, z is exterior to the secondary initial assemblies. This is done by transforming x, y, z to the coordinate system of each secondary initial assembly. If any one of the following inequalities is met for each secondary initial assembly, then the starting site in the primary initial assembly is acceptable:

1. if $x < 0$, or $y < 0$, or $z < 0$, or $z < Z_L^A$, or

2. $x > X_N^s(1 - V_g^s) + V_g^s M$, where $M = \min. \text{ value of } (X_N^s, Y_{n, M_n}^s)$, or
3. $y > Y_{n, M_n}^s - V_g^s x$.

Should the site not be acceptable, then we must redraw for the primary initial assembly IA, the parameters j, E, W_p, n, m, l as described in Chapter 2, and redraw x, y, z as above (again using the rejection technique if a P-list is assigned to n, m). This complete process is repeated until an acceptable x, y, z is obtained for the primary initial assembly.

We now have all the neutron parameters required to start the geometry tracking, i.e., FM, FA, δ_{IA} , $j, E, W_p, n, m, l, \mu, \gamma, \eta, x, y, z, k_s, \rho$. Here δ_{IA} is retained as well as FA in order to identify primary or secondary IA in a composite final assembly. The parameter k_s is a splitting (or Russian roulette) zone index and is defined in Chapter 5. The parameter ρ is a random number that is used for correlated sampling in RCP01, i.e. each history number has a unique starting random number determined from ρ regardless of the calculations being performed provided the same number of random numbers are “skipped” on the RCP input controls. The manner in which this is done in RCP is described in Appendix L.

5 SPLITTING PROCEDURES

5.1 General Description of RCP Splitting Procedures

The RCP splitting technique does not link the splitting to an explicit boundary crossing. Instead, for this technique the splitting or Russian roulette occurs only at the scattering site after a scattering event. The decision to split or play Russian roulette is controlled by a nested set of ellipsoids of revolution with common foci which are defined in the absolute coordinate system. In particular, if a scattering event occurs in a zone between ellipsoids of revolution that have smaller semi-minor axes than those for the previous scattering event, then splitting is performed. Should the reverse occur, then Russian roulette is played. The amount of splitting and the kill-off probability for Russian roulette are both controlled by a split factor for each ellipsoidal shell, κ_i .

5.2 Splitting Controlled by Scattering Events and Ellipsoids of Revolution (Prolate Spheroids)

5.2.1 Splitting and Russian Roulette Input Parameters

The following input parameters are used by RCP for splitting and Russian roulette:

1. $x_1^d, y_1^d, z_1^d, x_2^d, y_2^d, z_2^d$ - coordinates of foci for ellipsoids of revolution
2. $R_{\max}, R_{\min}$ - semi-minor axis sizes such that splitting and Russian roulette are not performed for scattering outside of the ellipsoid with semi-minor axis $R_{\max}$ nor for scattering inside the ellipsoid with semi-minor axis $R_{\min}$.
3. ΔR - semi-minor axis increments for ellipsoids. With $R_{\min}$ as first minor axis, $R_{\min} + \Delta R$ is the second, and so forth.

4. E_c - energy cut-off for splitting and Russian roulette. Splitting and Russian roulette are not performed for scattering events with neutron energies less than E_c .
5. $K_1, K_1, \dots, K_N$ - splitting parameters (also determine Russian roulette kill-off probability) described further below.

Note: Ellipsoid rotations are always about major axis. If non-modular geometry is used ($N_{FM} = 0$), the foci are given in the initial module coordinate system. If modular geometry is used ($N_{FM} > 0$), the foci are given in the absolute coordinate system.

5.2.2 Modified Expanded Input for Final Module

For modular geometry ($N_{FM} > 0$), the two foci are in the absolute coordinate system. They are transformed to the initial module coordinate system and held as part of the expanded input for a final module given in Section 4.4.3. The modified expanded input for a final module then becomes the following:

$$\text{FM, IM, } V_c^m, x_m, y_m, z_m, \theta_d, \theta_s, \theta_r, S_{FM}, \begin{pmatrix} a_1^m & a_2^m & a_3^m \\ b_1^m & b_2^m & b_3^m \\ c_1^m & c_2^m & c_3^m \end{pmatrix}, r_0, R_0, Z_{\max}, Z_{\min}, x_1^m, y_1^m, z_1^m, x_2^m, y_2^m, z_2^m$$

where the last six parameters are calculated as follows:

1. Set, for $l = 1, 2,$,

$$\begin{aligned}\hat{x}_l &= x_l^d - x_m \\ \hat{y}_l &= y_l^d - y_m \\ \hat{z}_l &= z_l^d\end{aligned}$$

$$\begin{aligned}x_l^m &= a_1^m \hat{x}_l + b_1^m \hat{y}_l + c_1^m \hat{z}_l \\ y_l^m &= a_2^m \hat{x}_l + b_2^m \hat{y}_l + c_2^m \hat{z}_l \\ z_l^m &= a_3^m \hat{x}_l + b_3^m \hat{y}_l + c_3^m \hat{z}_l - z_l\end{aligned}$$

2. For 60° geometry, make the additional adjustment, for $l = 1, 2$, as follows:

$$\begin{aligned}x_l^m &= -y_l^m \frac{1}{\sqrt{3}} + x_l^m \\ y_l^m &= y_l^m \frac{2}{\sqrt{3}}\end{aligned}$$

5.2.3 Determination of Ellipsoid Zone Index of Scattering Site

The following steps are taken to determine the ellipsoid zone index of a scattering site:

1. Bypass the determination of ellipsoid zone index if the exit energy from the scattering event, E_{ex} , is less than E_c .
2. Transform the foci to the local coordinate system of the scattering site:
 - (a) If $N_{FM} = 0$, then set $x_l^m = x_l^d, y_l^m = y_l^d, z_l^m = z_l^d, l = 1, 2$. Otherwise these values are calculated as indicated in the preceding section.
 - (b) If $FM = 0$ (module 0), then skip the next step and set $x_l^f = x_l^d, y_l^f = y_l^d, z_l^f = z_l^d, l = 1, 2$
 - (c) If FM does not equal 0, then set $\hat{x}_l^m = x_l^m - x_a, \hat{y}_l^m = y_l^m - y_a, l = 1, 2$

$$\begin{aligned} x_l^f &= e_1 \hat{x}_l^m + e_2 \hat{y}_l^m, \\ y_l^f &= f_1 \hat{x}_l^m + f_2 \hat{y}_l^m, \\ z_l^f &= z_l^m. \end{aligned}$$

- (d) If $\delta_{l_a} \neq 0$ (scattering site is in a secondary final assembly), then transform x, y, z of the scattering site to primary initial assembly coordinate system.
3. If locally within 60° geometry, then calculate distances as follows:

$$\begin{aligned} d &= \sqrt{(x_2^f - x_1^f)^2 + (x_2^f - x_1^f)(y_2^f - y_1^f) + (y_2^f - y_1^f)^2 + (z_2^f - z_1^f)^2} \\ s &= \sqrt{(x - x_1^f)^2 + (x - x_1^f)(y - y_1^f) + (y - y_1^f)^2 + (z - z_1^f)^2} \\ &\quad + \sqrt{(x - x_2^f)^2 + (x - x_2^f)(y - y_2^f) + (y - y_2^f)^2 + (z - z_2^f)^2} \end{aligned}$$

4. If locally within 90° geometry, then calculate distances as follows:

$$\begin{aligned} d &= \sqrt{(x_2^f - x_1^f)^2 + (y_2^f - y_1^f)^2 + (z_2^f - z_1^f)^2} \\ s &= \sqrt{(x - x_1^f)^2 + (y - y_1^f)^2 + (z - z_1^f)^2} + \sqrt{(x - x_2^f)^2 + (y - y_2^f)^2 + (z - z_2^f)^2} \end{aligned}$$

5. Compute $D = \frac{1}{2}\sqrt{S^2 - d^2 + 10^{-8}}$ and then set ellipsoidal zone index, k_s , as follows:
 - (a) If $D < R_{\min}$, then set $k_s = 0$.

(b) If $D > R_{\max}$,

$$k_s = \text{Integral part} \left\{ \left(\frac{R_{\max} - R_{\min}}{\Delta R} \right) \right\} + 2$$

(c) Otherwise,

$$k_s = \text{Integral part} \left\{ \left(\frac{D - R_{\min}}{\Delta R} \right) \right\} + 1$$

5.2.4 Splitting and Russian Roulette at Scattering Site

The processing of splitting and Russian roulette is handled as follows:

1. For each starting neutron location, determine a starting zone index k'_s according to which ellipsoids of revolution the location falls between.
2. Then, as each scattering event occurs determine a new ending zone index k_s for that event.
3. If $k_s = k'_s$ continue usual tracking.
4. If $k_s < k'_s$, then split the neutron $K^* = \prod_{i=1}^n K_{s-1+i}$ times, where $n = \min(k'_s - k_s, n_{\max})$. This is described below. Note: $n_{\max}$ may be supplied by the user. The default value is 1.
5. If $k_s > k'_s$, then play Russian roulette with survival probability $1/K^*$, where $n = \min(k_s - k'_s, n_{\max})$. This is described below.

5.2.4.1 Splitting Procedure

1. Set the exit neutron weight as $w_{ex} = (1/K^*)w_{ex}$
2. Record the neutron exit parameters in a temporary file and follow $K^* - 1$ additional neutrons with these parameters when that site is used.
3. If the exit energy from scattering is less than the current RCP supergroup energy cut-point, then the exit parameters with the exit weight given by $w_{ex} = (1/K^*)w_{ex}$ are written in the slowing down file together with the factor K^* which gives the number of times these parameters are to be used to define starting neutrons in their next RCP group.

4. For each neutron obtained from the slowing down file for a given RCP energy group, all sites in the temporary file are used before going to the next neutron in the slowing down file. This may result in writing another temporary file. This process is continued until the new temporary file is empty.

5.2.4.2 Russian Roulette Procedure

1. If $\rho < 1/K^*$, then continue usual tracking with $k'_s = k_s$ and $W = K^*W_{ex}$.
2. Otherwise, terminate the history.

5.2.5 Reverse Splitting and Russian Roulette

RCP also permits reverse splitting and Russian roulette. This is controlled by making the splitting parameter negative. $|K^*|$ is still used in the splitting and Russian roulette, but the checks for $k_s < k'_s$ and for $k_s > k'_s$ are interchanged. This has an effect which is opposite the usual effect of regular splitting and Russian roulette in RCP in that splitting occurs as particles move to shells farther from the ellipsoidal axis and roulette occurs as particles approach the axis.

6 RCP01 EIGENFUNCTION STRATEGY

RCP01 makes use of the Monte Carlo analog of the power method as an eigenfunction strategy. One of two methods for selecting the number of histories per iteration, or batchsize, is used. The first is a regularly increasing batchsize. The second is a “warmup/rampup/fixed” procedure in which a lower fixed batchsize is used for “warmup” iterations, followed by a brief “rampup” with increasing batchsize, followed by a higher fixed batchsize for the duration of a job. Statistics are only accumulated after iteration 0 for the first method and during the third or “fixed” phase for the second method. A detailed discussion of various batchsize strategies is given in Reference 6, “Monte Carlo Eigenfunction Strategy and Uncertainties.” That paper also gives a general discussion of fair game requirements.

This chapter will only give the details of the process of connecting iterations in RCP01. This process involves writing a fission file as each iteration is being performed with a limited set of “fission site parameters” recorded at each fission site. These parameters are FM, FA, $\delta I_{\alpha}, j, P_{c_j}, x, y$, and z , where P_{c_j} is the neutron production rate due to fission at collision c_j in composition j in iteration k . A few additional parameters occur on this file for other purposes which are not relevant here (see Section 8.6.2). Note that great flexibility is possible in the definition of a generation (i.e., an iteration) in an eigenfunction strategy; the one used here is from neutron birth in fission to neutron birth in fission, thus $n \rightarrow 2n$ and $n \rightarrow 3n$ neutrons are handled as they are created by increasing the weight of the surviving neutron.

A form of semi-systematic sampling is used to obtain the desired number of starting sites from the fission file for the next iteration. The number of starting sites in iteration k , say N^k , depends on the method used to set batchsizes. For a regularly increasing batchsize, N^k is given by the expression $N^k = M + kC$, where M is input (normally 500) and $C = 10$ (C can be input). For the “warmup/rampup/fixed” procedure, N^k will be M (normally 500) for the first w (default 50) iterations, followed by a period of iterations with $N^k = RN^{(k-1)}$ where $R = 1.2$ by default until N^k reaches target value M_2 (normally 5000), followed by fixed $N^k = M_2$ for all remaining iterations.

The complete process connecting iterations is defined as follows:

1. While iteration k is being performed:

- (a) Write the fission file with the parameters

$$F_m, F_a, \delta I_a, j, P_c, x, y, z$$

- (b) For each composition, accumulate the value of the total neutron production by composition, $SP_j^{k+1} = \sum_{c_j} P_{c_j}$, over all collisions c_j occurring in composition j during iteration k .

2. After iteration k is completed and before starting iteration $k+1$:

- (a) Determine the integral number of neutrons to start in the $(k+1)$ iteration in composition j , n_j^{k+1} , by semi-systematic sampling (the total number of neutron starts in the $(k+1)$ iteration must be N^{k+1}) as follows:

- (i) Set

$$\overline{SP}_j^{k+1} = \frac{SP_j^{k+1}}{\sum_j SP_j^{k+1}},$$

$$\begin{aligned} N_j^{k+1} &= \text{Integral part } \{\overline{SP}_j^{k+1} N^{k+1}\}, \\ f_j^{k+1} &= \text{Fractional part } \{\overline{SP}_j^{k+1} N^{k+1}\}, \\ N_L^{k+1} &= N^{k+1} - \sum_j N_j^{k+1}. \end{aligned}$$

- (ii) Draw N_L^{k+1} starting neutrons proportional to f_j^{k+1} by semi-systematic sampling by checking until

$$\rho < \sum_{i=1}^j f_i^{k+1}, \text{ and then set } N_j^{k+1} = N_j^{k+1} + 1.$$

- (iii) Set $\rho = \rho + 1$, again check above inequality starting with the composition last used until

$$\rho < \sum_{i=1}^j f_i^{k+1}, \text{ and then set } N_j^{k+1} = N_j^{k+1} + 1.$$

- (iv) Continue until the check of inequality has been met a total of N_L^{k+1} times. We will then have, as required,

$$\sum_j N_j^{k+1} = N^{k+1}.$$

- (b) Read the fission file and, using semi-systematic sampling and the values of SP_j^{k+1} and N_j^{k+1} , construct a standard format start file for iteration $k+1$ by the following process:

- (i) Set up counters (one for each composition j) for each of the three quantities $\hat{P}_j^c$, $\rho_j^k(n_j)$ and n_j . Here n_j are initialized to 1, $\hat{P}_j^c$ are initialized to zero, and $\rho_j^k(n_j)$ are initialized to $\rho_j^k(n_j)|_{n_j=1}$ where

$$\rho_j^k(n_j) = \frac{[n_j - 1 + \rho] SP_j^{k+1}}{N_j^{k+1}}.$$

- (ii) Read the parameters of the first fission site in the fission file, FM, FA, $\delta I_a, j, P_c, x, y, z$, and set $\hat{P}_c = \hat{P}_c + P_c$, for composition j only.
- (iii) If $\{(\rho_j^k(1) < \hat{P}_c) \text{ and } n_j \leq N_j^{k+1}\}$, then accept the site, draw an energy E from the fission spectrum, set neutron $W = 1$, draw μ, γ, η isotropically in lab system, and put the parameters FM, FA, $\delta I_a, j, E, W, \mu, \gamma, \eta, x, y, z$ on a start file for iteration $k+1$.
- (iv) Set $n_j = n_j + 1$. If $\{(\rho_j^k(2) < \hat{P}_c) \text{ and } n_j \leq N_j^{k+1}\}$ again accept the site as above but with independent values of E, μ, γ, η .
- (v) Set $n_j = n_j + 1$ and continue the process until either $\rho_j^k(n_j) \geq \hat{P}_c$ or $n_j > N_j^{k+1}$ (as each new $\rho_j^k(n_j)$ or n_j is constructed, it replaces the previous value in the computer).
- (vi) When $\{(\rho_j^k(n_j) \geq \hat{P}_c) \text{ or } (n_j > N_j^{k+1})\}$, go to the next site in the fission file.
- (vii) Continue the entire process over all points recorded on the fission file. We will then have a standard format start file with exactly N^{k+1} starting sites which is then used in the conventional manner to start tracking in iteration $k+1$.

7 FIXED SOURCE AND EIGENFUNCTION UNCERTAINTIES

A fixed source calculation in RCP01 uses a fixed number of histories per iteration k (i.e., N^k is a constant) but for an eigenfunction calculation N^k increases with increasing k . For this reason Appendix K derives a general approach for calculating variance with general values of N^k . Using the results of Appendix K, this chapter describes the steps used in RCP01 to calculate the fixed source and eigenfunction uncertainties. The latter will include a summary of the application of the modification of MacMillan's formula to obtain the total eigenfunction uncertainty (Reference 6). Finally, the problem of interpreting confidence statements obtained from the variance will be briefly discussed.

7.1 RCP01 Calculation of Fixed Source and Eigenfunction Uncertainties

For a fixed source calculation we may summarize the calculation of $\sigma_K^2(\bar{X})$ as (subscript denotes σ^2 estimated at end of K iterations):

Starting with two quantities per reaction rate X^k ,

$$\text{i.e., } \bar{X} = \frac{\sum_{k=1}^K N^k X^k}{\sum_{k=1}^K N^k} \text{ and } \overline{X^2} = \frac{\sum_{k=1}^K N^k (X^k)^2}{\sum_{k=1}^K N^k},$$

we may write the formula from Appendix K as:

$$\sigma_K^2(\bar{X}) = \frac{\sum_{k=1}^K N^k (X^k - \bar{X})^2}{K \sum_{k=1}^K N^k}$$

or

$$\sigma_K^2(\bar{X}) = \frac{1}{K} [\overline{X^2} - \bar{X}^2].$$

This approach is used for all fixed source uncertainties.

An eigenfunction calculation requires five accumulative counters per reaction rate X^k . We will here define these counters as is done in RCP01, i.e., in terms of the non-normalized reaction rates per iteration k , PP^k , where $PP^k = N^k X^k$.

1. PP^1
2. PP^k
3. $P^K = \sum_{k=1}^K PP^k$
4. $C^K = \sum_{k=1}^K \frac{(PP^k)^2}{N^k}$
5. $A^K = \sum_{k=2}^K \frac{PP^{k-1} PP^k}{\sqrt{N^{k-1} N^k}}.$

In addition, we need one counter per problem, namely

$$B^K = \sum_{k=2}^K \sqrt{N^{k-1} N^k}.$$

Define in the notation of Chapter 6,

$$N_T^K = \sum_{k=1}^K N^k = MK + \frac{C}{2} K(K+1).$$

We now calculate the purely statistical component of uncertainty as for a fixed source problem, i.e.,

$$\sigma_K^2 = \frac{1}{KN_T^K} \left[C^K - \frac{(P^K)^2}{N_T^K} \right].$$

If $\sigma_K^2 \leq 0$, set $\sigma_K^2 = 0$ (could occur due to roundoff). The formula for the serial correlation coefficient of lag 1, ρ_K , estimated at iteration K , as given in Section 3.3 of Reference 6, is now written in terms of the above counters as

$$\rho_K = \left[\frac{A^K}{B^K} - \frac{(P^K - PP^K)(P^K - PP^1)}{N_T^K - 1} \right] \frac{1}{N_T^K - N_T^1} \frac{1}{K\sigma_K^2}.$$

If $|\rho_K| \geq 1$ set $\rho_K = 0$; this can occur only when every history gives nearly the same reaction rate and is due to approximations in the formula for ρ_K , but for this case we know that ρ_K should be nearly zero. Now using the modification of MacMillan's formula given in Section 3.3 of Reference 6, we write the total eigenfunction variance as

$$\sigma_K^2 = \sigma_K^2 \left(1 + \frac{10\rho_K^2}{1 - \rho_K} \right).$$

In RCP01 a probable error (50% confidence interval) is obtainable per edit quantity as $P.E. = 0.6745 \sqrt{\sigma_K^2}$. The following three notations are used to denote the origin of the P.E. being printed.

- (a) P.E. - this error is computed for a given reaction rate per nuclide per RCP energy group using the fixed source formula where an experiment is taken as one history. Combination edits for these basic quantities are made assuming they are independent.
- (b) STAT. P.E. - this error is the same as (a) except an experiment is taken as one iteration.
- (c) TOT. P.E. - this error is the same as (b) except the modeled MacMillan factor is used to estimate total eigenfunction uncertainty.

On user option, the above $P.E. = 0.6745 \sqrt{\sigma_K^2}$ is replaced by a standard deviation $\sqrt{\sigma_K^2}$ or by a 95% confidence interval $= 1.96 \sqrt{\sigma_K^2}$; thus RCP01 can optionally compute: standard deviation, STAT standard deviation, and TOT standard deviation, or 95% C.I., STAT 95% C.I., and TOT 95% C.I.

7.2 Interpretation of Confidence Interval Statements

The calculation of variance for a neutron reaction rate $\bar{X}$, $\sigma_K^2(\bar{X})$, as described in Section 7.1 above, is of good accuracy if the number of experiments, K , contributing to the estimate of $\sigma_K^2(\bar{X})$ is reasonably large. This is evident from the formula for the uncertainty of the uncertainty

$$\sigma(\sigma_K(\bar{X})) = \frac{\sigma_K(\bar{X})}{\sqrt{2K}}$$

from Appendix K. Furthermore, from the central limit theorem, if K is sufficiently large, then the distribution function for $\bar{X}$ is approximately normal. Thus, under these circumstances, the use of a formula to obtain confidence intervals from variance, such as $P.E. = 0.6745 \sqrt{\sigma^2}$, is sound. However, large deviations from a normal distribution $\bar{X}$ could result in a faulty confidence interval statement. There are many tests available for testing normality of an initial population, say X^k , where

$$\bar{X} = \frac{\sum_{k=1}^K N^k X^k}{\sum_{k=1}^K N^k}.$$

However, even though the initial population is badly non-normal, the frequency distribution function for $\bar{X}$ will be more normal by the central limit theorem. Hence, what is desired is a normality test for $\bar{X}$, but we have only one value of $\bar{X}$ after performing a Monte Carlo calculation. One possible method of testing for non-normality of $\bar{X}$ involves initially the calculation of skewness of X^k , i.e., the 3rd moment normalized by $[\sigma(X^k)]^3$, say $g(X^k)$. Thus

$$g(X^k) = \frac{\sum_{k=1}^K N^k (X^k - \bar{X})^3}{[\sigma(X^k)]^3}.$$

It is known that an estimate of $g(\bar{X})$ is given by

$$g(\bar{X}) = \frac{g(X^k)}{\sqrt{K}}.$$

It is further known that if $\bar{X}$ is normally distributed, then $g(\bar{X})$ is approximately normally distributed with mean zero and a standard deviation given by,

$$\sigma(g(\bar{X})) = \sqrt{\frac{6}{K^*}}$$

where K^* is the sample size of the population of $\bar{X}$'s. In our case we have only one $\bar{X}$, but we may nonetheless compute an effective sample size K^* such that the value of $\sigma(g(\bar{X}))$ is at the 95% confidence limit (1.96σ), assuming $\bar{X}$ is normally distributed. That is,

$$K^* = 6 \cdot \left(\frac{1.96}{\sigma(g(\bar{X}))} \right)^2.$$

If this effective sample size is small, say $K^* < 30$, then we may label the confidence interval statement as doubtful. This non-normality test is not a part of RCP01 but is easily performed in post-editing.

Another consideration in the correct interpretation of a confidence interval statement starts with the recognition that the interval is centered about a draw of a random variable, i.e., $\bar{X}$. Once we have run the Monte Carlo calculation and obtained one value of $\bar{X}$ and constructed, say, a 95% confidence interval about $\bar{X}$, then we may ask what is the probabilistic interpretation of this interval.

For example, may we say that the probability is .95 that the true mean, say x , lies in this interval? Or may we say that if we repeat the process of obtaining $\bar{X}$ many times with different random number sequences, then the fraction of $\bar{X}$'s lying in the original interval is 0.95? The answer to both of these questions is no. Three correct views concerning confidence intervals are as follows: (we will use the 95% confidence interval as an example).

1. If we visualize many runs of the Monte Carlo calculation using different random number sequences, each producing an $\bar{X}$ and a 95% confidence interval centered about $\bar{X}$, then the fraction of such intervals that contain the true mean approaches 0.95 (note that if we are given only one interval, then all we may say technically is that the probability of the parameter x lying in this interval is 0 or 1).
2. We may visualize the use of a mathematical artifice whereby the parameter x and the random variable $\bar{X}$ are interchanged resulting in a probabilistic statement equivalent to the confidence interval statement. That is, if 2ϵ is the size of the 95% confidence interval, then

$$P(X - \epsilon < \bar{X} < X + \epsilon) = P(\bar{X} - \epsilon < X < \bar{X} + \epsilon)$$

where the left part of this equation is in the form of an ordinary probabilistic assertion for the random variable. By use of this artifice, we may now legitimately speak of the probability of the unknown parameter x lying in an interval centered about $\bar{X}$.

3. If we visualize one run of a Monte Carlo calculation producing an estimate of x , i.e., $\bar{X}$, and a 95% confidence interval centered about $\bar{X}$, $\bar{X} - \epsilon$ to $\bar{X} + \epsilon$, then subsequent $\bar{X}$'s produced from independent runs will have a less than 0.95 probability of lying in the

original interval. For example, if the first $\bar{x}$ should be a distance from x equal to ϵ then less than half of the subsequent independent runs will produce $\bar{x}$'s in this interval. Methods exist for obtaining a scale factor for a confidence interval to produce a "prediction" interval for subsequent $\bar{x}$'s, but this is generally of no interest in Monte Carlo since the principal concern is the probability that the true value, x , lies in the confidence interval as interpreted in (2) above.

8 PHOTON TRANSPORT, GAMMA ENERGY DEPOSITION, LINKED CALCULATIONS, AND REACTOR HEATING

The description of RCP photon calculations involves the following items: photon transport, form of photon cross sections and spectra, gamma ray sources treated, photon interactions treated, coupled neutron-photon calculations, and reactor heating.

8.1 General Description of Photon Transport in RCP

All the details of geometry tracking for neutrons, described in Chapter 4, once the number of mean free paths to be traversed on a free flight is determined, are the same for photon tracking. In a manner analogous to the neutron calculations, RCP works directly with photon collision densities, i.e., the incident photon weight, w_{i_0} , at a reaction site. w_{i_0} is a contribution to the total collision density over some region that contains this site. Thus the total amount of energy in a photon that will be required for determination of reactor heating is given by $w_{i_0} E_0$, where E_0 is the incident energy of the photon (an analogous expression yields the total amount of energy for a neutron).

In view of the complete parallel between photon and neutron transport calculations in RCP, all that is additionally required for a complete description of photon transport is a description of source spectra and photon interactions.

8.2 Form of Photon Cross Sections and Source Spectra on the Job Library

The photon cross sections in barns per nuclide i , made available to RCP on the job library from RCPL1 (Reference 2) consist of reaction cross sections for Compton scattering, σ_c^i , photoelectric effect, σ_{pe}^i , pair production, σ_{pp}^i and photo neutron production, σ_{pn}^i . The energy group structure of the job library for all nuclides is similar to that used for resonance detail for neutron cross sections; i.e., a maximum of 200 RCP groups with requestor specified group cut points and a maximum of 400 uniform energy subgroups per RCP group.

When the photon cross sections are required in RCP at energy E for free flight determination, or reaction type determination, then the cross sections are linearly interpolated over the subgroups.

Each nuclide on the job library is permitted to have one photon spectrum. Of course the two nuclide method for capture and fission used for the neutron job library carries over to the photon library. Thus the photon spectrum for a capture nuclide is that for neutron capture gammas and the photon spectrum for a fission nuclide is that for fission gammas (ordinarily this will be a combination of prompt and decay product fission gammas). In addition each job library has one spectrum, not linked to any nuclide, which is used as the source spectrum only in fixed source photon calculations (ordinarily this spectrum will be that for fission gammas). All job library photon spectra are defined over G groups ($G \leq 57$); normally 57 groups are used covering 0 to 10 MeV, where the lowest four groups starting at 0 eV are each of width 50 KeV, the next eight are each of width 100 KeV and the remainder are each of width 200 KeV. All job library photon spectra are group-wise integrated photon densities in accumulative form. For example, let $N(E)$ be an experimentally measured photon density. Then $N(E)dE$ is the total number of photons emitted between E and $E + dE$. A group integrated value of this spectrum, say N^g , is given by

$$N^g = \int_{E^g}^{E^{g-1}} N(E)dE$$

where E^{g-1} and E^g are the energies of the group end points. Before the values of N^g are put on the job library in accumulative form, they are adjusted to yield the correct total photon energy as well as the correct total number of photons. Letting these adjusted values also be denoted by N^g , then we must have

$$\sum_{g=1}^G N^g = \text{Total number of photons per fission event.}$$

$$\sum_{g=1}^G N^g \frac{(E^{g-1} + E^g)}{2} = \text{Total energy in photons per fission event.}$$

The accumulative form of the spectrum on the job library, say S^g , is given by

$$S^g = \sum_{g'=1}^g N^{g'}.$$

Thus for a group structure with G groups, S^g is the total number of photons per fission event (or per neutron capture for the case of a neutron capture gamma spectrum).

8.3 Gamma Ray Sources Treated in RCP

The means by which the various types of gamma ray sources are treated in RCP are described in the following subsections. The angular distribution for all gamma ray sources is taken as isotropic in the lab system.

8.3.1 Prompt, and Decay Product, Fission Gammas

As discussed previously, the photon job library for a fission nuclide would ordinarily have a spectrum for the combined steady state prompt and decay product fission gammas. Of course the job library for such a nuclide could contain any spectrum. For example, it could contain only the prompt spectrum. Or it could contain a shutdown decay product spectrum that results after a specified reactor power history and time after shutdown. This latter type of spectrum is used in the subcritical photoneutron calculations described in Chapter 9. All of the above comments also apply to the fixed source spectrum in the job library.

8.3.2 Neutron Capture, Reaction Product, and Activation Product Gammas

The term neutron capture gammas usually refers to only the prompt gammas emitted as a result of the (n, γ) reaction. For this reaction the total energy of the emitted photons for each capture must add up to the binding energy of the neutron plus its incident kinetic energy. Since neutron binding energies are usually in the range of 6 to 7 MeV, ranging from 2.2 MeV for hydrogen to 11 MeV for ^{14}N , and since the neutron cross section for an (n, γ) reaction is small for large neutron energies, then in practice the total energy of the photons is nearly the binding energy. In RCP it is assumed that the neutron capture gamma spectrum is that for thermal neutrons (most experimental measurements are for this case) and that the incident energy of the neutron for a high energy (n, γ) reaction is not carried off by the photons, but is deposited at the site of the (n, γ) reaction (this will be discussed in more detail in the section on reactor heating).

Other neutron capture reactions also produce prompt gammas. These are the charged particle reactions such as (n, α) or (n, p) . The resulting gammas are referred to as reaction pro-

duced gammas. The charged particle reactions deemed most likely to be important in reactor heating (excluding fission) are, ${}^6\text{Li}(n, \alpha)$, ${}^{10}\text{B}(n, \alpha)$, and ${}^{14}\text{N}(n, p)$ (Reference 8).

Still other neutron capture reactions will produce a residual nucleus that is radioactive and in decay will emit gamma rays. For example, in coolants the most important reactions of this type are ${}^{23}\text{Na}(n, \gamma)$, ${}^{24}\text{Na}$, ${}^{16}\text{O}(n, p)$, ${}^{16}\text{N}$, ${}^{18}\text{O}(n, \gamma)$, ${}^{19}\text{O}$ (Reference 8). The decay gammas resulting from these reactions are referred to as activation product gammas.

For both reaction product and activation product gamma spectra, the assumption is again made in RCP that these spectra are for thermal neutrons and the incident energy of the neutron is deposited at the reaction site. All three spectra, i.e., capture, reaction product, and activation product are combined per nuclide, using the corresponding thermal cross sections as weights, to produce one effective capture gamma spectrum per nuclide. It is this effective spectrum per nuclide that is available from the photon job library.

8.3.3 Annihilation Gammas

A positron is annihilated very close to its source producing two 0.5 MeV photons. Thus annihilation gammas resulting from fission product decay are already a part of the job library fission gamma spectrum. Likewise, annihilation gammas resulting from activation product decay are already a part of the job library nuclide effective capture gamma spectrum. The important annihilation gammas produced as a result of pair production by gamma rays are followed from the time of their birth and are discussed in Section 8.4.4.

8.3.4 Inelastic Scattering Gammas

The energy lost by a neutron scattering inelastically goes into excitation energy of the target nucleus, which is subsequently lost by the emission of one or more gamma rays. This gamma ray spectrum is strongly dependent on incident neutron energy. In RCP the assumption is made that the energy of the inelastic scattering gammas is deposited at their point of birth. Because such gammas may contribute significantly to heating rates in some problems, RCP edits this term separately.

8.3.5 Bremsstrahlung

The production of gamma rays (Bremsstrahlung) by the deceleration of electrons or positrons subsequent to positive or negative beta decay of fission products or activation products is included as part of the job library fission gamma, or effective capture gamma, spectra respectively.

8.4 Photon Interactions Treated in RCP

As stated earlier, the photon job library contains reaction cross sections per nuclide i for Compton scattering, σ_c^i , photoelectric effect, σ_{pe}^i , pair production, σ_{pp}^i , and photoneutron production, σ_{pn}^i . The RCP treatments of these reactions are defined as follows:

8.4.1 Determination of Type of Photon Reaction

The microscopic photon cross sections from the job library are combined with input nuclide densities for nuclide i in composition j , N_j^i (atoms/barn-cm), to form the following macroscopic cross sections for composition j ,

$$\begin{aligned}\Sigma_{cj} &= \sum_i N_j^i \sigma_c^i && \text{(Compton scattering)} \\ \Sigma_{pej} &= \sum_i N_j^i \sigma_{pe}^i && \text{(Photoelectric)} \\ \Sigma_{ppj} &= \sum_i N_j^i \sigma_{pp}^i && \text{(Pair production)} \\ \Sigma_{Tj} &= \Sigma_{cj} + \Sigma_{ppj} + \Sigma_{pej}\end{aligned}$$

A macroscopic cross section for photoneutron production is not formed since this cross section is very small; the photoneutron production is determined in RCP using a photon flux estimate as will be discussed in Section 8.4.5. The type of photon reaction (r , 1, 2, 3) is determined as follows:

If $\rho \Sigma_{Tj} < \Sigma_{cj}$; Compton scattering ($r = 1$)

If $\rho \Sigma_{Tj} < \Sigma_{cj} + \Sigma_{pej}$; Photoelectric ($r = 2$)

Otherwise; Pair production ($r = 3$)

8.4.2 Compton Scattering

In RCP all photon scattering is treated as Compton scattering, i.e., the scattering of photons by free electrons (At low photon energies, the binding of the electron to an atom or lattice is sensed with the result that little photon energy is lost in a scattering reaction; this form of scattering (Rayleigh) is neglected in RCP). Since the electrons are free in Compton scattering, then the compton scattering microscopic cross section on the job library for a given nuclide is simply the electron scattering cross section multiplied by the atomic number.

The scattering of unpolarized incident photons by electrons assumed to be free and at rest is defined by the well known Klein-Nishina formula for the differential cross section, $d\sigma$, which is frequently written as

$$d\sigma = \sigma(\alpha, \theta) \sin\theta d\theta.$$

$$= \pi r^2 \left[\frac{1}{1 + \alpha(1 - \cos\theta)} \right]^2 \cdot \left[1 + \alpha(1 - \cos\theta) + \frac{1}{1 + \alpha(1 - \cos\theta)} \sin^2\theta \right] \sin\theta d\theta,$$

where α is the photon energy measured in units of the rest mass energy of the electron (i.e.,

$$\alpha = \frac{h\gamma_0}{m_0 c^2},$$

where h is Planck's constant, γ_0 is the frequency of the incident photon, m_0 is the electron mass and c is the velocity of light), θ is the lab system scattering angle relative to the incident photon direction, and where r is the classical electron radius ($\pi r^2 = 0.2494$ barns). Let $E_0 = h\gamma_0$ be the energy of the incident photon, and let $E = h\gamma$ be the energy of the exit photon. Then conservation of energy and momentum requires that

$$\frac{E}{E_0} = \frac{1}{1 + \alpha(1 - \cos\theta)}.$$

The differential cross section for Compton scattering is sampled rigorously in RCP by use of a rejection technique. This technique is obtained as follows: Let

$$k = \frac{E}{E_0} = \frac{1}{1 + \alpha(1 - \cos\theta)}$$

where the range of k is $\frac{1}{1 + 2\alpha} \leq k \leq 1$.

Therefore,

$$dk = k^2 \alpha \sin\theta d\theta,$$

$$1 - \cos\theta = \frac{1}{\alpha} \left(\frac{1}{k} - 1 \right),$$

$$\sin^2\theta = \frac{2}{\alpha} \left(\frac{1}{k} - 1 \right) - \frac{1}{\alpha^2} \left(\frac{1}{k} - 1 \right)^2.$$

We may write

$$d\sigma = f(\alpha, \theta) d\theta = f(\alpha, k) dk$$

where

$$f(\alpha, k)dk = \frac{\pi r^2}{\alpha} \left[\frac{1}{k} + k - \frac{2}{\alpha} \left(\frac{1}{k} - 1 \right) + \frac{1}{\alpha^2} \left(\frac{1}{k} - 1 \right)^2 \right] dk$$

The term

$$g(\alpha, k) = -\frac{2}{\alpha} \left(\frac{1}{k} - 1 \right) + \frac{1}{\alpha^2} \left(\frac{1}{k} - 1 \right)^2$$

is ≤ 0 over the range of k . To see this, solve for values of k for which $g(\alpha, k) = 0$; this occurs only for $k = 1$ and $k = \frac{1}{1+2\alpha}$, i.e., the end points of the range of k . Insertion into $g(\alpha, k)$ of a midpoint of the range of k will demonstrate that $g(\alpha, k) \leq 0$. Thus we may write

$$f'(\alpha, k) = \frac{\pi r^2}{\alpha} \left(\frac{1}{k} + k \right) \geq f(\alpha, k) \text{ for } \frac{1}{1+2\alpha} \leq k \leq 1$$

We will draw a value of k using $f'(\alpha, k)$ as a distribution function and then use a rejection technique to see if k is acceptable. The efficiency of the rejection technique is given by

$$\int_{\frac{1}{1+2\alpha}}^1 f(\alpha, k) dk / \int_{\frac{1}{1+2\alpha}}^1 f'(\alpha, k) dk.$$

The efficiency varies from about 0.55 for $\alpha = 0$ to 1 for $\alpha = \infty$.

We need to sample analytically

$$f'(k) = \frac{1}{k} + k;$$

we will drop the factor of $\frac{\pi r^2}{\alpha}$ in f' and f .

$$\text{Let } a = \int_{\frac{1}{1+2\alpha}}^1 \frac{1}{k} dk = \ln(1+2\alpha)$$

$$b = \int_{\frac{1}{1+2\alpha}}^1 k dk = \frac{1}{2} \left(1 - \frac{1}{(1+2\alpha)^2} \right)$$

We may now use a random number to decide whether sampling is to be done from $\frac{1}{k}$ or k . If sampling is to be done from $\frac{1}{k}$, then we solve

$$\frac{1}{a} \int_k^1 \frac{1}{k} dk = \rho.$$

If sampling is to be done from k , then we solve

$$\frac{1}{b} \int_k^1 k dk = \rho.$$

We may now give a summary of the procedure for determining the photon exit energy E and the cosine of the lab system scattering angle, μ' , relative to the incident photon direction by use of the Klein-Nishina scattering law as follows:

Set $\alpha = \frac{E}{0.511 \times 10^6}$, where 0.511×10^6 is rest mass energy of electron in eV.

$$a = \ln(1 + 2\alpha),$$

$$b = \frac{1}{2} \left(1 - \frac{1}{(1 + 2\alpha)^2} \right).$$

If $\rho < \frac{a}{a+b}$, set $k = e^{-\rho a}$,

Otherwise, set $k = \sqrt{1 - 2\rho b}$.

If

$$\rho \left(\frac{1}{k} + k \right) < \frac{1}{k} + k - \frac{2}{\alpha} \left(\frac{1}{k} - 1 \right) + \frac{1}{\alpha^2} \left(\frac{1}{k} - 1 \right)^2,$$

then accept k ; otherwise using new random numbers repeat the entire process until k is accepted.

Then set

$$E = kE_0,$$

$$\mu' = 1 - \frac{1}{\alpha} \left(\frac{1}{k} - 1 \right),$$

$$\varphi = 2\pi\rho.$$

where φ is the azimuthal scattering angle relative to the incident photon direction. Knowing the incident photon direction cosines, μ_0, γ_0, η_0 , and the values of μ' and φ , we may obtain the exit direction cosines μ, γ, η by use of the formulas given in Section 3.3.4. Of course, the exit photon weight w_i is equal to the incident weight w_{i_0} .

8.4.3 Photoelectric Effect

In the photoelectric effect all the energy of the incident photon is transferred to one of the atomic electrons, thereby ejecting it from the atom. The kinetic energy of the emitted electron is equal to the incident photon energy less the ionization energy of the electron. The energy of the fluorescence gammas that would be emitted as atomic electron vacancies are filled is assumed in RCP to be deposited at the site of the photoelectric reaction; the same assumption is made for Bremsstrahlung from the ejected electron as it decelerates. Thus in RCP the photoelectric effect is a total photon absorption with all photon energy deposited at the reaction site. Of course, the photoelectric effect in RCP terminates the photon history and E and w_i are set to zero.

8.4.4 Pair Production

In pair production all the energy of the incident photon is transformed into an electron-positron pair. The kinetic energy of the pair is equal to the photon energy less two times the rest mass energy of the electron, i.e., $E_0 - 1.022(10^6)$ eV. The subsequent annihilation of the positron close to the site of the pair production results in two photons, each with an energy equal to the rest mass energy of the electron, i.e., $0.511(10^6)$ eV. The angular distribution of these photons is assumed to be isotropic in the lab system. The energy of Bremsstrahlung due to deceleration of the pair is assumed in RCP to be deposited at the pair production site. Thus in RCP a pair production reaction results in

$$\begin{aligned} E &= 0.511 \times 10^6 \text{ eV}, \\ W_i &= 2W_{i_0}, \\ \mu &= 2\rho - 1, \\ \varphi &= 2\pi\rho, \\ \gamma &= \sqrt{1 - \mu^2} \cos \varphi, \\ \eta &= \frac{2\rho - 1}{|2\rho - 1|} \sqrt{|1 - \mu^2 - \gamma^2|}. \end{aligned}$$

where E is the exit photon energy, w_i is the exit photon weight, and μ, γ, η are the exit photon direction cosines.

8.4.5 Photoneutron Production

As discussed earlier, the macroscopic photoneutron cross section for composition j , Σ_{pnj} , is very small relative to the sum of the Compton scattering, pair production, and photoelectric sections for composition j , i.e., $\Sigma_{Tj} = \Sigma_{cj} + \Sigma_{ppj} + \Sigma_{pej}$. If a binomial type of selection were used in RCP to see if photoneutron production occurred, then an extreme small-sampling problem would occur. The approach used in RCP is to obtain the photon flux estimate per collision by

simply dividing the incident photon weight, w_{i_0} by Σ_{Tj} . This photon flux multiplied by the photoneutron cross section for nuclide i in composition j yields the photoneutron production for nuclide i , that is

$$\text{Photoneutron production} = \frac{w_{i_0}}{\Sigma_{Tj}} N_j^i \sigma_{pn}^i \text{ (per nuclide } i \text{)}.$$

Because photon energy deposition occurs in every photon collision, the collision file written in RCP during a photon calculation will contain every collision site even though binomial estimation is used to determine the type of collision reaction. This is in contrast to a neutron calculation with binomial estimation when only the collision that results in kill-off is retained on the collision file. In the former case the flux estimate is $\frac{W_0}{\Sigma_{Tj}}$ as discussed above and in the latter

the flux estimate is $\frac{W_0}{\Sigma_{aj}}$ where Σ_{aj} is the total absorption cross section for composition j .

Because the neutrons born at photoneutron production sites are followed in a photon to neutron linked calculation (e.g., the subcritical calculations described in Chapter 9), we assume that the neutrons are born isotropically in the lab system (this is nearly the case). That is we take

$$\begin{aligned} \mu &= 2\rho - 1, \\ \varphi &= 2\pi\rho, \\ \gamma &= \sqrt{1 - \mu^2} \cos \varphi, \\ \eta &= \frac{2\rho - 1}{|2\rho - 1|} \sqrt{1 - \mu^2 - \gamma^2}. \end{aligned}$$

As is discussed in the next section, the neutron starting sites are sampled in proportion to the photoneutron production rate at the site, thus the neutron starting weight is set to a constant; in RCP $w_i = 1$ (overall normalization of the neutron to the photon calculation must be done externally).

To obtain the energy of the photoneutron we assume that the momentum of the incident photon is small. From conservation of energy and momentum, we may write

$$\frac{k}{2} v_1^2 + \frac{k}{2} M_2 v_2^2 = E_0 - E_t,$$

$$v_1 + M_2 v_2 = 0$$

where v_1 is the velocity of the neutron, v_2 is the velocity of the recoil particle, M_2 is the ratio of the recoil particle mass to the neutron mass (i.e., $M_2 = \text{Mass of target in neutron units} - 1$), E_0 is the energy of the incident photon, E_t is the threshold energy for the photoneutron reaction, and k is a units conversion factor. It follows that

$$E(\text{neutron}) = \frac{k}{2} v_1^2 = \frac{E_0 - E_t}{1 + \frac{1}{M_2}}.$$

This equation is quite accurate for deuterium for energies of interest but for heavier targets such as ^9Be , a range of exit neutron energies results. Photoneutron spectra are not available from a photon job library. The approach taken in RCP is that the requestor supplies, as part of the RCP input, the constants

$$\frac{1}{1 + \frac{1}{M_2}}$$

and E_t per photoneutron nuclide and the above equation is used to obtain the neutron energy. The values of E_t for several nuclides with important photoneutron production rates are (Reference 8):

$$^2\text{D } E_t = 2.23 \text{ MeV}$$

$$^9\text{Be } E_t = 1.67 \text{ MeV}$$

$$^{13}\text{C } E_t = 4.9 \text{ MeV}$$

$$^6\text{Li } E_t = 5.3 \text{ MeV}$$

8.5 Fixed Source Photon Calculations in RCP

A fixed source photon heating calculation, where the photon source is input directly into RCP, is performed in exactly the same manner as a fixed source neutron calculation. That is, a source strength is specified per final module and final assembly, and a source density is specified per composition. The photon source is spatially flat per composition within each final assembly. It is also isotropic in the lab system, and the photon starting weights are all set to unity. The source spectrum used is the library spectrum that is independent of nuclides.

8.6 Linked Neutron-Neutron, Neutron-Photon, and Photon-Neutron Calculations in RCP

The calculational details described in this section are primarily those for a linked neutron-photon calculation. However, these details are so similar to those for linked neutron-neutron, and linked photon-neutron that they all will be described here.

The “link” files used in RCP are subsets of general neutron, or photon, collision files (The actual files used in RCP are of several types, but are all subsets of the general collision file). The description of these collision files and link files, and the details of performing the linked calculations, are described in the following subsections.

8.6.1 Neutron and Photon Collision Files

The neutron and photon collision files are of the same format. Neutron collision parameters are written for every neutron collision with the exception that if a binomial estimator is used, then only a collision that results in neutron absorption is recorded. For a photon calculation, the collision parameters are written for every photon collision. Below are defined the parameters on the neutron collision file with the redefinition of some parameters in parentheses as required to define the photon collision file.

j - composition number

i_a - absorption nuclide, capture or fission; this parameter is determined at time of collision by use of a random number and checking until

$$\rho \Sigma_a < \sum_{i=1}^{i_a} \Sigma_a^i$$

where Σ_a is the total absorption cross section (photon: photoneutron nuclide, i_{pn} , obtained by

checking until $\rho \sum_i N_j^i \sigma_{pn}^i < \sum_{i=1}^{i_{pn}} N_j^i \sigma_{pn}^i$)

δ_a - if i_a is a neutron capture nuclide, i.e., without ν 's, then $\delta_a = 0$; if i_a is a neutron fission nuclide, i.e., with ν 's, $\delta_a = 1$ (photon: still refers to neutron properties).

i_s - scattering nuclide (photon: not used)

δ_s - if neutron scattering is elastic then $\delta_s = 0$; if scattering is inelastic then $\delta_s = 1$ (photon: type of reaction, r , where $r = 1$ for Compton scattering, $r = 2$ for photoelectric, and $r = 3$ for pair production).

g - RCP energy group number.

h - history number

FA - final assembly number

FM - final module number

K - splitting zone index

δ_{IA} - composite final assembly parameter; $\delta_{IA} = 0$ for primary final assembly; $\delta_{IA} = i$ for i th secondary final assembly.

μ_0 - cosine of scattering angle for neutrons (photon: flux)

P_{cj} - the total fission neutron production at collision c_j in composition j (photon: the total photoneutron production at collision c_j in composition j , i.e., $\frac{W_{t_0}}{\Sigma_{Tj}} \sum_i N_j^i \sigma_{pn}^i$).

x, y, z - spatial coordinates of collision site in local coordinate system, i.e., the initial assembly coordinate system corresponding to final assembly FA, or if collision is in module 0 (FM = 0), then in the absolute coordinate system.

n, m, l - basic region indices (See Section 2.1.1)

W_{t_0} - incident weight of neutron (or photon)

θ_{cj} - neutron flux estimate at collision site; i.e., $\frac{W_{t_0}}{\Sigma_T}$ if a $\frac{\Sigma_a}{\Sigma_T}$ terminating or non-terminating estimator is used, or $\frac{W_{t_0}}{\Sigma_a}$ if a binomial estimator is used (photon: energy deposition at collision site divided by composition macroscopic cross section for photon reaction type r , i.e., $\frac{W_{t_0}(E_0 - E)}{\Sigma_{cj}}$ for $r = 1$, $\frac{W_{t_0}E_0}{\Sigma_{pej}}$ for $r = 2$, and $\frac{W_{t_0}(E_0 - 1.022(10^6))}{\Sigma_{ppj}}$ for $r = 3$).

$(\Sigma_a \phi)_{cj}$ - total neutron absorption at collision site; capture plus fission (photon: not used; set to 0)

Σ_T - total cross section at incident energy; recorded if perturbation calculation is selected as described in Appendix J; otherwise $\Sigma_T = 0$ (photon: not used).

E - exit energy (e.v.) of neutron (or photon)

W_r - exit weight of neutron (or photon)

s - distance traveled in composition one since last collision; recorded if perturbation calculation is selected, as described in Appendix J, otherwise $s = 0$ (photon: not used; set to 0).

Σ_s - scattering cross section for scattering nuclide i_s ; if scattering is elastic ($\delta_s = 0$) then Σ_s is the elastic scattering cross section; if scattering is inelastic ($\delta_s = 1$) then Σ_s is the inelastic

scattering cross section (photon: not used; set to 0). This quantity is recorded only if perturbation calculation is selected, as described in Appendix J, otherwise $\Sigma_s = 0$.

E_0 - incident energy (eV) of neutron (or photon).

8.6.2 Linked Neutron-Neutron Calculations

The link file for neutron-neutron calculations is a subset of the neutron collision file parameters. This file consists of

$$x, y, z, (\Sigma_a \phi)_{cj}, P_{cj}, i_a, \delta_a, j, FA, FM, \delta_{IA}$$

for those sites with $P_{cj} > 0$ (sites with $P_{cj} = 0$ are dropped). Further, the calculation uses only files from a requestor-specified group of iterations. The fission file used to connect iterations in an eigenfunction calculation described in Chapter 6 is identical to this file; in that case, only the file from the preceding iteration is used. There are counters associated with these files that give the total neutron production by composition, say SP_j , where

$$SP_j = \sum_{cj} P_{cj},$$

where the summation is over all collisions cj in composition j and over all iterations requested. The sampling from these files, and the means of obtaining additional parameters to form a start file are identical to that for the fission file described in Chapter 6.

The neutron-neutron link file is ordinarily used to permit an estimate of the neutron production eigenfunction shape from one calculation to be the source guess for a similar calculation. It is also used to connect a neutron eigenfunction problem to a fixed source problem in order to obtain better correlations in sensitivity calculations.

8.6.3 Linked Neutron-Photon Calculations

A photon heating calculation is spliced to a neutron eigenfunction (or fixed source) calculation by use of the neutron-photon link file. All photon heating rates, fluxes, etc. are normalized to one neutron born in fission in the neutron calculation. The neutron-photon link file is also a subset of the neutron collision file and consists of the same parameters as the neutron-neutron link file, i.e.,

$$x, y, z, (\Sigma_a \phi)_{cj}, P_{cj}, i_a, \delta_a, j, FA, FM, \delta_{IA}$$

but this file contains all sites for which $(\Sigma_a \phi)_{cj} > 0$. As in the case of the neutron-neutron link file, the calculation also uses only files from a requestor-specified group of iterations.

There is one counter per composition associated with these files that gives the total neutron absorption by composition, say SP_j , where

$$SP_j = \sum_{cj} (\Sigma_a \phi)_{cj}$$

where the summation is over all collisions cj in composition j . The sampling from this file to form a photon start file is identical to that for the fission file described in Chapter 6 with the exception that the parameter $(\Sigma_a \phi)_{cj}$ replaces P_{cj} . The means of obtaining additional parameters required for the start file are identical to those used with the fission file with the following exceptions:

- (a) to obtain photon heating edits normalized for one neutron born in fission we set the photon starting weight, w_i , as

$$w_i = \left(\sum_j \frac{SP_j}{N_H} \right) S^{i_w} G$$

where N_H is the total number of histories in the neutron calculation ($\sum_j \frac{SP_j}{N_H}$ is the total neutron absorption per neutron born in fission), and where $S^{i_w} G$ is the total number of photons emitted per absorption event (capture or fission) with nuclide i_a .

- (b) the parameter δ_a is added to all photon files, i.e., starts, slowing down, and collision in order to separate photon heating rates due to fission gammas from those due to capture gammas. Thus the photon start (or slowing down) file consists of the parameters,

$$j, FA, FM, \delta_{IA}, K, \mu, \gamma, \eta, W_p, n, m, l, \rho, x, y, z, E, \delta_a$$

where ρ is a random number used to provide statistical correlation as discussed in Appendix L.

8.6.4 Linked Photon-Neutron Calculations

A neutron calculation may be performed in RCP using as a source the photoneutrons produced in a photon calculation. This is accomplished by use of the photoneutron link file which is a subset of the photon collision file. The parameters on this link file are

$$x, y, z, E_0, P_{cj}, i_{pn}, \delta_a, j, FA, FM, \delta_{IA}$$

where E_0 is the incident photon energy, P_{cj} is the total photoneutron production of collision c_j in composition j , i.e.,

$$P_{cj} = \frac{W_{t_0}}{\sum_j T_j} \sum_i N_j^i \sigma_{pn}^i,$$

and i_{pn} is the photoneutron nuclide associated with P_{cj} .

There are counters associated with photon-neutron link files that give the total photoneutron production by composition, say SP_j , where

$$SP_j = \sum_{c_j} P_{cj},$$

and where the summation is over all collisions c_j in composition j . The sampling of these files to form a neutron start file is identical to that for the fission file described in Chapter 6 with the exception that the neutron starting energy is set using the equation described in Section 8.4.5 (Photoneutron Production). The neutron starting weights, w_i , are set to unity and overall normalization of the neutron to the photon calculation must be done externally.

8.7 Reactor Heating in RCP

This section gives the calculational details involved in overall reactor heating. This involves fission fragment and beta decay heating, gamma energy deposition, charged particle reactions, and neutron heating.

8.7.1 Total Quantity of Heat

To obtain overall reactor heating requires a neutron eigenfunction calculation followed by a photon calculation using the neutron-photon link file. The fission fragment and beta decay heating, and the neutron heating are a part of the edits of all RCP neutron calculations. Of course the photon calculation yields the gamma energy deposition. Heating due to charged particle reactions must be accounted for external to RCP using the neutron reaction product rates from the neutron calculation.

An estimate of energy per fission event in ^{235}U is obtained as follows (Reference 9)

	MeV
Kinetic energy of fission fragments	169.12
β emission due to fission product decay	6.50
Kinetic energy of fission neutrons	4.80
Prompt gammas	6.97

Fission product delayed gammas	6.33
Neutrinos	<u>8.75</u>
Total energy per fission	202.47

The fission energy available for heating per fission event is about 193.7 MeV, i.e., the total energy minus the neutrino energy. For a typical ^{235}U -H₂O reactor, about 7 MeV results from the neutron capture gammas per fission event (the overall heating from charged particle reactions will be small but in local regions may be important; the same is true for gammas from inelastic scattering). Thus the overall energy available for heating per fission event is about 200 MeV. In RCP the photon link calculation is internally normalized to the neutron problem and the neutron problem is normalized to one neutron born in fission. The total heating from the RCP edits will be about 200 MeV/v where v is an average value for the number of neutrons per fission event, that is the total heating will be about 80 MeV.

8.7.2 Fission Fragment and Beta Decay Heating

The fission fragment and beta decay heating per nuclide i in composition j is obtained during the neutron calculation as follows: A counter $H_{f\beta}$ for each nuclide i in composition j is accumulated per collision, i.e.,

$$H_{f\beta} = H_{f\beta} + \delta_a(\Sigma_a\phi)_{cj} \cdot 1.7562(10^8)\text{eV, for } i_a \text{ in } j,$$

where i_a , δ_a , and $(\Sigma_a\phi)_{cj}$ are defined in the description of the neutron collision file (Section 8.6.1). This counter is normalized by dividing by the total number of neutron histories to yield the fission fragment and beta decay heating in eV per neutron born in fission.

8.7.3 Neutron Heating

The neutron heating in RCP is obtained as a combination of elastic scattering heating and neutron absorption incident energy heating. Recall that all gamma spectra (fission and capture) on the job library are for thermal neutrons, hence the incident neutron energy for a high energy absorption is not accounted for. Of course part of this energy would appear in gammas, but in RCP local deposition is assumed. A counter, H_{ea} , for each nuclide i in composition j is accumulated per collision as follows

$$H_{ea} = H_{ea} + (\Sigma_a\phi)_{cj}E_0 \text{ for } i = i_a \text{ in } j$$

$$H_{ea} = H_{ea} + (1 - \delta_s)W_f(E_0 - E) \text{ for } i = i_s \text{ in } j$$

where all quantities have been defined in the description of the neutron collision file (Section 8.6.1). This counter is normalized by dividing by the total number of neutron histories to yield the combined elastic scattering, and neutron absorption incident energy, heating in eV

per neutron born in fission. These results are not accurate if binomial estimation is used since only the termination collision is included.

8.7.4 Inelastic Scattering Gamma Heating

As discussed in Section 8.3.4, the energy lost by the neutron in inelastic scattering appears in gamma rays which are not permitted to transport in RCP, i.e., a local energy deposition is assumed. This heating is labeled in RCP as the inelastic gamma heating without transport. The treatment of inelastic gamma heating is complicated by the superposition of an average $n \rightarrow 2n$ exit energy spectrum with that for inelastic scattering on the neutron job library. This combined inelastic matrix also accounts for the increase in the exit neutron weight due to $n \rightarrow 2n$ reactions.

A brief physical description of the $n \rightarrow 2n$ reaction is as follows (Reference 10). The reaction between the incident neutron and a target of mass A results in a compound nucleus $A + 1$ with excitation energy equal to that of the incident neutron. If the energy carried off by the first neutron is such as to leave nucleus A excited to an energy less than the neutron binding energy for nucleus $A - 1$ (usually in the neighborhood of 6-7 MeV), then the $n \rightarrow 2n$ reaction will not take place and de-excitation of nucleus A occurs through gamma emission (i.e., inelastic scattering gammas). If the energy carried off by the first neutron is such as to leave nucleus A excited to an energy greater than the neutron binding energy for nucleus $A - 1$, then a second neutron may be emitted in the decay of compound nucleus A to form residual nucleus $A - 1$.

Since the $n \rightarrow 2n$ reaction does not yield significant gammas, in RCP we may reasonably assume that all the neutron incident energy is accounted for in the energy of the two emitted neutrons and the difference in the ground state energies between nucleus A and nucleus $A - 1$. That is, there will be no local gamma energy deposition for the $n \rightarrow 2n$ reaction.

Assuming for the moment that RCP is using the $\frac{\Sigma_a}{\Sigma_T}$ non-terminating estimator, then the incident neutron weight that is scattered inelastically with the combined inelastic matrix for nuclide i_s (here $\delta_s = 1$) in composition j is $w_i \frac{\Sigma_s}{\Sigma_T}$ where Σ_s is the total scattering cross section (elastic and inelastic) and Σ_T is the total cross section. The exit neutron weight w_i includes the effect of the $n \rightarrow 2n$ reaction, so $w_i - w_i \frac{\Sigma_s}{\Sigma_T}$ is a weight that accounts for one of the neutrons in the $n \rightarrow 2n$ reaction. If there were no $n \rightarrow 2n$ reactions in the inelastic matrix, then the local energy deposition of the inelastic scattered gammas is $w_i \frac{\Sigma_s}{\Sigma_T} (E_0 - E)$. Assuming no spectral differences between the $n \rightarrow 2n$ and inelastic scattering reactions leads to a local energy deposition per inelastic scattering event for the combined matrix of

$$\left[w_i \frac{\Sigma_s}{\Sigma_T} - \left(w_i - w_i \frac{\Sigma_s}{\Sigma_T} \right) \right] (E_0 - E).$$

The quantity $\Sigma_a \Phi_{cj}$ defined for the neutron collision file is equal to $w_{t_0} \frac{\Sigma_a}{\Sigma_T}$ for the $\frac{\Sigma_a}{\Sigma_T}$ estimator. This substitution is made so that the energy deposition equation is estimator independent. A counter H_{ig} for nuclide i in composition j is accumulated per collision as follows

$$H_{ig} = H_{ig} + \delta_s [2(W_{t_0} - (\Sigma_a \Phi)_{cj}) - W_t](E_0 - E)$$

for $i = i_s$ in composition j . This counter is normalized by dividing by the total number of neutron histories to yield the inelastic scattering gamma heating in eV per neutron born in fission.

8.7.5 Charged Particle Reactions

As discussed in Section 8.3.2, the charged particle reactions deemed most likely to be important in reactor heating (excluding fission) are ${}^6\text{Li}(n, \alpha)$, ${}^{10}\text{B}(n, \alpha)$ and ${}^{14}\text{N}(n, p)$. The resulting gammas from charged particle reactions are accounted for in the linked neutron-photon transport calculation. However, charged particle reactions are exothermic and no provision exists in RCP to obtain the local energy deposition of the charged particle and the target recoils. Thus this heating must be performed outside of RCP as follows. The energy of the emitted particle plus target recoil, assuming thermal incident neutrons, for the three reactions mentioned are (Reference 11)

$$\begin{array}{ll} {}^6\text{Li}(n, \alpha) & 4.787(10^6) \text{ eV} \\ {}^{10}\text{B}(n, \alpha) & 2.315(10^6) \text{ eV} \\ {}^{14}\text{N}(n, p) & 0.628(10^6) \text{ eV} \end{array}$$

Suppose, for example, that ${}^{10}\text{B}$ exists in some composition j . Let A_j be the RCP ${}^{10}\text{B}$ capture in composition j per neutron born in fission. Then $A_j(2.315)10^6$ eV is the ${}^{10}\text{B}$ charged particle plus recoil energy deposition in composition j in eV per neutron born in fission.

8.7.6 Gamma Energy Deposition After Photon Transport

The RCP photon transport calculation using the neutron-photon link file provides gamma energy deposition per nuclide i , per composition j , per few group per neutron born in fission in the neutron calculation. The fixed-source photon calculations are edited similarly, except that the gamma energy deposition is per source photon. The edits of gamma energy deposition in a linked calculation are split into depositions resulting from gammas born in fission ($\delta_a = 1$ on photon collision file) and depositions resulting from gammas born in capture ($\delta_a = 0$ on photon collision file). The edits of gamma energy depositions from a fixed source calculation are all identified as being from gammas born in fission.

Three counters per nuclide i , per composition j , per few group are used to record results of a photon collision. The first counter, H_{fg} , is for fission gamma heating, the second, H_{cg} , is for capture gamma heating and the third, P_{pn} is for photoneutron production (the manner of recording photoneutron production per photon collision is discussed in Section 8.4.5).

Gamma energy depositions are added to the counters H_{fg} and H_{cg} for each of the three types of photon collisions as follows:

(a) Compton Scattering ($r = 1$)

$$H_{fg} = H_{fg} + \delta_a \left[W_{t_0} (E_0 - E) \frac{N_j^i \sigma_c^i}{\Sigma_{cj}} \right],$$

$$H_{cg} = H_{cg} + (1 - \delta_a) \left[W_{t_0} (E_0 - E) \frac{N_j^i \sigma_c^i}{\Sigma_{cj}} \right].$$

(b) Photoelectric Effect ($r = 2$)

$$H_{fg} = H_{fg} + \delta_a \left[W_{t_0} E_0 \frac{N_j^i \sigma_{pe}^i}{\Sigma_{pej}} \right],$$

$$H_{cg} = H_{cg} + (1 - \delta_a) \left[W_{t_0} E_0 \frac{N_j^i \sigma_{pe}^i}{\Sigma_{pej}} \right].$$

(c) Pair Production ($r = 3$)

$$H_{fg} = H_{fg} + \delta_a \left[W_{t_0} (E_0 - 1.022(10^6)) \frac{N_j^i \sigma_{pp}^i}{\Sigma_{ppj}} \right],$$

$$H_{cg} = H_{cg} + (1 - \delta_a) \left[W_{t_0} (E_0 - 1.022(10^6)) \frac{N_j^i \sigma_{pp}^i}{\Sigma_{ppj}} \right].$$

At the end of the photon transport calculation, the above counters are normalized by dividing by the total number of photon histories.

9 SUBCRITICAL CALCULATIONS IN RCP01

9.1 Introduction

The subcritical calculations in RCP01 are performed assuming a steady state external neutron source. This is done in actuality by permitting the external source to appear only in the zeroth iteration. The neutron source shape for the first and subsequent iterations is then proportional to the neutron induced fissions in the previous iteration as is the case for the standard eigenfunction calculation (see Chapter 6). Now however, the number of neutron histories per iteration is proportional to the subcritical multiplication factor in the previous iteration, that is, the number of neutron histories per iteration decreases (on the average) as the iteration number increases. Neutron reaction rates summed over all iterations are the desired steady state reaction rates. That is, if the external source is emitting one neutron per second, then the zeroth iteration gives the direct external source neutron reaction rate contribution in neutrons per second, and the sum of the neutron reaction rates in the first and all subsequent iterations gives the subcritical multiplied neutron reaction rate contribution in neutrons per second.

The many types of reactor subcritical calculations possible in RCP01 are spanned by three realistic calculations which differ as to the initial source of neutrons and thereby they differ as to the number of "linked" calculations (see Section 8.6) required. These three subcritical calculations may be summarized as follows:

9.1.1 Subcritical Calculations with Spontaneous Fissions of Fuel as Source

This is the simplest type of subcritical calculation, especially if the spontaneous fuel fission spectrum is taken to be that of the thermal neutron induced fission spectrum.

9.1.2 Subcritical Calculations with Oxygen (α, n) Reaction in Oxide Fuel as Source

The natural α decay of uranium in oxide fuel results (without any appreciable transport of the α 's) in a neutron source stemming from the $^{18}\text{O}(\alpha, n)^{21}\text{Ne}$ reaction. Since the spectrum of this neutron source differs from the neutron induced fission neutron spectrum, the RCP01 calculational procedure requires two separate calculations. In the first, only the zeroth iteration is performed with the (α, n) source spectrum and results in some spatial distribution of neutron induced fission sites. In the second calculation, the first and subsequent iterations are performed with the fission neutron spectrum. The proper coupling of these two calculations is provided by the neutron-neutron link described in Section 8.6, however normalization must be performed externally.

9.1.3 Subcritical Calculations with Deuterium (γ, n) Reaction as Source

The photo-neutron reaction in deuterium constitutes an important source of neutrons after shutdown of an operating water reactor. Because the transport of photons must be treated, the RCP calculational procedure requires three separate calculations which are described as follows:

- (a) An RCP eigenfunction calculation is performed with nuclide inventories being those at the time of shutdown. This calculation provides eigenfunction fission sites and the fission rates at each site per neutron born in fission just prior to shutdown.
- (b) An RCP photon transport calculation is performed using the dominant source of photons after long shutdown periods, i.e., the delayed photons from fission products. This calculation provides photon reaction sites and the (γ, n) reaction rate at each site per neutron born in fission in calculation (a). The proper coupling of calculations (a) and (b) is provided by the neutron-photon link described in Section 8.6.
- (c) An RCP subcritical calculation through N iterations is performed using as a source the photo-neutrons from calculation (b) above. This calculation provides steady state subcritical neutron reaction rates for N iterations. The desired subcritical reactivity values for an infinite number of iterations is then obtained by an analytic extrapolation. The proper coupling of calculations (b) and (c) is provided by the photon-neutron link described in Section 8.6.

Since the three-step subcritical calculation with the deuterium (γ, n) reaction as the source is more complex than the first two types of subcritical calculations described earlier, the last part of this chapter will describe the external normalization procedures required for this calculation; this will include the analytic extrapolation to an infinite number of iterations. First, however, the next section will describe the form of the subcritical calculation through K iterations which is common to all types of subcritical calculations.

9.2 The Form of the RCP01 Subcritical Calculation

The RCP01 subcritical calculation requires no user input beyond that for a conventional eigenfunction calculation. Unlike the conventional eigenfunction calculation where the number of histories for an iteration is given either by $N^k = M + kC$ for regularly increasing batch sizes or by the “warmup/rampup/fixed” procedure (described in Chapter 6), the number of histories for iteration $k(k \geq 1)$ in a subcritical calculation is a function of the multiplication factors for iterations zero through $k-1$. Also unlike a conventional eigenfunction calculation, the zeroth iteration is not ignored; recall from above that the zeroth iteration gives the direct source neutron reaction rates and that iterations one to infinity give the subcritical multiplied neutron reaction rates. In a subcritical calculation the number of histories in iteration zero, i.e., M , is normally set much larger than the 500 frequently used for eigenfunction calculations.

After the zeroth subcritical iteration is completed in RCP01 (using input source densities if treating spontaneous fissions or if treating oxygen (α, n) reactions as source, or using the photon-neutron link if treating photoneutrons as the source), we have available the zeroth iteration multiplication factor, mf^0 , as defined in Chapter 11. Since it is desirable to have neutron starting weights, w_{i_0} , unity for all iterations in a subcritical calculation, the number of histories to be performed in the k^{th} iteration, N^k , is given by the following process:

$$N^k = \text{integral part } \{mf^{k-1}N^{k-1}\}$$

but if $\rho < \text{fractional part } \{mf^{k-1}N^{k-1}\}$, set $N^k = N^k + 1$. Here $N^0 = M$. If spontaneous fissions or photoneutrons constitute the initial source; or for the case of the oxygen (γ, n) reaction, as an initial source, a neutron-neutron link must be performed to connect the zeroth to the subsequent iterations.

Eigenfunction edit quantities defined in Chapter 11 all have identical definitions for the subcritical calculations (this results because the eigenfunction calculation was formulated for a variable number of histories per iteration), thus these edit quantities are all edited in the same manner for the subcritical calculation; the only difference is that the zeroth iteration is not neglected.

The standard deviation calculations for an eigenfunction calculation were formulated for unit neutron starting weights and a variable number of histories per iteration, however they do not apply to subcritical calculations since the asymptotic iterations alone do not yield the desired reaction rates. Uncertainties must be obtained by independent reruns of the entire subcritical calculation; e.g., through all three component calculations in the case of the deuterium (γ, n) source.

9.3 Normalization Procedure for Subcritical Calculations

As stated earlier, the normalization procedure for the third type of subcritical calculation described in the introduction is more complex than that for the first two. This results because three calculations are involved using two link procedures. Since this more complex normalization contains that which would be involved for the first two types of subcritical calculations, we will here consider only the third type, that is, a subcritical reaction calculation with deuterium (γ, n) reaction as source at a specified number of hours after shutdown and with a known power history before shutdown. We will further consider here only the normalization for subcritical detector counts for fission neutrons, that is detector counts due to direct neutrons born in the (γ, n) reaction will be considered a background term. Starting at the end of the three calculations and working backwards, we may describe the normalization procedure by the following four steps.

9.3.1 Detector Efficiency

At the end of the Monte Carlo run of the three linked calculations, the basic quantity obtained is $\bar{D}_a^K(E)$, that is, the energy dependent neutron absorptions in the detector per subcritical fission neutron through K iterations. Let $K(E)$ be the detector efficiency, i.e., $K(E)\bar{D}_a^K(E)\Delta E$ are the detector counts in energy interval ΔE at energy E . Then the total detector count per subcritical fission neutron through K iterations, $\bar{D}^K$ is given by

$$\bar{D}^K = \int_0^\infty K(E)\bar{D}_a^K(E)(dE).$$

9.3.2 Subcritical Normalization

Let D^k be the detector counts per fission neutron born in iteration k alone (D^0 is the detector counts per neutron born in (γ, n) reactions and constitutes the background term discussed above). Let the number of iterations performed in the subcritical calculation, K , be sufficiently large that D^k for $k > K$ is statistically the asymptotic eigenfunction detector count, say D^a . It then follows that the multiplication factor for the k^{th} iteration alone, say mf^k , for $k > K$ is statistically the eigenvalue mf^a .

We may write the detector count, D_s , excluding background, per neutron born in (γ, n) reactions as

$$D_s = mf^0 D^1 + mf^0 mf^1 D^2 + mf^0 mf^1 mf^2 D^3 + \dots,$$

or

$$D_s = \sum_{k=1}^K \left(\prod_{m=0}^{k-1} mf^m \right) D^k + D^a \left(\prod_{m=0}^{K-1} mf^m \right) \sum_{k=1}^{\infty} (mf^a)^k,$$

where

$$\sum_{k=1}^{\infty} (mf^a)^k = \frac{mf^a}{1 - mf^a}.$$

If we have knowledge that the true eigenvalue of the core, λ , is different from that inferred from the Monte Carlo calculation, mf^a , then we may approximately correct the above expression for D_s by assuming that the source shape of any iteration k is the eigenfunction source; this yields

$$D_s = \left(\frac{\lambda}{1 - \lambda} \right) \left(\frac{1 - mf^a}{mf^a} \right) \left[\sum_{k=1}^K \left(\prod_{m=0}^{k-1} mf^m \right) D^k + D^a \left(\prod_{m=0}^{K-1} mf^m \right) \frac{mf^a}{1 - mf^a} \right].$$

We may write the total detector count per subcritical fission neutron through K iterations, $\bar{D}^K$, as

$$\bar{D}^K = \frac{\sum_{k=1}^K \left(\prod_{m=0}^{k-1} mf^m \right) D^k}{\sum_{k=1}^K \left(\prod_{m=0}^{k-1} mf^m \right)}.$$

Let N^0 be the number of histories in the zeroth iteration of the subcritical calculation. Then the total number of histories through K iterations excluding the zeroth iteration, say N_T^K , is very nearly given by

$$N_T^K = N^0 \sum_{k=1}^K \left(\prod_{m=0}^{k-1} mf^m \right)$$

and the number of histories in the K^{th} iteration alone, say N^K , is very nearly given by

$$N^K = N^0 \left(\prod_{m=0}^{K-1} mf^m \right).$$

We may now write

$$D_s = \left(\frac{\lambda}{1-\lambda} \right) \left(\frac{1-mf^a}{mf^a} \right) \left[\bar{D}^K \frac{N_T^K}{N^0} + D^a \frac{N^K}{N^0} \left(\frac{mf^a}{1-mf^a} \right) \right].$$

This expression is directly usable if we have estimates of D^a and mf^a . If these estimates are not available, then we may approximately take $D^a = \bar{D}^K$ and $mf^a = \overline{mf}^K$ where $\overline{mf}^K$ is the accumulated multiplication factor through K iterations. With these approximations we have:

$$D_s = \left(\frac{\lambda}{1-\lambda} \right) \left(\frac{1-\overline{mf}^K}{\overline{mf}^K} \right) \left[\bar{D}^K \frac{N_T^K}{N^0} + \frac{N^K}{N^0} \left(\frac{\overline{mf}^K}{1-\overline{mf}^K} \right) \right].$$

The quantities N^0 , N_T^K , N^K , and $\overline{mf}^K$ are all available from the RCP subcritical calculation.

9.3.3 Photon Reaction Rate Normalization

The quantity D_s obtained in the preceding section is the detector counts per neutron born in (γ, n) reactions, i.e., the detector count per (γ, n) reaction. Thus, we must multiply D_s by the total number of (γ, n) reactions over the entire core per fission neutron born in calculation (a).

One should recall here that RCP properly normalizes a photon transport calculation to a neutron transport calculation provided that the library photon spectra are properly set per neutron reaction. For long shutdown periods, a proper spectrum for delayed photons from fission products is one that integrates over energy to the number of photons per second born from fission products a certain number of hours after shutdown per fission event per second that occurs during the last power period. Thus, this spectrum may be interpreted as number of photons per fission event.

Let $R_{\gamma, n}$ be the total number of (γ, n) reactions. We may now write the detector counts per fission neutron born in calculation (a), D_p , as

$$D_p = R_{\gamma, n} D_s$$

9.3.4 Power Level Normalization

The quantity D_p is the detector counts per fission neutron born in calculation (a) of Section 9.1.3. If we multiply D_p by the average number of neutrons born per fission, $\bar{\nu}$, then we will have the detector counts per fission event. If we further multiply by the number of fission events per second to obtain one watt of power (approximately $3.1(10^{10})$) and by the power level in watts, say P (watts), just prior to shutdown, then the detector counts per second, say D , is given by

$$D = \bar{v}P(\text{watts})3.1(10^{10}).$$

In summary, the approximation made to normalize the subcritical calculation and all other normalizations discussed above may be combined in a single expression to give detector counts per second excluding background as follows:

$$D = \bar{v}P(\text{watts})3.1(10^{10})R_{\gamma, n}$$

$$\left(\frac{\lambda}{1-\lambda}\right)\left(\frac{1-\overline{mf}^K}{\overline{mf}^K}\right)\left(\int_0^\infty K(E)\overline{D}_a^K(E)dE\left[\frac{N_T^K}{N^0} + \frac{N^K}{N^0}\left(\frac{\overline{mf}^K}{1-\overline{mf}^K}\right)\right]\right).$$

10 INPUT DESCRIPTION

This chapter describes the RCP01 computer program input format. In order to keep this chapter reasonably self-contained, a summary of the geometry description presented in Chapter 4 is provided here. Here however, the emphasis is on the input geometry parameters. In addition, pictorial examples are provided to illustrate the input required for subcells, initial assemblies, final assemblies (i.e., initial modules) including composite final assemblies, final modules, and module zero.

10.1 Summary of RCP01 Geometry

10.1.1 Initial Assembly Description

An initial assembly exterior boundary is either a 60° parallelogram or a rectangle. It is divided by mesh lines into basic regions where the basic regions are enclosed by the mesh lines - boundaries running parallel to the x and y axes respectively (Figure 10-1). All distances x_n, y_m in the x - y plane are measured relative to the initial assembly coordinate system origin $x_0 = 0, y_0 = 0$. These basic regions may be in turn further subdivided into repeating arrays of smaller regions by means of subcell descriptions called P-lists. Each initial assembly can have P-lists for describing such features as slab arrays or rod arrays in the basic regions.

As shown in Figure 10-1, all basic regions are defined in the x - y plane. The axial dimension is subdivided into z -zones, $Z_l, l = 0, 1, \dots, L$, which run uniformly across all basic regions. Changes in compositions radially and axially are permitted by defining composition stacks, called C-lists. A C-list is a list of composition numbers which are adjacent axially starting from the first (lowest) z -zone and going up to the last (highest) z -zone. For a basic region not subdivided by subcells, all that is required is the assignment of a C-list composition stack (CS) to that basic region. For a basic region which is subdivided by subcells, a P-list subcell description (PSS) is assigned to that basic region. The P-list itself will include several C-lists, one for each subcell region, as parameters.

The placement of composition stacks (CS) and subcell descriptions (PSS) is accomplished through an INITIAL ASSEMBLY OVERLAY (one-corner or two-corner on option).

A one-corner overlay is described by a sequence of sets of three numbers: ($n, m, \text{CS or PSS}$), see Figure 10-1, where n, m are the x, y indices of the lower left corner of the assignment region and CS or PSS is the composition stack or subcell description assigned. The over-

RECTANGULAR MODE

PARALLELOGRAM MODE

ALL DISTANCES x_n, y_m ARE MEASURED RELATIVE TO
INITIAL ASSEMBLY COORDINATE SYSTEM ORIGIN (x_0, y_0)

Figure 10-1 Initial Assembly Descriptions

lay is accomplished by moving from left to right on the x -axis and from bottom to top on the y -axis. The composition stack number CS or subcell description number PSS is assigned to every mesh parallelogram to the right of n and above m in the initial assembly.

The two corner overlay is described by a sequence of sets of five numbers ($n_l, m_l, n_u, m_u, \text{CS or PSS}$), where n_l, m_l are the x, y indices of the lower left corner and n_u, m_u are the x, y indices of the upper right corner of the assignment region. The overlay remains fixed throughout the problem. However, a change in compositions is permitted in final assembly descriptions through a composition variation.

All initial assemblies are set up in the standard orientation indicated in Figure 10-1, where side 1 is at the bottom and the other sides are numbered clockwise in sequence. The number of z -zones can vary from one initial assembly to the next. However, all initial assemblies used in a single initial module must have the same height and the same geometry index P/R (index that specifies parallelogram (hex) or rectangular mode; see Chapter 4), except in the case of a secondary initial assembly in a composite final assembly.

10.1.2 Subcell Description (P-List)

A subcell is a geometrical unit enclosed by boundaries D_x (subcell length along the x -axis) and D_y (subcell length along the y -axis) as illustrated in Figure 10-2. Some possible arrangements using 2 and 3 ellipses are illustrated in Figure 10-2. RCP01 allows an arbitrary number of ellipses in a P-list.

The ellipses assigned to a subcell are not permitted to intersect within the subcell boundaries but may intersect outside. The major axis of each ellipse can be tilted with respect to the x -axis by the angle θ .

The ellipses assigned to a subcell are truncated by the subcell boundaries to produce one or more regions within the subcell. The materials assigned to each region of the subcell are designated by composition stack numbers CS. Five parameters describe each ellipse, i . They are $(x_{e_i}, y_{e_i}, \mu_{e_i}, a_i, b_i)$, where x_{e_i} is the abscissa of the center of the ellipse, y_{e_i} is the ordinate of the center of the ellipse, μ_{e_i} is the cosine of the angle of tilt, a_i is the length of the semi-major axis, and b_i is the length of the semi-minor axis (semi-major is parallel to the x -axis, not necessarily larger than b_i). The center of each ellipse and the subcell lengths are measured relative to the anchor point (x_a, y_a) as indicated in Figure 10-2. The anchor point in turn is measured relative to the initial assembly coordinate system origin (x_0, y_0) . (Note: On option, the point (x_a, y_a) may be taken as the lower left corner of the basic region in which the P-list is assigned. This is called the "portable" subcell option. However, use of such portable subcells is discouraged.)

The subcell is repeated every distance D_x along the x -axis and every distance D_y along the y -axis, beginning at its anchor point, to produce an infinite array. This is called "double repeatability." When a subcell description is assigned to any basic region in an initial assembly, only that portion of the infinite array cut out by the basic region boundaries is included in the problem.

Figure 10-2 Subcell Descriptions

It is sometime convenient to approximate one or two straight lines with an ellipse. In such cases, a_i or b_i is assigned a large value, such as 10^{20} . A circle can be exactly represented by defining an ellipse with a_i and b_i both set equal to the radius of the circle.

10.1.3 Final Assembly Laydown: Initial Module Description

An initial module consists of a series of final assemblies arranged in a complete laydown. Each final assembly is essentially an initial assembly which is repositioned in any of the following ways (illustrated by examples in Figures 10-3 and 10-4):

1. (standard orientation) - The final assembly is an initial assembly in its standard orientation translated relative to the initial module coordinate system origin.
2. (mirror image) - The final assembly is an initial assembly translated relative to the initial module coordinate system origin and then reflected about side 1.
3. (rotation) - The final assembly is an initial assembly translated relative to the initial module coordinate system origin and then rotated counterclockwise in multiples of 60° for parallelogram geometry or 90° for rectangular geometry.
4. (mirror image after rotation) - The final assembly is an initial assembly translated relative to the initial module coordinate system, rotated counterclockwise in multiples of 60° for parallelogram geometry or 90° for rectangular geometry, and then reflected about side 1.
5. (geometry variation) - A variation is permitted for each of the above descriptions in parallelogram geometry only. This variation causes a 60° clockwise rotation of side 3 towards side 2 so that it touches side 1 or side 4 to produce a triangular or trapezoidal shape.

RCP01 permits up to 999 final assemblies in each initial module. Each final assembly is described by the following 7 parameters:

1. initial assembly referred to (negative for mirror image described above),
2. geometry variation (yes or no),
3. composition variation number,
4. number of 60° or 90° rotations, as described above,
5. x translation of the initial assembly relative to initial module coordinate system origin,
6. y translation of the initial assembly relative to initial module coordinate system origin,
7. relative source strength.

The use of final modules, described next, is not required in RCP01. If the geometry is not very complex, then final assemblies alone may suffice. An example of an RCP01 geometry using only final assemblies in a single initial module is shown in Figure 10-5. In addition, two simple examples of RCP01 initial modules are shown in Figures 10-6 and 10-7.

Figure 10-3 Final Assembly Descriptions - Parallelogram Geometry

10.1.4 Composite Final Assembly Description

A composite final assembly consists of a set of initial assemblies, all but the first of which, called "secondary" assemblies, are entirely contained within the first, called the "primary."

a. STANDARD ORIENTATION

IA - INITIAL ASSEMBLY

FA - FINAL ASSEMBLY

● - LOCATION OF IA ORIGIN
RELATIVE TO INITIAL MODULE
COORDINATE SYSTEM ORIGIN

(i) - SIDE NUMBERS $i = 1, 2, 3, 4$

b. MIRROR IMAGE

d. MIRROR IMAGE AFTER ROTATION

c. ROTATION

Figure 10-4 Final Assembly Descriptions - Rectangular Geometry

Secondary assemblies override the primary over the domains of the secondaries. They may be arbitrarily oriented relative to the primary initial assembly as long as they are completely contained within it. Composite final assemblies are especially useful in a final assembly laydown

Figure 10-5 Final Assembly Laydown - Initial Module
76 Final Assemblies

when there are subregions where it is desirable to have the axes of elliptical cylinders in P-lists pointed in a direction which is different from the z -axis of the primary initial assembly. All secondary assemblies must be disjoint.

The input parameters required to laydown the primary initial assembly in a composite final assembly laydown consist of the same parameters as for a regular final assembly. To these are added the parameters required to laydown the secondary initial assemblies relative to the coordinate system of the primary initial assembly. Thus the list of composite final assembly parameters is:

$$FA, \pm IA^p, V_g^p, V_c^p, x_a^p, y_a^p, A^p, S_F, \pm IA^{s_1}, V_g^{s_1}, V_c^{s_1}, x_a^{s_1}, y_a^{s_1}, z^{s_1}, \theta_d^{s_1}, \theta_s^{s_1}, \theta_r^{s_1}, f^{s_1}, \pm IA^{s_2}, \dots$$

INITIAL ASSEMBLY DESCRIPTION

(i) SIDE NUMBERS

X,Y MEASURED RELATIVE TO
INITIAL ASSEMBLY COORDINATE
SYSTEM ORIGIN

$X_0 = Y_0 = 0.0$

INITIAL MODULE RESULTING FROM FINAL ASSEMBLY DESCRIPTIONS

FA(1) IS IA (1) LOCATED AT $X_1, 0$ STD ORIENTATION

FA(2) IS IA (1) LOCATED AT $0, Y_1$ ROTATION 240°

FA(3) IS IA (1) LOCATED AT $X_1, 0$ MIRROR IMAGE

ALL LOCATIONS X, Y MEASURED RELATIVE TO INITIAL MODULE
COORDINATE SYSTEM ORIGIN.

Figure 10-6 Initial Module Example - 1

Here the superscript p denotes quantities used to laydown the primary initial assembly and the superscript s denotes quantities used to laydown the secondary initial assemblies. The source strength per composite final assembly, S_{Fa} , gives the relative total composite final assembly source strength within the initial module. The secondary source fractions, f^s , give

INITIAL ASSEMBLY DESCRIPTIONS

INITIAL MODULE RESULTING FROM FINAL ASSEMBLY DESCRIPTIONS

ALL LOCATION POINTS (X ,Y) ARE MEASURED RELATIVE TO
INITIAL MODULE COORDINATE SYSTEM ORIGIN.

Figure 10-7 Initial Module Example - 2

the fraction of the composite assembly source in each secondary assembly, in which case $1 - \sum_i f_i^{s_i}$ is the fraction of the source in the primary initial assembly. The parameters $x_a^{s_i}, y_a^{s_i}, z^{s_i}$ are the coordinates of the origin of the secondary initial assembly coordinate system in the coordinate system of the primary initial assembly. The angles $\theta_d^{s_i}, \theta_s^{s_i}, \theta_r^{s_i}$ are measured in a

right angled, right handed x, y, z coordinate system, whose origin is the origin of the secondary initial assembly coordinate system. The angles θ_d^s , θ_x^s , θ_r^s have exactly the same interpretation as for a final module laydown. See Figure 10-8 for illustrations of the use of θ_d , θ_x , and θ_r as applied in a final module laydown. An example of a composite final assembly is given in Figure 10-9.

10.1.5 Final Module Description

Each final module FM refers to an initial module denoted by an integer IM. The initial module may be translated and rotated, and compositions may be adjusted, as described below.

Compositions may be changed through use of a composition variation, v_c^m , as is similarly done for final assemblies. In cases where both final assembly and final module composition variations are used, the sequence of composition changes occurs by performing the final assembly composition changes first, followed by the final module changes.

The origin of the initial module coordinate system is translated in the absolute coordinate system to $(x_m, y_m, 0)$. An additional translation of the initial module along its own z -axis by the distance z_i is made after the angular orientation of the initial module coordinate system is set. This guarantees that the z -axis of the initial module coordinate system always passes through the point $(x_m, y_m, 0)$ in the absolute coordinate system.

The angular orientation of the final module is specified by a hierarchy of angular rotations. Initially the x - and z -axes of the initial module are parallel to the x - and z -axes of the absolute coordinate system. The first angle in the hierarchy, θ_m , is an optional rotation about the z -axis which results in the initial module positive x -axis pointing directly away from the absolute origin. This rotation is obtained automatically by the presence of a control card in the final module laydown, and is illustrated in Figure 10-10. It is useful when setting up certain types of annular arrays of final modules. If the control card is not present, then $\theta_m = 0^\circ$.

The second angle in the hierarchy is θ_d . This rotation is about the initial module y -axis if the initial module geometry is 90° ($P/R = 1$) or about an altered y -axis which is perpendicular to the x - z plane for a 60° geometry. This angle is measured counterclockwise when looking toward the initial module origin.

The third angle in the hierarchy is θ_x . This rotation is about the x -axis of the initial module, which may have already been moved by the θ_m and θ_d rotations. This angle is also measured counterclockwise when looking toward the initial module origin.

The fourth angle in the hierarchy is θ_r . This rotation is about the z -axis of the initial module, which may have already been moved by the previous rotations. This angle is also measured counterclockwise when looking toward the initial module origin.

The final module description is completed by specifying a relative source strength, s_{f_m} , which provides the final module source strength relative to the total over all final modules in the complete final module laydown.

Figure 10-8 Final Module Description

INITIAL ASSEMBLY (90° GEOMETRY)

INITIAL ASSEMBLY (60° GEOMETRY)

COMPOSITE FINAL ASSEMBLY

Figure 10-9 Composite Final Assembly Description

RCP01 permits a total of 999 final modules. Figure 10-10 illustrates the use and non-use of the automatic rotation θ_m for a final module which utilizes an initial module similar to that of Figure 10-6. Figure 10-8 illustrates the sequential use of $x_m, y_m, \theta_m, \theta_d, \theta_s, \theta_r, z_i$. Note that for the final module in Figure 10-8 with $\theta_d = 90^\circ$, $\theta_s = 90^\circ$, and $\theta_r = 90^\circ$, the same final module would result with $\theta_d = 0^\circ$, $\theta_s = 0^\circ$ and $\theta_r = 0^\circ$.

NON-USE OF AUTOMATIC ROTATION: $\theta_m = 0$

USE OF AUTOMATIC ROTATION

Figure 10-10 Final Module Automatic Rotation for Light Water Breeder Reactor (LWBR)

10.1.6 Module 0 Description

Module 0 is defined by a set of concentric circular cylinders whose axis is the absolute z-axis and by a set of z-planes which define axial zones. On option, the concentric cylinders may be replaced by concentric spheres whose centers lie at the origin of the absolute coordinate

system. The input parameters consist of M radii, $R_1, \dots, R_M$, and L z -zones specified by $z_0'', z_1'', \dots, z_L''$, some of which may be negative. Both the M radii and the $L+1$ z 's must be monotonically increasing. The outermost cylinder (or sphere) is required to have a vacuum boundary condition. The top and bottom z planes can have either vacuum or reflecting boundary conditions. Final modules override and replace module 0 within their domains, while module 0 acts as a base or background over which final modules are placed. An example of the use of module 0 regions to represent a pressure vessel and additionally the use of a final module to represent a pressure vessel nozzle is given in Figure 10-11.

10.2 RCP01 Geometry Creation Strategy

The first step in creating an RCP01 model for a reactor should be to examine the real geometry of the reactor. See which features are rectangles, 60° parallelograms (or hexagons or triangles) or ellipses (or circles), or portions thereof. See what features are repetitive, or nearly so, and whether there is symmetry. Note how features are oriented. Judicious use of appropriate RCP01 geometry constructs can save a lot of effort in model creation by allowing reuse of the same RCP01 item to describe identical or similar reactor features. The second step is to determine what information will be wanted from the output of the RCP01 problem, particularly for what regions will reaction rates be desired.

Although the actual geometry will often make the appropriate modeling obvious, there are some special cases for which additional guidance may be helpful. These are addressed in the following subsections.

10.2.1 Movable Components

Users often need to run a sequence of RCP01 jobs which differ from each other only in that they represent different positions of a movable component. If a reactor component moves only back and forth along a straight line, and if it is appropriate for that line to be the z axis of the movable component, and if it is reasonable to approximate that motion as a series of steps along the z mesh, then one may be able to model the motion by describing it through a series of composition variations. This approach models the motion not as a change in the geometry itself but merely as a change in which materials are occupying specific locations within the geometry.

For movable components that do not satisfy all the requirements of the preceding paragraph, the flexibility with which initial assemblies or initial modules are laid down as final assemblies or final modules allows RCP01 to model movable components by changing the parameters in the final laydown. Whether the moving component is best modeled as an assembly or a module depends primarily on two features - the complexity of the component's geometry and materials, and its neighborhood. Because modules are built from assemblies, possibly including composite assemblies, they more readily model more complex features. The final

Figure 10-11 Module Zero and Final Module Description

assemblies comprising an initial module must touch whereas final modules must not touch, so the neighborhood of the moving component may dictate one or the other choice.

10.2.2 Incomplete Elliptical (or Circular) Regions

If a reactor feature is a finite ellipse (or circle) that is truncated in some fashion, then its boundary is an elliptical arc that has end points. Modeling such a feature in RCP01 requires making any such end point lie on a side of a basic region; that is, an x mesh line or a y mesh line should pass through that end point. Depending on circumstances, it may be necessary to have that end point be a corner of a mesh region; that is, both an x mesh line and a y mesh line should pass through that end point. Once that requirement is met for every such end point, determining the subcell and P-list descriptions will usually be fairly straightforward.

10.2.3 Large Circular Regions Not Centered on the Problem Center

RCP01 geometry has two constructs which can be circular - a P-list component and a module 0 cylinder. However, a module 0 cylinder must be centered about the module 0 z axis, whereas a P-list component can be anywhere. Thus if one needs to model a large circular component whose center does not lend itself to being the module 0 z axis, or if one needs to model more than one nonconcentric circular component, the only option is to model it (them) with P-lists. If the circular component has little internal geometry one might model it as a single P-list, but it would then need to be within an initial assembly that would extend beyond the circle. When such an extensive initial assembly is not appropriate, the solution is to create a set of smaller initial assemblies each containing a portion of the circular component and assemble the component as an RCP01 initial module. By choosing a sufficient number of initial assemblies, the resulting module can be made to stay within a tight tolerance of the circular component. Such a module can also model extensive internal detail of the component. Figure 10-12, an RCP01 model of a control drum from the Advanced Test Reactor (Reference 16), illustrates the principles of both this and the preceding paragraph.

10.3 RCP01 Input Deck Structure

The remaining sections of this chapter describe all input card images used in RCP01. All card images are used in the standard RINP form described in Reference 14.

The most general form of input to RCP01 is that of "modular geometry." In that mode, a problem consists of one case of control card images, *NIA* initial assembly cases, one module 0 case, *NIM* initial module cases, and finally a single case of card images for the final modules. That form is described in the following sections of this chapter.

A simpler form of input is the "single initial module" mode. In that mode, a problem consists of one case of control card images, *NIA* initial assembly cases, and a single initial module case. In this mode there is no module 0 and no final modules. The boundary condition for this

Figure 10-12 RCP01 Model of ATR Control Drum

mode is reflection on all external surfaces. Also, in this mode, the region-edit and collision file card images described here as part of the final module input are instead included with the single initial module input.

A complete RCP01 job submission contains the following card images in sequence:

1. JOB CONTROL:

- (a) job card image (memory limits, time limits, ...)
- (b) file manager directives (identify library, restart files, collision files, ...)
- (c) RCP01 executable

2. INPUT CONTROL (see Section 10.4):
/ (case separation card image)
3. INITIAL ASSEMBLY 1 DATA (see Section 10.5)
/ (case separation card image)
4. INITIAL ASSEMBLY 2 DATA (see Section 10.5)
/ (case separation card image)
- .
- .
- .
5. MODULE ZERO DATA (see Section 10.6)
/ (case separation card image)
6. INITIAL MODULE 1 DATA (see Section 10.7)
/ (case separation card image)
7. INITIAL MODULE 2 DATA (see Section 10.7)
/ (case separation card image)
- .
- .
- .
8. FINAL MODULE DATA (see Section 10.8)
. (end of input card images)

10.3.1 Cardfiles

RCP01 includes a facility for the insertion of specified groups of card images into its input stream. Each collection of card images to be inserted must have been previously created and stored as a case either in an FMG (interface format) file or in a system format file.

AFM files are normally stored as Data Type 21.

Card images in the standard input stream which trigger this insertion begin with the keyword "CARDFILE" (upper or lower case), and indicate (by their content) what is to be inserted and (by their location) where it is to be inserted. Any number of these card images may be used.

Each such card image is of the form

CARDFILE, case, version, synonym

where “case” is a positive integer indicating the ordinal of the case to select from the file specified by the remainder of the card image. (A zero of a blank is also accepted, and is treated as a one.)

If “version” is a positive integer or zero, then “version” is used as an AFM version number and “synonym” is used as an AFM synonym. Otherwise (when “version” is negative or non-numeric), the value of “version” is ignored and “synonym” is used as a Unix file name (which can include full or partial path specification).

10.4 Control Input

Listing of control input can be disabled by executing the unix command: `setenv NOLISTRCP yes` prior to executing RCP01. Control input includes the following input card images, which may appear in any order:

* Control input (Optional comment card images preceded by *.)

- **Title**

(a) Syntax (exactly 1 item):

= TITLE

(b) Variables:

Variable	# Words	Type	Description
TITLE	80 characters	character	Arbitrary alphanumeric string used in the headings for output pages.

- **Card 1**

(a) Syntax (exactly 18 items):

000001, MR, LSC, LOPT, LRNDM, LSQHX, 1, L HIST, NIA, 0, NGST, NLAST,
LED1, LED2, LED3, LPED, NITER, IESTF, PROBTYP E

(b) Variables:

Variable	# Words	Type	Description
MR	1	integer	Number of compositions (>0).
LSC	1	integer	Gaussian ordinate scattering approximation: = 0 4 ordinates (only value permitted).
LOPT	1	integer	0, normally 1, 2, ..., 15 - special source options in fixed source (see Section 10.9).

Variable	# Words	Type	Description
LRNDM	1	integer	Random number skip option. For each neutron (or photon in a gamma problem), LRNDM random numbers are skipped prior to source parameter selection and before starting tracking in each RCP group in which the particle interacts. Random number skipping permits independent sampling for the same problem input. If LRNDM = 0, it is treated as if it were 1. (LRNDM ≥ 0)
LSQHX	1	integer	Initial assembly coordinate system = 0 or 4 60 degree parallelogram. = 1 or 5 Rectangle.
LHIST	1	integer	Number of histories per iteration. (>0)
+/- NIA	1	integer	Number of initial assemblies (non-zero). Set NIA negative for perturbation option (both base and perturbed cases - see Appendix J).
NGST	1	integer	Starting RCP group number. (>0)
NLAST	1	integer	Last RCP group number. ($\geq$ NGST)
LED1, LED2, LED3	3	integer	Few group breakpoints. the first few-group includes RCP groups NGST through LED1, the second LED1+1 through LED2, etc. If fewer than three few-groups are desired, the final LED value may be set to zero. In neutron problems, these few-groups may not include the thermal group, the last library group. (These breakpoints can be overridden using card series 20000s.)
LPED	1	integer	Library edit and input check only option: = -1 Check input, do not edit library, run problem. = 0 Check input, edit library, run problem. = +1 Check input, generate plot files unless card 17000, 0 is present, edit library, and do not run problem. The recommended method of checking input without running the problem is to eliminate the library FETCH card image. See note below.
NITER	1	integer	Final iteration to be performed. If a restart file is FETCHed, the first iteration performed will be that following the iteration of the FETCHED file. If there is insufficient time to complete iteration NITER, RCP01 will terminate with full edits after the last iteration for which adequate time exists.
IESTF	1	integer	Statistical estimator control for non-thermal neutron groups. = -1 Binomial (0,1) = 0 Non-terminating Σ_t/Σ_t N>0 Non-terminating Σ_t/Σ_t in RCP groups 1 through N, binomial in other groups. In perturbation jobs and photon jobs, the input value of IESTF is ignored. In such jobs, IESTF always has value 0.

Variable	# Words	Type	Description
+/-PROBTYPE	1	integer	<p>Type of RCP01 calculation.</p> <p>= 1 Fixed source neutron transport.</p> <p>= 2 Iterative eigenvalue neutron transport.</p> <p>= 3 Fixed source photon transport.</p> <p>The negative sign in front of PROBTYPE causes a reedit at the iteration of FETCHed restart file. A standard re-edit is performed if no Collision Files are involved in the job. There are three kinds of Collision File re-edit jobs: perturbation re-edits, region-edit re-edits, and composition Collision File re-edits. In all of these jobs, the iteration range is from 0 or the iteration of a FETCHed re-edit restart file to that of the final base problem restart file. Region-edit re-edit jobs seek a file with synonym REGEDIT. The others seek a file with synonym PERTURB. All of these jobs read a file with synonym RESTART. They first seek such a file with V=NITER as specified on card 000001; if no such file is found, they use the first available RESTART file.</p>

- **Card 4 (Optional)**

(a) Syntax:

000004, CCC(1), ±CCC(2), ..., ±CCC(N)

(b) Variables:

Variable	# Words	Type	Description
+CCC(i)	N	integer	A composition number in which collisions are not to be recorded in Collision Files.
-CCC(i)	N	integer	Negative entry directs inclusion of all compositions from CCC(i-1) through CCC(i) in the set where collisions are to be excluded from Collision Files.

(c) Notes:

This card image has no effect if Collision Files are not being written. It is ignored in perturbation jobs.

- **Card 5 (Optional in neutron jobs)**

(a) Syntax:

```
000005, CCC(1), Killoff(1), CCC(2), Killoff(2), ..., CCC(N),
      Killoff(N)
```

(b) Variables:

Variable	# Words	Type	Description
CCC(i)	N	integer	A composition for which thermal "Russian Roulette" is desired.
Killoff(i)	N	real	The corresponding "kill off" probability to be used in that composition. ($0.0 \leq \text{Killoff}(i) < 1.0$)

(c) Notes:

This series may be continued on card images 000006, 000007, ..., 000015.

- **Card 171ss (Optional)**

(a) Syntax:

```
171ss, synonym1, version1, synonym2, version2, ...
```

(b) Variables:

Variable	# Words	Type	Description
synonym _i	N	character	The afm synonym of the ith composition file. (≤ 8 characters).
version _i	N	integer	The afm version number of the ith composition file.

(c) Notes:

The MR compositions for a job can be provided:

- on card images, or
- The first $n \geq 0$ can be on card images with the remaining compositions defined in one or more type 262 AFM interface files.

If files are used, card image series 171ss lists them. The sequence number takes on values 01, 02, ..., 99.

- **Card 9CCCs or 8CCCCCS or 9CCCCCS**

(a) Syntax:

```
09CCCs, ISO(CCC,1), DEN(CCC,1), ISO(CCC,2), DEN(CCC,2), ...,
      ISO(CCC,N), DEN(CCC,N)
```

or

```
8CCCCCS, IXX1, ISO(CCCCC,1), DEN(CCCCC,1), IXX2, ISO(CCCCC,2),
      DEN(CCCCC,2), ...,
```

or

```
9CCCCCS, ISO(CCCCC,1), DEN(CCCCC,1), ISO(CCCCC,2), DEN(CCCCC,2),
      ...,
```

(b) Variables:

Variable	# Words	Type	Description
ISO(CCC,i)	N	integer	The numeric ID of a nuclide in the job library to be included in composition CCC.
Den(CCC,i)	N	real	The corresponding number density (atoms/barn-cm).
IXX _i	N	integer	Arbitrary integer (ignored).

(c) Notes:

Composition data are specified on these card images. The subseries number CCC or CCCCC is the composition number (001,..., MR). The sequence number s takes on values 1, 2,..., 9. No nuclide may appear more than once within a single composition definition. All compositions defined on card images must use the same one of these three series.

- **Card 70sss**

(a) Syntax:

```
070sss, SRCDEN(1), SRCDEN(2), ..., SRCDEN(MR)
```

(b) Variables:

Variable	# Words	Type	Description
SRCDEN(i)	MR	real	Floating point value of the starting source density per cc for composition i. (SRCDEN(i) ≥ 0.0) (Default values = 1.0 for all compositions.)

(c) Notes:

These card images are ignored in flat source and link calculations. If they are omitted in a fixed source neutron job, starts will be selected proportional to the calculated slowing down power by composition. Note - a slowing down source is forbidden when NGST is an inelastic scattering group. The sequence number sss takes on values 001, 002, ..., 999.

- **Card 90s (Optional)**

(a) Syntax:

```
00090s, nuc1, src1, ..., nucNSRC, srcNSRC
```

(b) Variables:

Variable	# Words	Type	Description
nuc _i	NSRC	integer	Nuclides whose concentrations are used to determine starting source densities.
src _i	NSRC	real	Relative source strengths per atom of the corresponding nuclides.

(c) Notes:

These data cause non-zero input source densities per composition to be overridden by values computed by multiplying the nuclide concentrations by their corresponding source strengths. Source fractions per final assembly and per final module are then calculated using the generated values.

This feature is useful for generating a source shape for depleted fuel and for producing results due to spontaneous neutron emission due to transuranic nuclides.

The sequence number s takes on values 1, 2, ..., 9.

- **Card 71001 (Optional)**

(a) Syntax:

```
071001, JREGFL
```

(b) Variables:

Variable	# Words	Type	Description
JREGFL	1	integer	Number of the composition for which the optional edit of fluxes for each MUFT group and thermal subgroup is to be generated. If Ipchflux = 1 on card image 240001, these fluxes will also be written to the output card image file. ($0 \leq \text{JREGFL} \leq \text{MR}$) (default = 0 - no flux edit.)

- **Card 71mms**

(c) Notes:

Special Source Input (see Section 10.9)

- **Card 72mm1**

(c) Notes:

Special Source Input - Thermal Groups (see Section 10.9)

- **Card 2sss (Optional)**

(a) Syntax:

002sss, $\pm\Sigma_{\text{delt}}(1)$, $\pm\Sigma_{\text{delt}}(2)$, ..., $\pm\Sigma_{\text{delt}}(\text{MR})$

(b) Variables:

Variable	# Words	Type	Description
$\pm\Sigma_{\text{delt}}(i)$	MR	real	Macroscopic cross section for non-library delta-scattering in composition i. In perturbation problems, $\Sigma_{\text{delt}}(1) = 0.0$. The sequence number sss takes on values 001, 002, ..., 999. (default $\Sigma_{\text{delt}}(i) = 0.0$)

(c) Notes:

In neutron jobs, negative values cause the use of the Σ_a/Σ_t estimator instead of the binomial estimator for the thermal group in composition i. If any values are provided, all MR must be provided.

- **Card 62CVRs (Optional)**

(a) Syntax:

62CVRs, JJ(1), JJ'(1), JJ(2), JJ'(2), ..., JJ(N), JJ'(N)

(b) Variables:

Variable	# Words	Type	Description
JJ(i)	N	integer	The number of the ith composition to be replaced in composition variation CVR. ($1 \leq \text{JJ}(i) \leq \text{MR}$) Within a composition variation, no two values of JJ(i) can be the same.
JJ'(i)	N	integer	The number of the composition replacing JJ(i) in composition variation CVR. ($1 \leq \text{JJ}'(i) \leq \text{MR}$)

(c) Notes:

Composition variation CVR is defined by these card images.

Each pair of composition numbers specifies that the second item $JJ'(i)$, replaces the first, $JJ(i)$, wherever $JJ(i)$ is used in the unvaried geometry laydown. Any composition number not appearing in the set of $JJ(i)$'s is invariant under composition variation CVR.

Several Final Assemblies can refer to the same Initial Assembly. Composition variations permit changes in compositions of the Initial Assembly. Similarly, several Final Modules can refer to the same Initial Module. Composition variations can also be used in this case. The Final Assembly variation is applied before the Final Module variation. Composition variations must be consecutively numbered from 1 to NCVR without any omission. The sequence number s takes on values 1, 2, ..., 9. These card images are omitted if there are no composition variations.

- **Card 299 (Optional)**

(a) Syntax:

000299, IEditAll

(b) Variables:

Variable	# Words	Type	Description
IEditAll	1	integer	= 0 Use LED(1), LED(2), LED(3) on card image 000001 as few-group cutpoints for standard few-group edits. (default) Card images 20000s override this default. = 1 Treat each RCP group as a few-group cutpoint for few-group edits.

- **Card 20000s (Optional)**

(a) Syntax:

20000s, NG(1), NG(2), ..., NG(N)

(b) Variables:

Variable	# Words	Type	Description
NG(i)	N	integer	The last RCP group to be included in the i th few group. $NGST \leq NG(1) < NG(2) < \dots < NG(N) \leq NLAST$.

(c) Notes:

If this card image series is present, the few groups defined here override those defined on card 1. The last group, and if a neutron problem, the last fast group, is added to the set of few group cut-points if not included on this card image. The sequence number s takes on values 1, 2, ..., 9.

- **Card 17000 (Optional)**

(a) Syntax:

017000, IDOPLT

(b) Variables:

Variable	# Words	Type	Description
IDOPLT	1	integer	= 0 Do not generate plot files. (default)
			= 1 Generate plot files. (default if LPED=1 on card image 00001 or card image 14000 is present)

- **Card 13998 (Optional)**

(a) Syntax:

013998, MaxSeg, MinSeg

(b) Variables:

Variable	# Words	Type	Description
MaxSeg	1	integer	Maximum number of line segments to be used in plotting circles and ellipses. (default = 200)
MinSeg	1	integer	Minimum number of line segments to be used in plotting circles and ellipses. (default = 20) ($3 \leq \text{MinSeg} \leq \text{MaxSeg}$)

(c) Notes:

This optional card image may contain one or two items. The number of line segments used to plot circles and ellipses is linearly reduced from MaxSeg based on the plot size relative to 29.5 inches and the radius relative to the plot scale. At least MinSeg segments are used. Computer and plotter times are reduced by using fewer segments.

- **Card 13999 (Optional)**

(a) Syntax:

013999, LCXY

(b) Variables:

Variable	# Words	Type	Description
LCXY	1	integer	= 0 Standard Initial Assembly plots. (default)
			= 1 Constant mesh is used in Initial Assembly plots.

- **Card 14000 (Optional)**

(a) Syntax:

014000, PlotUnit, IMDetail, IMPlotSize, IADetail, IAPlotSize,
SliceDetail, SlicePlotSize

(b) Variables:

Variable	# Words	Type	Description
PlotUnit	1	character	= CALCOMP Plot sizes are determined by IMPlotSize, IAPlotSize, and SlicePlotSize. Plots should be realized onto a wide span plotter. ≠ CALCOMP Plots are 8 inches square.
IMDetail	1	integer	= 0 Final Assembly numbers are not to be included on Initial Module plots. (default) = 1 Final Assembly numbers are to be included on Initial Module plots. = 2 Include geometric detail in Initial Module plots. = 3 Produce color Initial Module plots. = 4 Produce Initial Module plots containing labels for depletion compositions.
IMPlotSize	1	real	Fractional reduction of CALCOMP plots from standard size of 29.5 inches. ($0.0 < \text{IMPlotSize} \leq 1.0$) This parameter has no effect if PlotUnit is not CALCOMP. (default = 1.0)
IADetail	1	integer	= 0 Mesh line numbers and composition stack numbers are not to be included on Initial Assembly plots. (default) = 1 Mesh line numbers and composition stack numbers are to be included on Initial Assembly plots. = 3 Produce color Initial Assembly plots.
IAPlotSize	1	real	Fractional reduction of Initial Assembly CALCOMP plots from standard size of 29.5 inches. ($0.0 < \text{IAPlotSize} \leq 1.0$) This parameter has no effect if PlotUnit is not CALCOMP. (default = 1.0)
SliceDetail	1	integer	= 0 Final Module numbers, Final Assembly numbers, and Final Assembly edges interior to Final Modules are not to be included on slice plots. (default) = 1 Final Module numbers, Final Assembly numbers, and Final Assembly edges interior to Final Modules are to be included on slice plots. = 2 Include geometric detail in slice plots. = 3 Produce color slice plots. = 4 Produce slice plots containing labels for depletable compositions.

Variable	# Words	Type	Description
SlicePlotSize	1	real	Fractional reduction of slice CALCOMP plots from standard size of 29.5 inches. ($0.0 < \text{SlicePlotSize} \leq 1.0$) This parameter has no effect if PlotUnit is not CALCOMP. (default = 1.0)

(c) Notes:

This optional card image may contain from 1 to 7 items. Its presence turns on plotting unless card image 017000, 0 is present.

- **Card 1400s (Optional)**

(a) Syntax:

```
01400s, IMPlot(1), IMPlot(2), ..., IMPlot(N)
```

(b) Variables:

Variable	# Words	Type	Description
IMPlot(i)	N	integer	The number of the ith Initial Module to be plotted. The sequence number s takes on values 1, 2, ..., 9.

- **Card 1401s (Optional)**

(a) Syntax:

```
01401s, IAPlot(1), IAPlot(2), ..., IAPlot(N)
```

(b) Variables:

Variable	# Words	Type	Description
IAPlot(i)	N	integer	The number of the ith Initial Assembly to be plotted. The sequence number s takes on values 1, 2, ..., 9.

(c) Notes:

If card image 017000 is present and either card image 014000 is absent or PlotUnit is not CALCOMP, then if neither card image 01400s nor 01401s is present, plots will be generated for all Initial Modules and all Initial Assemblies. Otherwise, only those plots selected by these card images will be generated.

- **Card 40000 (Color plotting only)**

(a) Syntax:

040000, ColorModel

(b) Variables:

Variable	# Words	Type	Description
ColorModel	1	integer	= 1 Use RGB (Red, Green, Blue) color model. = 2 Use HSV (Hue, Saturation, Value) model. (default) = 3 Use HSV model.

(c) Notes:

See Section 14.6.

- **Card 40NNN (Color plotting only)**

(a) Syntax:

040nnn, X, Y, Z, C₁, C₂, ..., C_N

(b) Variables:

Variable	# Words	Type	Description
X, Y, Z	3	real	If ColorModel = 1 (RGB) then X, Y, Z are Red, Green, Blue. If ColorModel = 2 (HSV) then X, Y, Z are Hue, Saturation, Value. $0.0 \leq X, Y, Z \leq 1.0$
C _i	N	integer	Compositions which have color nnn. ($1 \leq nnn \leq 248$)

(c) Notes:

Sequences of consecutive composition numbers C_I, C_{I+1}, ..., C_J can be assigned color nnn by including in the list of Cs, the substring C_I, 0, C_J.

Only one color number may be associated with a composition C_i.

Compositions m without color assignments will be assigned arbitrary colors = m (mod 256).

See Section 14.6.

- **Card 41000 (Color plotting only)**

(a) Syntax:

041000, IAZONE

(b) Variables:

Variable	# Words	Type	Description
IAZONE	1	integer	The z-zone to be used for selecting materials, and hence colors for initial assembly plots. (default = 1)

(c) Notes:

Although RCP01 may reduce the number of zones by eliminating redundant z-boundaries, IAZONE refers to the input zones.

- **Card 42000 (Color or depletion initial module plots only)**

(a) Syntax:

042000, ZIM

(b) Variables:

Variable	# Words	Type	Description
ZIM	1	real	The value of Z at which color (IMdetail = 3) or depletion (IMdetail = 4) initial module plots are to be generated. Units are centimeters or inches as determined by card image 13000. (default = 0)

- **Card 190 (Optional)**

(a) Syntax:

000190, Ifp, Yfp, λfp, Power

(b) Variables:

Variable	# Words	Type	Description
Ifp	1	integer	Numeric ID of Xenon in the job library.
Yfp	1	real	Total yield from fission (direct and through precursors).
λfp	1	real	The Xenon decay constant (units are inverse seconds).
Power	1	real	Power level for normalization (units are watts).

(c) Notes:

This card image is used only in neutron jobs. Its presence triggers the equilibrium Xenon feedback option.

- **Card 200 (Optional)**

(a) Syntax:

000200, IERFAC

(b) Variables:

Variable	# Words	Type	Description
IERFAC	1	integer	= 0 Error edits print probable errors. (default) = 1 Error edits print standard deviation (σ). = 2 Error edits print 95% confidence intervals.

- **Card 300 (Optional)**

(a) Syntax:

000300, IEDFRQ, IEDGEOM, IEDFIN, IEDBOL, IEDCHL

(b) Variables:

Variable	# Words	Type	Description
IEDFRQ	1	integer	Frequency of iteration edits. (default = 1)
IEDGEOM	1	integer	= 0 Eliminate geometry input edit except card image listing, composition volumes, and nuclide loadings. = 1 Print complete geometry input edit. (default)
IEDFIN	1	integer	Frequency of edits in depletion timesteps. (default = 1 (every depletion timestep))
IEDBOL	1	integer	= 0 Eliminate edit of nuclide concentrations for depletable compositions at beginning of life. = 1 Print them. (default)
IEDCHL	1	integer	= 0 Eliminate edit of chain list assignments to depletable compositions. = 1 Print them. (default)

(c) Notes:

If fewer than five items appear on this card image, the default values of the absent variables are used.

- **Card 990 (Optional)**

(a) Syntax:

000990, IFSTRK

(b) Variables:

Variable	# Words	Type	Description
IFSTRK	1	integer	= 0 Standard subcell tracking. (default)
			= 1 "Fast" tracking in subcell regions. Fast tracking is delta tracking based on the maximum cross section in the subcell.

- **Card 991 (Optional)**

(a) Syntax:

000991, Newbnd, Ebindo

(b) Variables:

Variable	# Words	Type	Description
Newbnd	1	integer	= 1 Use new epithermal binding formulation to remove flux discontinuity at upper epithermal binding cut-point. (mandatory)
Ebindo	1	real	Upper epithermal binding cut-point. An input value of Ebindo = 0.0 is the default and sets the cut-point used by RCP01 to the top of the RCP group above thermal. A non-zero Ebindo must be supplied on this card image whenever more than one RCP group is to be included in the binding range. A negative value of EBINDO turns off the binding treatment. If only one item appears on this card image, the default value of Ebindo is used.

- **Card 1000 (Optional)**

(a) Syntax:

001000, SynLibrary

(b) Variables:

Variable	# Words	Type	Description
SynLibrary	1	character	The AFM synonym of the job library file (type 105). (default = LIBRARY).

- **Card 1010 (Optional)**

(a) Syntax:

001010, SynRestart

(b) Variables:

Variable	# Words	Type	Description
SynRestart	1	character	The AFM synonym of the restart files (type 250) to be read and/or written in this Job. (default = RESTART).

- **Card 1020 (Optional)**

(a) Syntax:

001020, SynSource

(b) Variables:

Variable	# Words	Type	Description
SynSource	1	character	The AFM synonym of the source files (type 250) to be read if the job is linked to a previous job. (default = SOURCE).

- **Card 1030 (Optional)**

(a) Syntax:

001030, SynCollision

(b) Variables:

Variable	# Words	Type	Description
SynCollision	1	character	The AFM synonym of the Collision Files (type 285) to be read and/or written in the job. (default = COLLIDE).

- **Card 1040 (Optional)**

(a) Syntax:

001040, SynRegedit

(b) Variables:

Variable	# Words	Type	Description
SynRegedit	1	character	The AFM synonym of the region-edit restart files (type 281). (default = REGEDIT).

- **Card 1050 (Optional)**

(a) Syntax:

001050, SynPerturb

(b) Variables:

Variable	# Words	Type	Description
SynPerturb	1	character	The AFM synonym of the perturbation restart files (type 281) to be read and/or written. (default = PERTURB).

- **Card 1060 (Optional)**

(a) Syntax:

001060, SynGeomIn₁, SynGeomIn₂, ..., SynGeomIn_N

(b) Variables:

Variable	# Words	Type	Description
SynGeomIn	N	character	The AFM synonyms of the input Geometry Files (type 261) to be read in the job (default = RCPGEOM). (N ≤ 50)

- **Card 1070 (Optional)**

(a) Syntax:

001070, SynGeomOut

(b) Variables:

Variable	# Words	Type	Description
SynGeomOut	1	character	The AFM synonym of the output Geometry File (type 261) to be written in the job. (default = GEOMOUT)

- **Card 1100 (Optional)**

(a) Syntax:

001100, SynDeplConc

(b) Variables:

Variable	# Words	Type	Description
SynDeplConc	1	character	The AFM synonym of the concentration file (type 284) to be read and/or written in the job. (default = DEPLCONC)

- **Card 1110 (Optional)**

(a) Syntax:

001110, SynChanTrack

(b) Variables:

Variable	# Words	Type	Description
SynChanTrack	1	character	The AFM synonym of the channel-track file (type 300) to be written in the job. (default = CHANTRCK)

- **Card 11000 (Optional)**

(a) Syntax:

011000, NOFILES

(b) Variables:

Variable	# Words	Type	Description
NOFILES	1	integer	= 0 No restart files are to be written. = 1 Normal operation. (default) = 2 Write short files for continuation at the next depletion time step. = 3 Write short files for statistical post-processing. (not usable for RCP01 continuation).

(c) Notes:

Card image 011000, 0 should be used only in problems which are not to be continued later. Collision Files are written if requested. When this card image is present, recovery from machine error is limited to starting over at the beginning of the job.

NOFILES = 2 prevents continuation within a time step.

NOFILES = 3 prevents any continuation.

- **Card 12000 (Optional)**

(a) Syntax:

012000, Iterfreq

(b) Variables:

Variable	# Words	Type	Description
Iterfreq	1	integer	The iteration frequency with which restart files are to be written. (Iterfreq > 0)

(c) Notes:

Such files will be written at the completion of every iteration whose number is divisible by Iterfreq. (default = 1000)

- **Card 12001 (Optional)**

(a) Syntax:

012001, Itimefreq

(b) Variables:

Variable	# Words	Type	Description
Itimefreq	1	integer	The time frequency in integer minutes with which restart files are to be written. Itimefreq must be non-negative. A value of zero will cause a file to be written after each iteration. (default = 2880 (48 hours))

(c) Notes:

Such files will be written at the completion of any iteration if at least Itimefreq minutes of chargeable computer time has elapsed since the last such file was written. It is intended that no more than Itimefreq minutes will be lost due to machine error. A restart file will also be written on the completion of the final requested iteration, NITER, or when there does not appear to be adequate time remaining to complete another iteration.

- **Card 13000 (Optional)**

(a) Syntax:

013000, ICNVRT

(b) Variables:

Variable	# Words	Type	Description
ICNVRT	1	integer	= 0 All geometric input is in centimeters. (default) = 1 All geometric input is in inches. RCP01 converts to centimeters.

- **Card 15000 (Optional - neutron eigenvalue only)**

(a) Syntax:

015000, LHistIncrement

(b) Variables:

Variable	# Words	Type	Description
LHistIncrement	1	integer	Increase in history count per iteration in eigenvalue calculation. (default = 10). A negative value indicates alternate iteration strategy specified on card image 2.

- **Card 2 (Optional - eigenvalue only)**

(a) Syntax:

000002, Kwarmup, HistTarget, Rampfactor

(b) Variables:

Variable	# Words	Type	Description
Kwarmup	1	integer	Number of iterations to be run at LHIST (card image 1) histories per iteration (default = 50). ($0 \leq \text{Kwarmup} \leq 100000$)
HistTarget	1	integer	Final fixed batch size (default = 5000). ($0 \leq \text{HistTarget} \leq 1000000$)
Rampfactor	1	real	Increase factor in batch size rampup (default = 1.25). ($1.01 \leq \text{Rampfactor} \leq 2.00$)

(c) Notes:

Missing terminal entries on card image 2 will be provided from defaults. A negative entry on card image 15000 causes the following iteration strategy: Kwarmup iterations of LHIST histories are run to provide a reasonable source shape. Additional iterations growing gradually by Rampfactor are run until the final batch size of HistTarget is attained. At this point, accumulated results are discarded but the source shape is used for the first of the NITERS iterations of size HistTarget.

- **Card 16000 (Optional - neutron only)**

(a) Syntax:

016000, NSITSV

(b) Variables:

Variable	# Words	Type	Description
NSITSV	1	integer	= 1 A section (section 280) containing all fission sites is to be written after each iteration of a neutron (fixed source or eigenvalue) job as part of the file RESTART, even when not writing a full RESTART file. 1 is the only acceptable value on this card image. Such files can then be used as SOURCE files for a subsequent calculation.

(c) Notes:

The default value is zero. In the default case, section 280 contains fission sites and is included whenever a RESTART file is being written during eigenvalue jobs only. These fission sites provide the source locations for the subsequent iteration.

- **Card 16 (Optional)**

(a) Syntax:

000016, IESF

(b) Variables:

Variable	# Words	Type	Description
IESF	1	integer	<p>= 0 No effect. (default)</p> <p>= 1 (Neutron jobs) - A section (section 280) containing all fission sites is to be written after each iteration of a neutron (fixed source or eigenvalue) job as part of the file RESTART, even when not writing a full RESTART file. Such files can then be used as SOURCE files for a subsequent calculation.</p> <p>= 2 (Neutron Jobs) - A section (section 280) containing both capture and fission sites is to be written after each iteration of a neutron (fixed source or eigenvalue) job as part of the file RESTART, even when not writing a full RESTART file. These files are used to satisfy the normal need for fission source sites in eigenvalue jobs, but serve the additional purpose of supplying source sites for both fission and capture generated photons in a subsequent photon calculation.</p> <p>= 1 (Photon Jobs) - A section (section 280) containing all (γ,n) collision sites is to be written after each iteration of a photon job as part of the file RESTART, even when not writing a full RESTART file. These files should normally be generated only in the second job of a neutron-photon-neutron subcritical sequence and provide the source to the third job of the sequence.</p>

- **Card 17 (Optional)**

(a) Syntax:

000017, Iter1, Iter2, NSUBCR

(b) Variables:

Variable	# Words	Type	Description
Iter1	1	integer	Iteration number of first FETCHed SOURCE file to use as a link to a previous job.
Iter2	1	integer	Iteration number of last FETCHed SOURCE file to use as a link to a previous job. ($0 \leq \text{Iter1} \leq \text{Iter2}$)

Variable	# Words	Type	Description
NSUBCR	1	integer	<p>Subcritical option (optional)</p> <p>= 0 Standard link calculation. (default)</p> <p>For fixed source neutron or photon jobs, the source to each iteration will be selected from the specified SOURCE files.</p> <p>For neutron eigenvalue jobs, the source guess to iteration zero will be selected from the specified SOURCE files. The source to each subsequent iteration will be selected from its predecessor.</p> <p>= 1 For neutron eigenvalue jobs, perform the subcritical multiplication factor calculation using the photo-neutron collision sites from the specified photon SOURCE files as the source to iteration zero. The source to each subsequent iteration will be selected from its predecessor and represents neutron multiplication. Card images 076iis are required to determine the energy relationships between photon and neutron energies. In this mode, the number of histories in each subsequent iteration decays proportionally to the iteration eigenvalues.</p> <p>For fixed source photon jobs the source to each iteration will be selected from the specified neutron fission SOURCE files.</p> <p>= 2 (Neutron eigenvalue only) Neutron-neutron subcritical option.</p> <p>Perform the subcritical multiplication factor calculation using the neutron fission sites from the specified SOURCE files as the source to iteration zero. The source to each subsequent iteration will be selected from its predecessor and represents neutron multiplication. The number of histories in each subsequent iteration decays in this mode proportionally to the iteration eigenvalues.</p> <p>= -1 or -2 (Neutron eigenvalue only)</p> <p>Perform repeated initial iterations of the same type as those of options +1 or +2 respectively. In this mode, the number of histories per iteration remains constant.</p>

(c) Notes:

Optional card image 000017 may contain either 2 or 3 items. If this card image is present, the current job is linked to a previous job through files FETCHed as SOURCE files. If this card image is absent, there is no such link and the default value of NSUBCR will be used. Any files in the range Iter1 through Iter2 which have not been FETCHed will be ignored as long as at least one file is FETCHed.

The neutron-photon-neutron subcritical sequence consists of three jobs. The first is a neutron eigenvalue calculation with PROBTYP = 2, NSUBCR = 0, and with

card image 000016, 1 to save fission files. The second is a photon calculation with PROBTYP = 3, NSUBCR = 1 and card image 000016, 1 to save photo-neutron collision files. The third is a neutron subcritical calculation with PROBTYP = 2 and NSUBCR = 1.

The neutron-neutron subcritical sequence consists of two jobs. The first is a fixed source neutron calculation with PROBTYP = 1, NSUBCR = 0, and with card image 000016, 1 to save fission files. The second is a neutron subcritical calculation with PROBTYP = 2 and NSUBCR = 2.

- **Card 76iis (Optional)**

(a) Syntax:

```
076iis, Evcut(ii), Constant(ii)
```

(b) Variables:

Variable	# Words	Type	Description
Evcut(ii)	1	real	Threshold energy of photon captures producing neutrons on photon collision with nuclide ii.
Constant(ii)	1	real	Multiplicative factor for energies of photo-neutrons generated by photon collisions with nuclide ii, i.e., $M2/(M2+1.0)$.

(c) Notes:

These card images are used only in the third job of a neutron-photon-neutron subcritical sequence. In such a job, neutrons generated by the previous job's photon absorption are tracked. ii denotes the nuclide's identification number in the job library. For each nuclide generating such neutrons, the neutrons are generated only by photons with energies above Evcut(ii). Each such neutron generated has energy $E_{vneut} = Constant(ii) * (E_{vphoton} - E_{vcut}(ii))$. Nuclides for which these data are not provided do not generate neutrons. The sequence number s takes on values 1, 2, ..., 9.

- **Card 18 (Optional)**

(a) Syntax:

000018, JRADTP

(b) Variables:

Variable	# Words	Type	Description
JRADTP	1	integer	Module Zero cylinder or sphere number at which a trapping surface section (section 282) is to be written after each iteration as part of the file RESTART, even when not writing a full RESTART file. If JRADTP is positive, such sections contain records of all outward-travelling particles crossing surface JRADTP. If JRADTP is negative, they contain records of all inward-travelling particles crossing surface JRADTP. These files may be used as SOURCE files to a subsequent job by including card images 000017 and 000019 in that job's input. (default = 0 - No trapping surface file to be written).

- **Card 19 (Optional)**

(a) Syntax:

000019, JTRAPP,,,

Possible forms:

000019, 1

000019, 2, TpAng, Dpang

000019, 3, TpZ1, TpZ2

000019, 4, TpAng, DpAng, TpZ1, TpZ2

(b) Variables:

Variable	# Words	Type	Description
JTRAPP	1	integer	= 0 The source to this job is not a trapping surface file. (default) = 1 Select sites from SOURCE without restriction. = 2 Select only those sites from SOURCE with polar angular coordinate between TpAng-DpAng and TpAng+DpAng. = 3 Select only those sites from SOURCE with z-coordinate between TpZ1 and TpZ2. = 4 Select only those sites from SOURCE with z-coordinate between TpZ1 and TpZ2 and with polar angular coordinate between TpAng-DpAng and TpAng+DpAng.
TpAng	1	real	Center of polar angle range (degrees) (default = 0.0) ($0.0 \leq \text{TpAng} < 360.0^\circ$).
DpAng	1	real	Half-span of polar angle range (degrees) (default = 180.0°) ($0.0 \leq \text{DpAng} < 180.0^\circ$).
TpZ1	1	real	Minimum z-coordinate (centimeters or inches as determined by card image 013000). The default value is -10^{20} cm.
TpZ2	1	real	Maximum z-coordinate (centimeters or inches as determined by card image 013000). The default value is $+10^{20}$ cm. ($\text{TpZ2} > \text{TpZ1}$).

(c) Notes:

Card image 000019 is effective only in linked jobs (i.e., card image 000017 present) and indicates that the SOURCE files provide a trapping surface source to the current job.

- **Card 199 (Optional)**

(a) Syntax:

000199, KGCUT1, KGCUT2

(b) Variables:

Variable	# Words	Type	Description
KGCUT1	1	integer	Lowest numbered group in which to select sites from a trapping surface source file. (default = 1)
KGCUT2	1	integer	Highest numbered group in which to select sites from a trapping surface source file. (default = 200)

(c) Notes:

KGCUT1 and KGCUT2 refer to the originating program's group structure. If this card image is absent, all groups are used. ($1 \leq \text{KGCUT1} \leq \text{KGCUT2} \leq 200$)

- **Card 180 (Optional)**

(a) Syntax:

000180, TOFMAX

(b) Variables:

Variable	# Words	Type	Description
TOFMAX	1	real	Time (in seconds) after neutron birth at which neutrons are to be terminated. (TOFMAX > 0.0)

(c) Notes:

This card image is used only in fixed-source neutron jobs. Its presence triggers the time-of-flight option.

- **Card 400 (Optional)**

(a) Syntax:

000400, Ephoton, Iphoton

(b) Variables:

Variable	# Words	Type	Description
Ephoton	1	real	Energy loss (electron volts) at which photons are to be counted and terminated. (Ephoton $\geq$ 0.0)
Iphoton	1	integer	Composition where energy loss is measured.

(c) Notes:

This card image is used only in photon jobs. Its presence triggers the photon threshold energy decay detection (scintillator) option.

- **Card 19000 (mandatory for adjoint problems)**

(a) Syntax:

019000, K2ADJ

(b) Variables:

Variable	# Words	Type	Description
K2ADJ	1	integer	Starting nuclide for simplified adjoint mode.

(c) Notes:

The presence of this card image triggers the adjoint mode. It is only read in neutron jobs.

- **Card 19ii1 (adjoint only)**

(a) Syntax:

019ii1, ADJTHA(ii), ADJTHS(ii)

(b) Variables:

Variable	# Words	Type	Description
ADJTHA(ii)	1	real	Average Σ_a (thermal) for nuclide ii.
ADJTHS(ii)	1	real	Average Σ_s (thermal) for nuclide ii.

(c) Notes:

ii takes as values the numbers of all nuclides occurring in all compositions in the job. For any nuclide for which this card image is absent, ADJTHA and ADJTHS will be set to 0.0. These data are used to meet the one thermal group adjoint mode assumption. These card images are used only when card image 019000 is present.

- **Card 19501 (mandatory for adjoint problems)**

(a) Syntax:

019501, ADJHFS

(b) Variables:

Variable	# Words	Type	Description
ADJHFS	1	real	Average fast hydrogen scattering cross section. This datum is used to meet the constant hydrogen scattering assumption in the simplified adjoint mode.

- **Card 20000 (Optional)**

(a) Syntax:

020000, Z2Dopt

(b) Variables:

Variable	# Words	Type	Description
Z2Dopt	1	real	Z-coordinate selected for the two-dimensional option. The problem to be solved is an x-y slice perpendicular to the global z-axis. The presence of this card image triggers the two-dimensional option. The units of Z2Dopt are centimeters or inches as determined by card image 013000.

- **Card 2500s (Optional)**

(a) Syntax:

02500s, Kspltt, Ecutoff, Rmin, Rmax, ΔR , X1, Y1, Z1, X2, Y2, Z2

(b) Variables:

Variable	# Words	Type	Description
Kspltt	1	integer	Number of particles resulting after a splitting event. Set negative for reverse splitting. ($ Kspltt \geq 2$).
Ecutoff	1	real	Energy below which there is no splitting.
Rmin	1	real	Radius of ellipsoid within which there is no splitting.
Rmax	1	real	Radius of ellipsoid outside of which there is no splitting.
ΔR	1	real	Thickness of ellipsoidal shells within which scattering events cause splitting.
X1, Y1, Z1 and X2, Y2, Z2	6	real	Coordinates of foci of ellipsoids.

(c) Notes:

This card image turns on the particle splitting option. Particle splitting is forbidden in perturbation jobs. The units of R_{min} , R_{max} , ΔR , $X1$, $Y1$, $Z1$, $X2$, $Y2$, $Z2$ are centimeters or inches as determined by card image 013000. The sequence number s takes on values 1, 2, ..., 9.

- **Card 25101 (Optional for splitting jobs)**

(a) Syntax:

025101, Irlete, Kspexp

(b) Variables:

Variable	# Words	Type	Description
Irlete	1	integer	= 0 Turn off Russian roulette when travelling opposite to the splitting direction.
			= 1 Turn on Russian roulette when travelling opposite to the splitting direction. (default, recommended).
Kspexp	1	integer	Maximum exponent on Kspl when crossing multiple ellipsoids between scattering events (default = 1). If only one item appears on this card image, the default value of Kspexp is used. ($Kspexp \geq 1$)

- **Card 2520s (Optional for splitting jobs)**

(a) Syntax:

02520s, KVSPLT₁, KVSPLT₂, ..., KVSPLT_{KSLARJ}

(b) Variables:

Variable	# Words	Type	Description
KVSPLT _i	# of splitting ellipsoids	integer	Variable split factors for ellipsoidal splitting shells.

(c) Notes:

$KSLARJ = \left\lceil \frac{R_{max} - R_{min}}{\Delta r} \right\rceil + 1$ is the number of splitting shells. If fewer than KSLARJ values are provided, the last value provided is used for missing entries. The sequence number s takes on values 1, 2, ..., 9.

- **Card 200000 (Optional)**

(a) Syntax:

200000, Ieditbulk, Ieditres

(b) Variables:

Variable	# Words	Type	Description
Ieditbulk	1	integer	= 1 Produce the absorption edit of every few group for each composition for each nuclide.
			= 2 Produce the absorption edit of every few group for each region-edit region for each nuclide.
			= 3 Produce the absorption edit of every few group for each composition and for each region-edit region for each nuclide.
			= 0 Neither. (default)
Ieditres	1	integer	= 1 Produce the edit of resonance integrals.
			= 0 Do not produce the edit of resonance integrals. (default)

(c) Notes:

If only one item appears on card image 200000, the default value of Ieditres is used.

- **Card 210001 (Optional)**

(a) Syntax:

210001, ENRICH

(b) Variables:

Variable	# Words	Type	Description
ENRICH	1	real	The ratio of fissile atoms to fissile + fertile atoms.

(c) Notes:

This card image causes generation of the edit of neutron balance modification to achieve criticality. It will be ignored unless the breeder ratio edits are being performed as specified on card image 220001.

- **Card 220001 (Optional)**

(a) Syntax:

220001, IDferc, IDferf, IDfisc, IDfisf, IDstrc, IDmodr, IDoxyg

(b) Variables:

Variable	# Words	Type	Description
IDferc	1	integer	Sequential type number of the type defining fertile capture nuclides.
IDferf	1	integer	Sequential type number of the type defining fertile fission nuclides.
IDfisc	1	integer	Sequential type number of the type defining fissile capture nuclides.
IDfisf	1	integer	Sequential type number of the type defining fissile fission nuclides.
IDstrc	1	integer	Sequential type number of the type defining structure nuclides.
IDmodr	1	integer	Sequential type number of the type defining moderator nuclides.
IDoxyg	1	integer	Sequential type number of the type defining oxygen.

(c) Notes:

This card image must contain exactly 7 integer type numbers, which must be defined on card images 230tts. It causes the special breeder ratio edits of η , ϵ , α , conversion ratio, etc. to be generated. It applies only to neutron jobs with at least 7 types defined. The 7 types must be disjoint.

- **Card 230tts (Optional)**

(a) Syntax:

230tts, Name(tt), Iso(tt,1), Iso(tt,2), ..., Iso(tt,n)

(b) Variables:

Variable	# Words	Type	Description
Name(tt)	1	character	Alphanumeric name of special edit type tt. A special edit type is a group of nuclides to be collected for certain edits.
Iso(tt,i)	N	integer	The number of the ith nuclide in type tt. Each such nuclide must be included in some composition definition.

(c) Notes:

The type numbers tt can have the values 01, 02, ..., 10. The type numbers selected need not take on sequential values. No nuclide may be included in more than one type. The sequence number s takes on the values 1, 2, ..., 9.

- **Card 88001 (Optional)**

(a) Syntax:

088001, 0, Ipchlamd, Lcardbase

(b) Variables:

Variable	# Words	Type	Description
Ipchlamd	1	integer	= 0 No eigenvalue punched card images. (default) = 1 Eigenvalue punched card images are to be generated.
Lcardbase	1	integer	Base to which iteration number is added to determine eigenvalue card image number (default = 0). If only two items appear on this card image, the default value of Lcardbase is used. ($0 \leq \text{Lcardbase} \leq 999998000$) The data on these card images are the accumulated eigenvalue estimate and the iteration eigenvalue estimate.

(c) Notes:

In perturbation re-edit jobs, this option causes similar card images to be punched - the card image numbers are higher by 1000, and the data are the number of histories in the current iteration and the iteration eigenvalue estimate.

• **Card 240001 (Optional)**

(a) Syntax:

240001, Ipchcs, Ipchflux, Ipchabs, Ipchsg

(b) Variables:

Variable	# Words	Type	Description
Ipchcs	1	integer	= 0 No cross section card images produced. (default) = 1 Produce card images containing composition definitions and macroscopic few-group neutron cross sections for compositions. = 2 Produce card images containing composition definitions and macroscopic few-group neutron cross sections for edit regions. = 3 Produce card images containing composition definitions and macroscopic few-group neutron cross sections for both compositions and edit regions. = -m Produce card images for only composition m.
Ipchflux	1	integer	= 1 Produce card images containing multigroup and thermal group fluxes for the composition selected for multigroup flux edit (card image 71001). (default = 0 - No punching). Muft energies are produced on card images 1000001-1000010, fluxes on card images 10CCC01-10CCC09. Thermal energies are punched on cards 2000001-2000005, fluxes on card images 20CCC01-20CCC05.
Ipchabs	1	integer	= 1 Replace cross sections on above card images by activities (multiply by flux). = 0 Cross sections. (default)
Ipchsg	1	integer	= 1 Append uncertainties to results on above card images. = 0 No uncertainties. (default)

(c) Notes:

Composition definition card images produced by RCP01 have the form CCCIII, NUCLIDEID, DENSITY where CCC = composition number and III = nuclide number. Cross section card images have forms RRRGII, Σ_a , $v\Sigma_f$ and RRRG00, DIFFREE, DIFTRANSPORT, Σ_R , FLUX. RRR is the composition or region number. If region data card images are produced, the region names are also produced, five per card image, on card images 5000sss.

If fewer than four items appear on this card image, the default values of the missing variables are used.

- **Card 6725 (Optional - Neutron only)**

(a) Syntax:

006725, ITSSPC, ITELAS

(b) Variables:

Variable	# Words	Type	Description
ITSSPC	1	integer	Source spectrum option: = -1 Positive linear spectrum from library. = 0 MUFT histogram spectrum. = -2 Use default.
ITELAS	1	integer	Elastic scattering option: = 0 P - 3. = 1 Histograms. = 2 Interpolation of histograms. = -1 Use default.

(c) Notes:

Defaults for these options depend on the RCPL1 job library used:

For libraries containing pointwise spectra and scattering histograms, the defaults are pointwise linear source spectra and interpolated histograms for elastic scattering (preferred).

For libraries without these data, the defaults are MUFT source spectra and P - 3 elastic scattering.

- **Card 992 (Optional - Neutron only)**

(a) Syntax:

000992, BNDBRK

(b) Variables:

Variable	# Words	Type	Description
BNDBRK	1	real	The nuclide mass below which the full epithermal binding treatment is used. Above this mass, simplified heavy element binding is used (default = 2.5: full treatment for Hydrogen and Deuterium).

- **Card 3iii (Optional - Neutron only)**

(a) Syntax:

3iii, T*(iii)

(b) Variables:

Variable	# Words	Type	Description
T*(iii)	1	real	Epithermal binding temperature in ev for nuclide iii $T^*(iii) \geq 0$. (default = 0)

- **Card 201sss (Optional - Neutron only)**

- **Card 202sss (Optional - Neutron only)**

- **Card 203sss (Optional - Neutron only)**

(a) Syntax:

201sss, TmpMaxwEv(1), TmpMaxwEv(2), ..., TmpMaxwEv(MR)

202sss, TmpMaxwFahr(1), TmpMaxwFahr(2), ..., TmpMaxwFahr(MR)

203sss, TmpMaxwCent(1), TmpMaxwCent(2), ..., TmpMaxwCent(MR)

(b) Variables:

Variable	# Words	Type	Description
TmpMax-wEv(i)	MR	real	Maxwellian temperature (ev) for calculations of Mixed Number Density (MND) values of D, the diffusion coefficient, for each composition i.
TmpMaxw-Fahr(i)	MR	real	Equivalent Fahrenheit temperatures for each composition i.
TmpMaxw-Cent(i)	MR	real	Equivalent Centigrade temperatures for each composition i.

(c) Notes:

One set of these temperatures may be provided. Default values are 20°C. Input values of 0.0 are replaced by 20°C. These data are used to calculate values of D_{MND} .

- **Card 17999 (Optional)**

(a) Syntax:

17999, IFLAT

(b) Variables:

Variable	# Words	Type	Description
IFLAT	1	integer	= 0 Use SRCDEns to select source sites for iteration 0 of eigenvalue jobs and all iterations of fixed source jobs. (normal default)
			= 1 Select source sites uniformly within Final Assemblies. (default for predivided depletion jobs).

(c) Notes:

This card image is not read if card image 17 (source file versions) is present.

- **Card 302 (Optional)**

(a) Syntax:

000302, IEDIMV, IEDFMV

(b) Variables:

Variable	# Words	Type	Description
IEDIMV	1	integer	= 0 Eliminate edits of composition volumes per initial module.
			= 1 Print composition volumes per initial module. (default)
IEDFMV	1	integer	= 0 Eliminate edits of composition volumes totalled over all final modules.
			= 1 Print composition volumes totalled over all final modules. (default)

- **Card 195 (Optional)**

(a) Syntax:

000195, LCOMLD

(b) Variables:

Variable	# Words	Type	Description
LCOMLD	1	integer	= 0 Do not edit nuclide loadings by composition. (default)
			= 1 Edit nuclide loadings by composition.

- **Card 981 (Optional)**

(a) Syntax:

981, IPACEF

(b) Variables:

Variable	# Words	Type	Description
IPACEF	1	integer	=1 Causes collision files to be expanded to include cross section values. =0 No cross sections. (default)

(c) Notes:

The cross sections included in collision files are used by some post-processing programs.

- **Card 194 (Optional)**

(a) Syntax:

000194, TpY1, TpY2

(b) Variables:

Variable	# Words	Type	Description
TpY1	1	real	Minimum y-coordinate for sites selected from X-Y trapping surface. (default = -10^{20} cms)
TpY2	1	real	Maximum y-coordinate for sites selected from X-Y trapping surface. (default = $+10^{20}$ cms)

(c) Notes:

Units are centimeters or inches as determined by card image 13000.

- **Card 3 (Optional - eigenvalue only)**

(a) Syntax:

000003, IterBatch, Itrend

(b) Variables:

Variable	# Words	Type	Description
IterBatch	1	integer	Number of iterations to batch together for startbias testing (default = 5).

Variable	# Words	Type	Description
Itrend	1	integer	Number of iterations to batch together for trendbias testing (default = 3).

(c) Notes:

These variables determine the grouping of iteration results in the statistical analysis of convergence performed at the end of an RCP01 job.

- **Card 18000 (Optional - Required for Depletion)**

(a) Syntax:

18000, Deplete, Table, EditDetail, Sav284, PreDiv, Spatial

(b) Variables:

Variable	# Words	Type	Description
Deplete	1	integer	= 1 Depletion. = 0 No depletion. (default = 0)
Table	1	integer	= 1 Print a table showing the relationship between automatically generated depletable compositions and input compositions. = 0 No table. (default = 0)
EditDetail	1	integer	= 1 Edit results by automatically generated depletable composition. = 0 Edit results by input composition. (default = 0)
Sav284	1	integer	= 1 Write concentrations in a type 284 file. = 0 Include concentrations in the type 250 restart file. (defaults: 1 if depletion, 0 if not)
PreDiv	1	integer	= 0 Automatic generation of depletable compositions. = 1 No automatic generation since fine mesh already done. (default= 0)
Spatial	1	integer	= 0 Perform Monte Carlo tracking ("Spatial") and depletion calculation. = 1 Perform Spatial only for current timestep. (default= 0)

- **Card 1800s (Optional - Depletion only)**

(a) Syntax:

1800s, Comp₁, Comp₂, ..., Comp_{MRNOND}

(b) Variables:

Variable	# Words	Type	Description
COMP _i	MRNOND	integer	Compositions which are not to be depleted. The sequence number s takes on values 1, 2, ..., 9.

- **Card 18100 (Optional - Required for Depletion)**

(a) Syntax:

18100, POWER

(b) Variables:

Variable	# Words	Type	Description
POWER	1	real	Power level in watts.

- **Card 1810s (Optional - Required for Depletion)**

(a) Syntax:

1810s, Timestep(1), Timestep(2), ..., Timestep(NDSTEP)

(b) Variables:

Variable	# Words	Type	Description
Timestep(i)	NDSTEP	real	Length of depletion timestep i in hours. The sequence number s takes on values 1, 2, ..., 9.

- **Card 1811s (Optional - Depletion only)**

(a) Syntax:

1811s, Region₁, Region₂, ..., Region_{NREGS}

(b) Variables:

Variable	# Words	Type	Description
Region _i	NREGS	integer	Numbers of edit regions to be included in the calculation of the depletion flux normalization.

(c) Notes:

If one or more region numbers are included on these card images, flux normalization is determined by integrating the power over the total of those regions. If these card images are absent, the integration is over all depletable compositions.

- **Card 182ss (Depletion only)**

(a) Syntax:

0182ss, IDCHAIN₁, IDLIB₁, IDCHAIN₂, IDLIB₂, ..., IDCHAIN_N, IDLIB_N

(b) Variables:

Variable	# Words	Type	Description
IDCHAIN _i	N	integer	ID of a nuclide in a depletion chain.
IDLIB _i	N	integer	Corresponding ID of that nuclide in the job library.

(c) Notes:

The sequence number ss takes on values 01, 02, ..., 99.

- **Card 18500 (Depletion only)**

(a) Syntax:

18500, ChannelTrack

(b) Variables:

Variable	# Words	Type	Description
ChannelTrack	1	integer	= 1 Generate file of correspondences between depletable compositions and diffusion theory fine blocks. = 0 Do not generate the file. (default = 0)

- **Card 20 (Optional)**

(a) Syntax:

000020, IFISRT

(b) Variables:

Variable	# Words	Type	Description
IFISRT	1	integer	= 0 Write fission file in the order in which sites are generated. (default) = 1 Sort fission sites in fission file by history number within each RCP group.

(c) Notes:

Sorting the fission file increases the probability of agreement of results between scalar and vector tracking in eigenvalue jobs.

- **Card 6477 (Optional)**

(a) Syntax:

6477, MXDART

(b) Variables:

Variable	# Words	Type	Description
MXDART	1	integer	The maximum number of attempts to find a source point with a selected composition in a selected mesh region. (default = 10000).

- **Card 6479 (Optional)**

(a) Syntax:

6479, IOK300

(b) Variables:

Variable	# Words	Type	Description
IOK300	1	integer	= 0 Forbid the use of nuclides with masses greater than 300. (default) = 1 Allow unlimited nuclide masses.

(c) Notes:

This card image disables a valuable input check but allows testing of theoretical concepts such as “infinite mass” scattering.

- **Card 6723 (Optional)**

(a) Syntax:

006723, MNVECO, MNVCIA, MNVCLF, MNVCLT, MNTAIL, MNCOLL

(b) Variables:

Variable	# Words	Type	Description
MNVECO	1	integer	The vector length above which vector tracking is performed in module zero.

Variable	# Words	Type	Description
MNV CIA	1	integer	The vector length above which vector tracking is performed in initial assemblies.
MNV CLF	1	integer	The vector length above which particles colliding with energies above the thermal group are retained for vector collision processing.
MNV CLT	1	integer	The vector length above which particles colliding with energies in the thermal group are retained for vector collision processing.
MN TAIL	1	integer	The vector length above which colliding particles are retained for vector collisions.
MN COLL	1	integer	Ignored.

(c) Notes:

On the DEC system, which has no vector processing capability, the default value for all of the variables is set to 1000000.

On Cray computers, which have vector processing capability, MNVECO has default value 0; the other variables have default values of 25.

- **Card 980 (Optional)**

(a) Syntax:

000980, AGEFAC

(b) Variables:

Variable	# Words	Type	Description
AGEFAC	1	real	Age correction factor for fitted diffusion constant calculations. (default = 1.35)

- **Card 10nnns (Optional)**

(a) Syntax:

10nnns, Name_{nnn}, $\pm$ Type₁, FewGroup₁, Comp₁, Nuc₁,
 $\pm$ Type₂, FewGroup₂, Comp₂, Nuc₂,
 $\vdots$
 $\pm$ Type_N, FewGroup_N, Comp_N, Nuc_N,

(b) Variables:

Variable	# Words	Type	Description
Name _{nnn}	1	character	Name of edit nnn.
$\pm$ Type _i	N	integer	= 1 For absorption. = 2 For production. = 3 For slowing down. + for add, - for subtract.
FewGroup _i	N	integer	0 for sum over all groups, else few group.
Comp _i	N	integer	0 for sum over all compositions, else composition number.
Nuc _i	N	integer	0 for sum over all nuclides, else nuclide number.

(c) Notes:

Each nnn defines a generalized edit comprising sums and differences of basic results. Each edit has an arbitrary number of terms. Slowing down is not available by nuclide so if Type_i = 3, Nuc_i must be zero. Slowing down cannot be summed over groups. The number nnn can take on values 1, 2, ..., 999. The sequence number s takes on values 1, 2, ..., 9.

- **Card 110nnn (Only if series 10nnns is present)**

(a) Syntax:

110nnn, RName_{nnn}, Sum₁, Sum₂, Sum₃, Sum₄

(b) Variables:

Variable	# Words	Type	Description
RName _{nnn}	1	character	Name of Ratio nnn.
Sum ₁	1	integer	Generalized Edit #1.
Sum ₂	1	integer	Generalized Edit #2.
Sum ₃	1	integer	Generalized Edit #3.

Variable	# Words	Type	Description
Sum ₄	1	integer	Generalized Edit #4.

(c) Notes:

Each Ratio Edit nnn defines $\frac{SUM_1 \times SUM_4}{SUM_2 \times SUM_3}$ where the SUM_i are generalized sums and differences defined by card images 10nnns.

- **Card 298 (Optional)**

(a) Syntax:

298, ModZeroReflect

(b) Variables:

Variable	# Words	Type	Description
ModZeroReflect	1	integer	= 0 Top and bottom z surfaces of Module zero are leakage surfaces. = 1 Top and bottom z surfaces of Module zero are reflective. (default = 0)

- **Card 301 (Optional)**

(a) Syntax:

301, IedComp, IedFast, IedTher, IedTot, IedDiff, IedHeat

(b) Variables:

Variable	# Words	Type	Description
IedComp	1	integer	= 0 Omit edits of composition definitions and Maxwellian temperatures. = 1 Generate edits. (default = 0 if flat source or predivided depletion, otherwise default = 1)
IedFast	1	integer	= 0 Omit edits of results by fast few group. = 1 Provide the edits by composition. = 2 Edit by composition and nuclide. (default = 2)
IedTher	1	integer	Same as IedFast for the thermal group. (default = 2)
IedTot	1	integer	Same as IedFast for the edit of totals over all few groups. (default = 2)
IedDiff	1	integer	= 0 Omit edit of diffusion coefficients. = 1 Generate the edit. (default = 1)

Variable	# Words	Type	Description
IedHeat	1	integer	= 0 Omit edit of neutron heating. = 1 Generate the edit. (default = 1)

(c) Notes:

For jobs with many compositions and many nuclides card image 301, 0, 0, 0, 0, 0, 0 will reduce output file size. If fewer than 6 items are included on this card image, defaults will be used for the missing entries.

- **Card 77001 (Optional)**

(a) Syntax:

077001, μ , γ , η

(b) Variables:

Variable	# Words	Type	Description
μ	1	real	Cosine of the angle between the monodirectional source direction and the Initial Assembly x-axis.
γ	1	real	Cosine of the angle between the monodirectional source direction and the Initial Assembly y-axis (perpendicular to the x-z plane).
η	1	real	Cosine of the angle between the monodirectional source direction and the Initial Assembly z-axis.

(c) Notes:

This very special option is used to produce an arbitrary monodirectional source even for eigenvalue problems. For the special sources specified by LOPT (Section 10.9), this angle overrides the axis selection specified for monodirectional or conical sources. Values input as 0.0 are replaced by 0.0001, +1.0 by 0.99999999, and -1.0 by -0.99999999. ($-1.0 \leq \mu, \gamma, \eta \leq +1.0$). ($0.99999 < \mu^2 + \gamma^2 + \eta^2 < 1.00001$). This option is not permitted with the Legendre coefficient source option (LOPT = 1, 2, 3).

- **Card 6478 (Optional)**

(a) Syntax:

006478, Irefct

(b) Variables:

Variable	# Words	Type	Description
Irefct	1	integer	The maximum number of Final Assembly crossings and/or boundary reflections to be permitted between collision interactions before the problem is to be aborted as a potential infinite loop. Irefct > 0. (default = 1000)

- **Card 6722 (Optional)**

(a) Syntax:

006722, INKITE, INGRUP, INHIST

(b) Variables:

Variable	# Words	Type	Description
INKITE	1	integer	The number of the iteration during which particles are to be traced.
INGRUP	1	integer	The RCP group in which particles are to be traced. If INGRUP = 0, all groups are to be traced.
INHIST	1	integer	The number of the particle to be traced. If INHIST = 0, all histories are to be traced.

(c) Notes:

This card image triggers the particle trace edit. It can cause the production of vast amounts of printing and, therefore, should be used only to track down the cause of strange behavior. Even then one should be as specific as possible in selecting tracing parameters.

- **Card 999 (Optional)**

(a) Syntax:

000999, NORESTR

(c) Notes:

A card image of exactly this form will turn off the recovery capability until after the successful writing of a restart file. Normally a job will recover at its start if no

file has been written. The recovery capability is unavailable on current computer systems.

- **Card 1900ss or 19ssssss (Required for Depletion)**

(a) Syntax:

1900ss, CHAINLIST(1), COMP(1), ..., CHAINLIST(MR), COMP(MR) ($1 \leq ss \leq 99$)

1900ssssss, CHAINLIST(1), COMP(1), ..., CHAINLIST(MR), COMP(MR) ($1 \leq ssssss \leq 999999$)

(b) Variables:

Variable	# Words	Type	Description
CHAINLIST(i)	MR	integer	Id of a chain list. The chain lists are defined on the 19LLss series of card images. CHAINLIST(i) = 0, represents a non-depletable composition.
COMP(i)	MR	integer	Id of the composition to which CHAINLIST(i) is to be assigned. These composition id numbers must be in strictly increasing order, and the last such number must be equal to MR given on card image 1. MR is the number of compositions at BOL.

- **Card 19LLss (Required for Depletion)**

(a) Syntax:

19LLss, CHAINID(1), ..., CHAINID(N) ($01 \leq LL \leq 99$) ($01 \leq ss \leq 99$)

(b) Variables:

Variable	# Words	Type	Description
CHAINID(i)	N	integer	Chain id. ($1 \leq \text{CHAINID}(i) \leq 99$)

(c) Notes:

These card images define chain list number LL. The order in which the chains are listed determines the order in which the chains are solved. Each chain list may contain any combination of chains defined on the 3CCNNs series of card images.

- **Card 3CC000 or 3CCC000 (Required for Depletion)**

(a) Syntax:

3CC000, NUCLIDES, TYPE, MAXDT ($01 \leq CC \leq 99$)

3CCC000, NUCLIDES, TYPE, MAXDT ($001 \leq CCC \leq 999$)

(b) Variables:

Variable	# Words	Type	Description
NUCLIDES	1	integer	Number of nuclides in chain number CC or CCC ($1 \leq \text{NUCLIDES} \leq 99$).
TYPE	1	integer	= 1 Chain is a depletion chain with no direct yield term. = 2 Chain is a fission product chain.
MAXDT	1	real	Maximum subinterval length in hours. ($\text{MAXDT} \geq 1.0\text{E-}5$)

- **Card 3CCNN1 or 3CCCNN1 (Required for Depletion)**

(a) Syntax:

3CCNN1, ID(NN), FORM(NN), DECAY(NN) ($01 \leq CC \leq 99$) ($01 \leq NN \leq 99$)

3CCCNN1, ID(NN), FORM(NN), DECAY(NN) ($001 \leq CCC \leq 999$) ($01 \leq NN \leq 99$)

(b) Variables:

Variable	# Words	Type	Description
ID(NN)	1	integer	Id of the NN-th nuclide.
FORM(NN)	1	integer	= 0 The nuclide appears only in this chain in a chain list or this is the nuclide's first appearance. = -1 This is a duplication of an appearance of the nuclide in a previous chain. = +1 This is a partial contribution to a previous appearance of the nuclide.
DECAY(NN)	1	real	Decay constant for the nuclide in inverse seconds.

(c) Notes:

NN refers to the NN-th nuclide in chain number CC or CCC.

- **Card 3CCNNs or 3CCCNs (Required for Depletion)**

(a) Syntax:

3CCNNs, COUP(J), ID(J), FRACTION(J) ($01 \leq CC \leq 99$) ($01 \leq NN \leq 99$) ($2 \leq s \leq 9$)

3CCCNs, COUP(J), ID(J), FRACTION(J) ($001 \leq CCC \leq 999$) ($01 \leq NN \leq 99$) ($2 \leq s \leq 9$)

(b) Variables:

Variable	# Words	Type	Description
COUP(J)	1	integer	Describes the type of coupling from nuclide ID(J) to nuclide ID(NN) in chain CC or CCC.
ID(J)	1	integer	Id of the nuclide coupled to.
FRACTION(J)	1	real	Fractional yield.

(c) Notes:

If $NN = 01$, the first nuclide in the chain, then $COUP(J) = 1, 2$, or 3 is not allowed. $COUP(J) = 4$, means that the equation $DN/DT = Y$ or $DN/DT = 0$ is solved, and in that case set $ID(J) = ID(NN)$, $FRACTION(J) = 0.0$, and $NUCLIDES = 1$ on card image 3CC000 or 3CCC000. $COUP(J) = 5$, is allowed if $TYPE = 2$ on card image 3CC000 or 3CCC000, unless the special equation given when $COUP(J) = 4$ is desired. No coupling card image is allowed for $NN = 01$ in a depletion chain. If $NN > 01$, one triplet with $COUP(J) = 1, 2$, or 3 is required and these specify decay, capture, or decay + capture, respectively, and therefore $ID(J) = ID(NN-1)$. $COUP(J) = 4$, is not allowed. $COUP(J) = 5$, is allowed if $TYPE = 2$ on card image 3CC000 or 3CCC000.

For any NN , if $TYPE = 2$ on card image 3CC000 or 3CCC000, use $COUP(J) = 5$ to specify the yield term for fission products. In this case $ID(J)$ is the numeric id of a fissile nuclide and $FRACTION(J)$ is the fractional yield of nuclide $ID(NN)$ from fissile nuclide $ID(J)$. Several such triplets are allowed. If the special equation $DN/DT = Y$ is desired, then these triplets follow the $COUP(J) = 4$, $ID(J) = ID(NN)$, $FRACTION(J) = 0.0$ triplets.

Card images of all three series must be of the 3CCXXX type or the 3CCCXXX type. Mixing the types is not handled by RCP.

Case separator - A / is placed in column 1 of the input card image to indicate end of input control cards.

10.5 Initial Assembly Input

*Input for Initial Assembly #IA (Optional comment card images preceded by *.)

- **Card 6000 (Optional)**

(a) Syntax:

006000, IANameIN, GeomFileSyn

(b) Variables:

Variable	# Words	Type	Description
IANameIN	1	8 character	The name of the section in an input geometry file containing the initial assembly description.
GeomFileSyn	1	8 character	The synonym of the input geometry file (type 261) containing section IANameIN.

(c) Notes:

If GeomFileSyn is not specified, the first Type 261 file present of those with synonyms on card image 1060 of control input is used.

If GeomFileSyn is specified, the first such file with synonym GeomFileSyn is used.

If card image 1060 is absent, the default synonym RCPGEOM comprises the list scanned.

The presence of card image 6000 causes the description of the initial assembly to be obtained from the specified file section except as overridden and/or extended by input card images.

If input card images specify a different number of x or y values than are specified in the file, then the overlay must also be specified on card images.

If card images specify a different number of z values, then C-lists must also be specified.

- **Card 6010 (Optional)**

(a) Syntax:

6010, IAName

(b) Variables:

Variable	# Words	Type	Description
IAName	1	8 character	Name of Initial Assembly section in output geometry (type 261) file.

(c) Notes:

If card image 6010 is absent and card image 6000 is present, the default value of IAName is IANameIN from card image 6000.

If neither card image is present, the default value is IAnnn where nnn is the initial assembly number.

The card image is effective only if an output geometry file is being written.

- **Card 30000 (Optional)**

(a) Syntax:

030000, LGIA

(b) Variables:

Variable	# Words	Type	Description
LGIA	1	integer	Initial Assembly coordinate system. = 0 60° parallelogram. = 1 Rectangle.

(c) Notes:

Default = LSQHX on card image 000001 of control input.

- **Card 30sss**

(a) Syntax:

030sss, X(0), X(1), X(2), ..., X(NPXX)

(b) Variables:

Variable	# Words	Type	Description
X(i)	NPXX + 1	real	Abscissa of the ith slab boundary. (X(0) = 0.0, NPXX ≥ 1). The units of X(i) are centimeters or inches as determined by card image 013000 in the control input. No two values of X(i) may be the same. The values need not be in ascending order. Negative values are not permitted. The sequence number sss takes on values 001, 002, ..., 999.

- **Card 40sss**

(a) Syntax:

040sss, Y(0), Y(1), Y(2), ..., Y(NPYY)

(b) Variables:

Variable	# Words	Type	Description
Y(i)	NPYY + 1	real	Ordinate of the ith slab subdivision boundary. (Y(i) = 0.0, NPYY ≥ 1). The units of Y(i) are centimeters or inches as determined by card image 013000 in the control input. No two values of Y(i) may be the same. The values need not be in ascending order. Negative values are not permitted. The sequence number sss takes on values 001, 002, ..., 999.

- **Card 45sss**

(a) Syntax:

045sss, Z(0), Z(1), Z(2), ..., Z(NPZZ)

(b) Variables:

Variable	# Words	Type	Description
Z(i)	NPZZ + 1	real	Location of the ith plane perpendicular to the z-axis. (Z(0) = 0.0, NPZZ ≥ 1). The units of Z(i) are centimeters or inches as determined by card image 13000 in the control input. Z(i) > Z(i-1); that is, the values must be in ascending order. Negative values are not permitted. The sequence number sss takes on values 001, 002, ..., 999.

- **Card 100 (Optional)**

(a) Syntax:

100, NPlistBase

(b) Variables:

Variable	# Words	Type	Description
NPlistBase	1	integer	The value above which C-list/P-list overlay values are references to P-lists. P-list n is referred to as NPlistBase + n.

(c) Notes:

Default NPlistBase = 100. If NPlist = 0, then the default NPlistBase is max(100, NClst).

- **Card 50sss**

(a) Syntax:

050SSS, N(1), M(1), CS(1)/PSS(1), N(2), M(2), CS(2)/PSS(2), ...,
N(K), M(K), CS(K)/PSS(K)

(b) Variables:

Variable	# Words	Type	Description
N(i)	K	integer	Index of X(i)
M(i)	K	integer	Index of Y(i)
CS(i) PSS(i)	total of K	integer	Composition stack number to be assigned, or Partial subcell number to be assigned.

(c) Notes:

The placement of composition stacks and partial subcells is specified by the sequence of integers on either these overlay card images or on those of the 150sss series. This overlay is accomplished by moving from left to right on the x-axis and from bottom to top on the y-axis. For example, the triplet (N(i),M(i),CS(i)) would assign composition stack CS(i) to every "mesh rectangle" to the right of X(N(i)) and above Y(M(i)). N(i) and M(i) refer to the sequential positions of X(i) and Y(i) on the 030sss and 040sss card images, prior to sorting. N(1) = 0 and M(1) = 0. When a "mesh rectangle" is overlayed by more than one triplet, the last such triplet determines the assignment. No triplet may completely erase the effect of the previous triplet. The sequence number sss takes on values 001, 002, ..., 999.

Composition stacks are represented by C-list numbers from 1 to NCLIST, standard partial subcells by subcell numbers from NPLISTBase+1 to NPLISTBase+NPLIST, and portable subcells by subcell numbers from NPLISTBase+101 to NPLISTBase+100+NPLIST.

- **Card 150sss**

(a) Syntax:

150SSS, N1(1), M1(1), N2(1), M2(1), CS(1)/PSS(1), N1(2), M1(2),
N2(2), M2(2), CS(2)/PSS(2), ..., N1(K), M1(K), N2(K), M2(K),
CS(K)/PSS(K)

(b) Variables:

Variable	# Words	Type	Description
N1(i)	K	integer	Index of the left X(i).
M1(i)	K	integer	Index of the lower Y(i).
N2(i)	K	integer	Index of the right X(i).

Variable	# Words	Type	Description
M2(i)	K	integer	Index of the upper Y(i).
CS(i)	total of K	integer	Composition stack number to be assigned, or
PSS(i)			Partial subcell number to be assigned.

(c) Notes:

The placement of composition stacks and partial subcells is specified by the sequence of integers on either these overlay card images or on those of the 050sss series. For example, the quintuplet (N1(i), M1(i), N2(i), M2(i), CS(i)) would assign composition stack CS(i) to every "mesh rectangle" with X between X(N1(i)) and X(N2(i)) and Y between Y(M1(i)) and Y(M2(i)). N1(i), N2(i), M1(i), and M2(i) refer to the sequential positions of X(i) and Y(i) on the 030sss and 040sss card images, prior to sorting. $X(N1(i)) < X(N2(i))$ and $Y(M1(i)) < Y(M2(i))$. When a "mesh rectangle" is overlaid by more than one quintuplet, the last such quintuplet determines the assignment. No quintuplet may completely erase the effect of the previous quintuplet. Every "mesh rectangle" in the Initial Assembly must be covered by the overlay. The sequence number sss takes on values 001, 002, ..., 999.

Composition stacks are represented by C-list numbers from 1 to NCLIST, standard partial subcells by subcell numbers from NPlistBase+1 to NPlistBase+NPLIST, and portable subcells by subcell numbers from NPlistBase+101 to NPlistBase+100+NPLIST.

- Card 60CSs
- Card 60CCCSs

(a) Syntax:

060CSs, C(1), C(2), ..., C(NPZZ)

60CCCSs, C(1), C(2), ..., C(NPZZ)

(b) Variables:

Variable	# Words	Type	Description
C(i)	NPZZ	integer	The composition number assigned to the ith zone in the z-direction in composition stack or C-list CS/CCCS.

(c) Notes:

Starting with the bottom zone, composition numbers are entered in order on these card images. C-list numbers CS and/or CCCS must be consecutive starting with 1. NCLIST is the number of C-lists defined on these card images. The sequence number s takes on values 1, 2, ..., 9. ($1 \leq \text{NCLIST} \leq 9,999$)

For C-lists 1 through 100, either of these card images may be used. For C-lists beyond 100 the 60CCCSs card images must be used.

- **Card 6PSSs**

(a) Syntax:

```
06PSSs, Xa, Ya, Dx, Dy, G, CS(0), Xe(1), Ye(1), MUE(1), A(1), B(1),
      CS(1), Xe(2), Ye(2), MUE(2), A(2), B(2), CS(2), ..., Xe(Lipct),
      Ye(Lipct), MUE(Lipct), A(Lipct), B(Lipct), CS(Lipct)
```

(b) Variables:

Variable	# Words	Type	Description
Xa, Ya	2	real	Coordinates of the anchor point, the lower left corner of the first subcell in the array, relative to the Initial Assembly origin X0,Y0. The units of Xa and Ya are centimeters or inches as determined by card image 013000 in the control input. Xa and Ya are ignored when the subcell is used as a portable subcell.
Dx, Dy	2	real	Repeat distances in the x and y directions respectively. Dx and Dy are the subcell dimensions. The partial subcell will be repeated every Dx cms or ins in the x-direction and every Dy in the y-direction - both positive and negative. The units of Dx and Dy are centimeters or inches as determined by card image 013000 in the control input. Dx > 0.0, Dy > 0.0.
G	1	integer	Ellipse arrangement = 0 1 ellipse; Lipct = 1 = 1 or 2 2 ellipses; Lipct = 2 > 2 G ellipses; Lipct = G
CS(0)	1	integer	Composition stack number assigned to the region not inside any ellipse.
CS(i)	Lipct	integer	Composition stack number assigned to ellipse i.
Xe(i), Ye(i)	2 * Lipct	real	Coordinates of the center of ellipse i relative to the anchor point. The units of Xe(i) and Ye(i) are centimeters or inches as determined by card image 013000 in the control input.
MUE(i)	Lipct	real	The cosine of the angle between the semi-major axis of ellipse i and the Initial Assembly x-axis. MUE(i) ≤ 1.0
A(i), B(i)	2 * Lipct	real	The semi-major and semi-minor axes of ellipse i. The units of A(i) and B(i) are centimeters or inches as determined by card image 013000 in the control input. A(i) > 0.0, B(i) > 0.0.

(c) Notes:

IPL is the P-list number. $PSS = 100 + IPL$. P-list numbers must be consecutive starting with 001. NPLIST is the number of P-lists defined on these card images. The sequence number s takes on values 1, 2, ..., 9. ($0 \leq NPLIST \leq 899$)

A portable subcell is an instance of the corresponding standard subcell except that in each "mesh rectangle" X_a and Y_a are replaced by the left and bottom mesh rectangle boundaries.

Any combination of sets of nested ellipses is permitted subject to the following constraints:

1. No two ellipses may intersect within that part of a subcell actually appearing in an initial assembly.
2. If one ellipse is interior to another, the interior ellipse must be described later in the list of ellipses than the exterior one.
3. No two ellipses may be identical.

All elliptical surfaces described are truncated first by the subcell boundaries. The resulting subcell is then repeated, starting at the anchor point, positively and negatively in both the x and y directions. The resulting infinite array of subcells is then truncated by the basic region boundaries so that only that part of the array is present which corresponds with the basic region of the Initial Assembly.

- **Card 998 (Optional)**

(a) Syntax:

000998, ISaveInput

(b) Variables:

Variable	# Words	Type	Description
ISaveInput	1	integer	= 0 Do not retain input from current case as basis for next case. (default) = 1 Retain input from current case as basis for next case and for all succeeding Initial Assembly cases until turned off by card image 000998, 0 or 000998, -1. = -1 Retain input from current case as basis for next Initial Assembly case only.

(c) Notes:

In RCP01, input is not carried forward from input case to input case except by use of card 000998. Initial Assembly input cannot be carried past the last Initial Assembly. To carry data through a sequence of Initial Assemblies, the simplest

approach is to include card image 000998, 1 with the card images describing the first such Initial Assembly and card image 000998, 0 with the last.

- **Card 450000 (Optional - depletion only)**

(a) Syntax:

450000, IUSEZ

(b) Variables:

Variable	# Words	Type	Description
IUSEZ	1	integer	= 1 z-zone boundaries are to be used as depletion zone boundaries (i.e., the depletable composition number changes when the boundary is crossed). (default) = 0 Adjacent z-zones containing the same input composition number are to contain the same depletable composition. This only applies when neither of the adjacent z-zones contains depletion zones as defined on card images 45ZZZs.

- **Card 45ZZZs (Optional - depletion only)**

(a) Syntax:

45ZZZs, DZ(1), ..., DZ(N)

(b) Variables:

Variable	# Words	Type	Description
DZ(i)	N	real	DZ(i) is the thickness in the z-direction of the i^{th} depletion zone of z-zone ZZZ. The bottom of the first depletion zone is the bottom of the z-zone. The top of the last depletion zone is the top of the z-zone. N values of DZ thus determine N + 1 depletion zones. The units of DZ(i) are centimeters or inches as determined by card image 13000 in the control input. DZ(i) > 0. ZZZ takes on values up to min(NPZZ, 999); s takes on values 1, 2, ..., 9. N ≤ 99.

- **Card 7PSSs (Optional - depletion only)**

(a) Syntax:

07PSSs, DX(1), DX(2), ..., DX(NX_{IPL})

(b) Variables:

Variable	# Words	Type	Description
DX(i)	NX _{IPL}	real	The width in the x-direction of the ith depletion block of P-list IPL. The units of DX(i) are centimeters or inches as determined by card image 13000 in the control input. DX(i) > 0. NX _{IPL} ≤ 99.

(c) Notes:

IPL is the P-list number. PSS = 100 + IPL. The DX(i) divide the P-list into NX_{IPL} + 1 depletion blocks in the x-direction. The left edge of the first depletion block is the left edge of the P-list. The right edge of block NX_{IPL} + 1 is the right edge of the P-list. This series may appear for any P-list in the initial assembly. The sequence number s takes on values 1, 2, ..., 9.

- **Card 8PSSs (Optional - depletion only)**

(a) Syntax:

08PSSs, DY(1), DY(2), ..., DY(NY_{IPL})

(b) Variables:

Variable	# Words	Type	Description
DY(i)	NY _{IPL}	real	The height in the y-direction of the ith depletion block of P-list IPL. The units of DY(i) are centimeters or inches as determined by card image 13000 in the control input. DY(i) > 0. NY _{IPL} ≤ 99.

(c) Notes:

IPL is the P-list number. PSS = 100 + IPL. The DY(i) divide P-list IPL into NY_{IPL} + 1 depletion blocks in the y-direction. The bottom edge of the first depletion block is the bottom edge of the P-list. The top edge of block NY_{IPL} + 1 is the top edge of the P-list. This series may appear for any P-list in the initial assembly. The sequence number s takes on values 1, 2, ..., 9.

- **Card 70PSS0 (Optional - depletion only)**

(a) Syntax:

70PSS0, Iorient(IPL)

(b) Variables:

Variable	# Words	Type	Description
Iorient(IPL)	1	integer	= 1 Channels are parallel to the x-axis in P-list IPL and tracks are parallel to the y-axis. = 0 Channels are parallel to the y-axis and tracks are parallel to the x-axis. (default = 1)

(c) Notes:

IPL is the P-list number. PSS = 100 + IPL. For further information on the channel/track file, see Chapter 14.

- **Card 70PSSs (Optional - depletion only)**

(a) Syntax:

70PSSs, TR(1), ..., TR(NX_{IPL} + 1)

(b) Variables:

Variable	# Words	Type	Description
TR(i)	NX _{IPL} + 1	integer	Integer label associated with the ith depletion block in the x-direction of P-list IPL. Default values are 1, 2, ..., NX _{IPL} + 1.

(c) Notes:

IPL is the P-list number. PSS = 100 + IPL. NX_{IPL} is determined by card images 7PSSs. The sequence number s takes on values 1, 2, ..., 9. These are the track numbers unless Iorient(IPL) = 0 in which case they are the channel numbers.

- **Card 80PSSs (Optional - depletion only)**

(a) Syntax:

80PSSs, CH(1), ..., CH(NY_{IPL} + 1)

(b) Variables:

Variable	# Words	Type	Description
CH(i)	NY _{IPL} + 1	integer	Integer label associated with the ith depletion block in the y-direction of P-list IPL. Default values are 1, 2, ..., NY _{IPL} + 1.

(c) Notes:

IPL is the P-list number. $PSS = 100 + IPL$. NY_{IPL} is determined by card images 8PSSs. The sequence number s takes on values 1, 2, ..., 9. These are the channel numbers unless $Iorient(IPL) = 0$ in which case they are the track numbers.

- **Card 9PSS1 (Optional - depletion only)**

(a) Syntax:

09PSS1, NEWCSC, DELTR, DELCH

(b) Variables:

Variable	# Words	Type	Description
NEWCSC	1	integer	Control variable for expansion of depletable compositions. = 1 Each subcell copy is given a new set of depletable compositions. (default = 1) = 0 Each subcell copy uses the same set of depletable compositions throughout a basic region. Multiple basic regions with the same P-list are given different sets of depletable compositions. = -1 BOL (input) compositions that appear within different ellipses in a single z-zone within a depletion block do not deplete independently. If no depletion blocks are specified on card images 07PSSs or 08PSSs, subcell copies use the same set of depletable compositions throughout each basic region as for NEWCSC = 0.
DELTR	1	integer	Bias applied to the track labels TR(i) each time the subcell (P-list) is repeated in the x-direction. (Default = 0, set to 0 if NEWCSC < 1).
DELCH	1	integer	Bias applied to the channel labels CH(i) each time the subcell is repeated in the y-direction. (Default = 0, set to 0 if NEWCSC < 1).

(c) Notes:

IPL is the P-list number. $PSS = 100 + IPL$. These card images control the assignment of depletable compositions to multiple copies of P-lists. For further information on depletion and the channel/track files, see Chapter 14.

- **Card 50PSSs (Optional - depletion only)**

(a) Syntax:

50PSSs, TRBias(1), CHBias(1), ..., TRBias(N_{IPL}), CHBias(N_{IPL})

(b) Variables:

Variable	# Words	Type	Description
TRBias(i)	N_{IPL}	integer	Bias factor to be applied to TR labels for the ith appearance of P-list IPL in the final laydown.
CHBias(i)	N_{IPL}	integer	Bias factor to be applied to CH labels for the ith appearance of P-list IPL in the final laydown.

(c) Notes:

IPL is the P-list number. $PSS = 100 + IPL$. $N_{IPL} \leq 2000$. If this card image is missing for P-list IPL, the bias values default to 0.

Case separator - A / is placed in column 1 of the input card image to indicate end of Initial Assembly #IA input cards.

10.6 Module Zero Input

*Input for Module Zero (Optional comment card images preceded by *.)

- **Card 6000 (Optional)**

(a) Syntax:

006000, Mod0NameIN, GeomFileSyn

(b) Variables:

Variable	# Words	Type	Description
Mod0NameIN	1	8 character	The name of the section in an input geometry file containing the module zero description.
GeomFileSyn	1	8 character	The synonym of the input geometry file (type 261) containing section Mod0NameIN

(c) Notes:

If GeomFileSyn is not specified, the first type 261 file present of those with synonyms on card image 1060 of control input is used.

If GeomFileSyn is specified, the first such file with synonym GeomFileSyn is used.

If card image 1060 is absent, the default synonym RCPGEOM comprises the list scanned.

The presence of card image 6000 causes the description of module zero to be obtained from the specified file section except as overridden and/or extended by input card images.

If card images specify a different number of z-values than are specified in the file, the C-lists must also be specified.

- **Card 6010 (Optional)**

(a) Syntax:

6010, Mod0Name

(b) Variables:

Variable	# Words	Type	Description
Mod0Name	1	8 character	Name of Module zero section in output geometry (type 261) file.

(c) Notes:

If card image 6010 is absent and card image 6000 is present, the default value of Mod0Name is Mod0NameIN from card image 6000.

If neither card image is present, the default value is MOD0.

This card image is effective only if an output geometry file is being written.

- **Card 35000 (Optional)**

(a) Syntax:

035000, LGMO

(b) Variables:

Variable	# Words	Type	Description
LGMO	1	integer	= 0 Module Zero is a set of concentric spheres.
			= 1 Module Zero is a set of concentric right circular cylinders. (default)

- **Card 35sss**

(a) Syntax:

035sss, R(1), R(2), ..., R(NPRR)

(b) Variables:

Variable	# Words	Type	Description
R(i)	NPRR	real	Radius of the ith spherical or cylindrical shell. $R(1) > 0.0$ and $R(i) > R(i-1)$; that is, the radii must be listed in ascending order. ($NPRR \geq 1$). The units of R(i) are centimeters or inches as determined by card image 013000 in the control input. The sequence number sss takes on values 001, 002, ..., 999.

- **Card 45sss**

(a) Syntax:

045sss, Z(0), Z(1), Z(2), ..., Z(NPZZ)

(b) Variables:

Variable	# Words	Type	Description
Z(i)	NPZZ + 1	real	Location of the ith plane perpendicular to the z-axis. Z(0) need not be 0.0. ($NPZZ \geq 1$). The units of Z(i) are centimeters or inches as determined by card image 013000 in the control input. $Z(i) > Z(i-1)$; that is, the values must be in ascending order. The sequence number sss takes on values 001, 002, ..., 999.

- **Card 6CCSs**

- **Card 60CCCSs**

(a) Syntax:

06CCSs, C(1), C(2), ..., C(NPZZ)

60CCCSs, C(1), C(2), ..., C(NPZZ)

(b) Variables:

Variable	# Words	Type	Description
C(i)	NPZZ	integer	The composition number assigned to the ith zone in the z-direction in spherical or cylindrical shell CCS/CCCS.

(c) Notes:

Starting with the bottom zone, composition numbers are entered in order on these card images. C-list numbers CCS and/or CCCS must be consecutive starting with 1 and correspond directly with radial shells. The first C-list is assigned to the innermost cylinder or sphere, the second to the region between the first and second cylinders or spheres, etc. Therefore, NCLIST, the number of C-lists defined on these card images, must equal NPRR as determined from card images 35sss. The sequence number s takes on values 1, 2, ..., 9.

For C-lists 1 through 999, either of these card images may be used. For C-lists beyond 999, the 60CCCSs card images must be used.

- **Card 47000**

(a) Syntax:

47000, M, N1, N2, EPS

(b) Variables:

Variable	# Words	Type	Description
M	1	integer	M > 0 Perspective plot to be magnified by M. M < 0 Reduce by 1/ABS(M). M = 0 Write file movie.byu for use with AVS.
N1	1	integer	First cylinder to plot. (N1 > 0) (default = 1)
N2	1	integer	Last cylinder to plot. (N2 > N1) (default = 1)
EPS	1	real	Smallest distance between successive cylinders for which the second of the pair is to be drawn. The units of EPS are centimeters or inches as determined by card image 13000 in the control input. (default = 0)

(c) Notes:

The presence of card image 47000 causes the perspective plots to be generated.

- **Card 470ss (Optional)**

(a) Syntax:

0470ss, Zplot(1), Zplot(2), ..., Zplot(NZplot)

(b) Variables:

Variable	# Words	Type	Description
Zplot(i)	NZplot	real	Value of Z in the global coordinate system where an X-Y slice plot is to be generated. The units of Zplot(i) are centimeters or inches as determined by card image 013000 in the control input. The sequence number ss takes on values 01, 02, ..., 51.

(c) Notes:

If no X-Y slice plot is selected and plots are being generated, a default slice plot is generated. If $Z(0) < 0.0 < Z(NPZZ)$, the default is at $Z = 0.0$; otherwise, it is at $(Z(0) + Z(NPZZ)) / 2$.

- **Card 50000 (Optional)**

(a) Syntax:

50000, x_{min} , x_{max} , y_{min} , y_{max}

(b) Variables:

Variable	# Words	Type	Description
x_{min}	1	real	Minimum x value for x-y slice plots.
x_{max}	1	real	Maximum x value for x-y slice plots.
y_{min}	1	real	Minimum y value for x-y slice plots.
y_{max}	1	real	Maximum y value for x-y slice plots.

(c) Notes:

These values have units of centimeters or inches as determined by card image 13000 in control input. The default values are $\pm RADMAX$, the radius of the largest module zero cylinder. This card image provides a zoom plotting capability.

- **Card 480ss (Optional)**

(a) Syntax:

0480ss, Yplot(1), Yplot(2), ..., Yplot(NYplot)

(b) Variables:

Variable	# Words	Type	Description
Yplot(i)	NYplot	real	Value of Y in the global coordinate system where an X-Z slice plot is to be generated. The units of Yplot(i) are centimeters or inches as determined by card image 013000 in the control input. The sequence number ss takes on values 01, 02, ..., 51.

- **Card 490ss (Optional)**

(a) Syntax:

0490ss, Xplot(1), Xplot(2), ..., Xplot(NXplot)

(b) Variables:

Variable	# Words	Type	Description
Xplot(i)	NXplot	real	Value of X in the global coordinate system where a Y-Z slice plot is to be generated. The units of Xplot(i) are centimeters or inches as determined by card image 013000 in the control input. The sequence number ss takes on values 01, 02, ..., 51.

- **Card 57nnn (Optional)**

(a) Syntax:

57nnn, x, y, z, OPACITY, C₁, C₂, ..., C_N

(b) Variables:

Variable	# Words	Type	Description
x, y, z, OPACITY	4	real	If IColorModel on card image 40000 of control input = 1 for RGB (red, green, blue) then x, y, z are red, green, blue. If IColorMode = 2 for HSV (hue, saturation, value), then x, y, z are hue, saturation, value. (0 ≤ x, y, z; OPACITY ≤ 1.0)
C _i	N	integer	C _i are compositions to be colored with color nnn.

(c) Notes:

A single composition cannot be assigned multiple colors. Unassigned compositions receive the default color for HSV (x, y, z, OPACITY = 0, 0, 0.7, 0.15) or

RGB (x, y, z, OPACITY = 0.7, 0.7, 0.7, 0.15). See Chapter 14. Color number nnn takes on values 1, 2, ..., 255.

- **Card 46sss (Optional - For r-z Discrete Ordinate Source file)**

(a) Syntax:

```
46sss,  $\theta_0$ , SourceDensity(0),  $\theta_1$ , SourceDensity(1), ...,  $\theta_N$ ,
      SourceDensity(N)
```

(b) Variables:

Variable	# Words	Type	Description
θ_i	N+1	real	Azimuthal angles (in degrees) defining intervals for source density histogram. ($\theta_0 = 0$, $\theta_N = 360$).
SourceDensity (I)	N+1	real	Source density values for the corresponding intervals. (SourceDensity _i ≥ 0)

(c) Notes:

In the case of a cylindrical source from a discrete ordinate program, the azimuthal source distribution supplied on these card images is superimposed on that R-Z shape. The sequence number sss takes on values 001, 002, ..., 499.

The default shape is uniform in azimuthal angle θ .

- **Card 46sss (Optional - For x-y Discrete Ordinate Source file)**

(a) Syntax:

```
46sss,  $Z_0$ , SourceDensity(0),  $Z_1$ , SourceDensity(1), ...,  $Z_N$ ,
      SourceDensity(N)
```

(b) Variables:

Variable	# Words	Type	Description
Z_i	N+1	real	Axial z-values defining intervals for source density histogram. The units of Z_i are centimeters or inches as determined by card image 13000 in the control input. ($Z_i < Z_{i+1}$)
SourceDensity (i)	N+1	real	Source density values for the corresponding intervals. (SourceDensity(i) ≥ 0)

(c) Notes:

In the case of a planar source from a discrete ordinate program, the axial source distribution supplied on these card images is superimposed on that X-Y shape. The sequence number sss takes on values 501, 502, ..., 999.

The default shape is uniform in z.

Case separator - A / is placed in column 1 of the card image to indicate end of Module Zero input.

10.7 Initial Module Input

*Input for Initial Module #IM (Optional Comment card images preceded by *)

- **Card 630000 (Optional)**

(a) Syntax:

630000, ICNTCS

(b) Variables:

Variable	# Words	Type	Description
ICNTCS	1	integer	= 0 A Final Assembly disjoint from all other Final Assemblies in the Initial Module is not permitted. (default)
			= 1 A Final Assembly disjoint from all other Final Assemblies in the Initial Module is permitted. This option disables a valuable input check and should be used only with intentionally disconnected regions.

- **Card 6020 (Optional)**

(a) Syntax:

006020, IMNameIn, GeomFileSyn

(b) Variables:

Variable	# Words	Type	Description
IMNameIn	1	8 character	The name of the section in an input geometry file containing the initial module description.
GeomFileSyn	1	8 character	The synonym of the input geometry file (type 261) containing section IMNameIn.

(c) Notes:

If GeomFileSyn is not specified, the type 261 file present earliest on the list of synonyms on card image 1060 of control input is used.

If GeomFileSyn is specified, the first such file with synonym GeomFileSyn is used.

If card image 1060 is absent, the default synonym RCPGEOM comprises the list scanned.

The presence of card image 6020 causes the description of the initial module to be obtained from the specified file section except as overridden and/or extended by input card images.

- **Card 6030**

(a) Syntax:

6030, IMName

(b) Variables:

Variable	# Words	Type	Description
IMName	1	8 character	Name of this initial module section in output geometry (type 261) file.

(c) Notes:

If card image 6030 is absent and card image 6020 is present, the default value of IMName is IMNameIN from card image 6020.

If neither card image is present, the default value is IMiim where iim is the initial module number.

- **Card 63FFAs**

(a) Syntax:

63FFAs, $\pm$ IaP, VgP, VcP, AP, XfaP, YfaP, SfaP (for standard Final Assemblies)

63FFAs, $\pm$ IaP, VgP, VcP, AP, XfaP, YfaP, SfaP, $\pm$ IaS₁, VgS₁, VcS₁, XfaS₁, YfaS₁, ZfaS₁, AngDS₁, AngSS₁, AngRS₁, SfaS₁, DispComp₁; $\pm$ IaS₂, VgS₂, ... (for composite Final Assemblies)

(b) Variables:

Variable	# Words	Type	Description
$\pm$ IaP	1	integer	Primary Initial Assembly referenced. ($1 \leq \text{IaP} \leq \text{NIA}$)
+IaP			Standard orientation.
-IaP			Mirror image.
VgP	1	integer	Geometry variation of the Primary Final Assembly - 60° parallelogram geometry only. = 0 No variation (Required for rectangular geometry). = 1 Side 3 rotated 60° clockwise about the point of intersection of sides 2 and 3 (equilateral triangle or trapezoid).

Variable	# Words	Type	Description
VcP	1	integer	Number of the composition variation to be used in the Primary Final Assembly. ($0 \leq VcP \leq NCVR$) = 0 No variation.
AP	1	integer	Number of 60° or 90° rotations of the Primary Initial Assembly relative to the x-axis of the Initial Module coordinate system. The angle of orientation is $AP \cdot 60^\circ$ for parallelogram geometry ($0 \leq AP \leq 5$) and $AP \cdot 90^\circ$ for rectangular ($0 \leq AP \leq 3$).
XfaP, YfaP	2	real	Location of the Primary Final Assembly origin relative to the Initial Module coordinate system. The units of XfaP and YfaP are centimeters or inches as determined by card image 013000 in the control input.
SfaP	1	real	Share of source particles for Final Assembly FFA relative to all Final Assemblies of this Initial Module. ($SfaP \geq 0.0$)
$\pm IaS_i$ +IaS _i -IaS _i	NSEC	integer	Initial Assembly referenced for the ith Secondary Final Assembly. ($1 \leq IaS_i \leq NIA$) Standard orientation. Mirror image.
VgS _i	NSEC	integer	Geometry variation of the ith Secondary Final Assembly - 60° parallelogram geometry only. = 0 No variation (Required for rectangular geometry). = 1 Side 3 rotated 60° clockwise about the point of intersection of sides 2 and 3 (equilateral triangle or trapezoid).
VcS _i	NSEC	integer	Number of the composition variation to be used in the ith Secondary Final Assembly. ($0 \leq VcS_i \leq NCVR$) = 0 No variation.
XfaS _i , YfaS _i , ZfaS _i	3*NSEC	real	Location of the ith Secondary Final Assembly origin relative to the Primary Initial Assembly coordinate system. The units of XfaS _i , YfaS _i , and ZfaS _i are centimeters or inches as determined by card image 013000 in the control input.
AngDS _i , AngSS _i , AngRS _i	3*NSEC	real	Angles of the rotations of the ith Secondary Initial Assembly axes in degrees.
SfaS _i	NSEC	real	Fraction of source particles for Final Assembly FFA to be assigned to the ith Secondary Final Assembly. ($0.0 \leq SfaS_i \leq 1.0$) (default = 0.0) The fraction assigned to the Primary Final Assembly is $1 - \sum_i SfaS_i$.

Variable	# Words	Type	Description
DispComp _i	NSEC	integer	Composition in the Primary Final Assembly assumed to be displaced by the <i>i</i> th Secondary Final Assembly in volume and loading calculations. (default = 0; no volume compensation)

(c) Notes:

All Primary Final Assemblies of an Initial Module must have the same corner angle (60° or 90°).

Composite Final Assemblies provide the capability to overlay up to seven Initial Assemblies as Secondary Final Assemblies with arbitrary orientation totally inside another Initial Assembly, the Primary Final Assembly. The secondary Final Assemblies need not have the same corner angle, 60° or 90°, as the Primary Final Assembly.

FFA is the Final Assembly number. Final Assembly numbers must be consecutive starting with 001. NFA(IM) is the number of Final Assemblies defined on these card images. ($1 \leq \text{NFA(IM)} \leq 999$)

For each standard Final Assembly, card image series 63FFAs must contain exactly 7 items. A composite Final Assembly with only one Secondary Final Assembly may be described with 16, 17 or 18 items. The sequence number *s* takes on values 1, 2, ..., 9.

- **Card 660000 or 66000 (Optional - applies only to problems with one Final Assembly, one Initial Module, no Module Zero and no Final Modules)**

(a) Syntax:

66000, LBC or

660000, LBC

(b) Variables:

Variable	# Words	Type	Description
LBC	1	integer	Cell boundary condition. = 1 Reflection on all sides. (default) = 2 In a 60° rhombus, 120° rotational symmetry on the upper left adjacent boundaries and the lower right adjacent boundaries. In a square, 90° rotational symmetry on those boundaries. = 3 Reflection on the upper left adjacent boundaries and, in a 60° rhombus, 120° rotational symmetry on the lower right adjacent boundaries; in a square, 90° rotational symmetry on the lower right adjacent boundaries. = -1 180° rotational symmetry on $Y_{\max}$ surface.

- **Card 66FFA1 (Optional)**

(a) Syntax:

66FFA1, IfaBC, IfaSN

(b) Variables:

Variable	# Words	Type	Description
IfaBC	1	integer	Final Assembly to which all particles about to enter Final Assembly FFA are transferred. ($1 \leq \text{IfaBC} \leq \text{NFA(IM)}$)
IfaSN	1	integer	The side number of the side of Final Assembly IfaBC from which such particles will be leaving. ($1 \leq \text{IfaSN} \leq 4$)

(c) Notes:

Final Assembly IfaBC must be a representation of the same Initial Assembly as Final Assembly FFA. Final Assembly FFA and Final Assembly IfaBC must both have $\text{SfaP} = 0.0$ and $\text{VgP} = 0$.

The special boundary condition must also be applied to Final Assembly IfaBC. The values of IfaSN for the two Final Assemblies must differ by exactly two.

If $\text{IfaBC} = \text{FFA}$, then side IfaSN of Final Assembly FFA is reflecting.

In the very unusual case of combining a standard orientation and a mirror image final assembly as a boundary condition pair, -IfaSN is used.

In problems with no Module Zero and no Final Modules, side IfaSN of Final Assembly IfaBC must not be exterior.

These cards can be used to supply a variety of special boundary conditions.

- **Card 63FFA0 (Optional)**

(a) Syntax:

63FFA0, TRBiasP, CHBiasP, TRBiasS₁, CHBiasS₁, ...

(b) Variables:

Variable	# Words	Type	Description
TRBiasP, CHBiasP	2	integer	Bias values added, respectively, to all the TR and CH label values for all the fineblocks in the primary initial assembly referenced by final assembly FFA.
TRBiasS _i , CHBiasS _i	2-NSEC	integer	Bias values added, respectively, to all the TR and CH label values for all the fineblocks in secondary initial assembly i of final assembly FFA.

(c) Notes:

If the card image is not present, the bias values are set to zero.

- **Card 998 (Optional)**

(a) Syntax:

000998, ISaveInput

(b) Variables:

Variable	# Words	Type	Description
ISaveInput	1	integer	<p>= 0 Do not retain input from current case as basis for next case. (default)</p> <p>= 1 Retain input from current case as basis for next case and for all succeeding cases until turned off by card image 000998, 0 or 000998, -1.</p> <p>= -1 Retain input from current case as basis for next case only.</p>

(c) Notes:

In RCP01, input is not carried forward from input case to input case except by use of card image 000998. Initial Module input can be carried past the last Initial Module, so card 000998, 0 should be included with the last Initial Module case to prevent including those card images with the Final Modules. To carry data through a sequence of Initial Modules, the simplest approach is to include card image 000998, 1 with the card images describing the first such Initial Module and card image 000998, 0 with the last.

Case separator - A / is placed in column 1 of the input card image to indicate end of Initial Module #IM input.

10.8 Final Module Input

*Input for all Final Modules (Optional Comment card images preceded by *)

- **Card 650000 (Optional)**

(a) Syntax:

650000, IAutoRotation

(b) Variables:

Variable	# Words	Type	Description
IAutoRotation	1	integer	= 0 Final Module angles are used as provided on card images 65FFMs. (default)
			= 1 Automatically rotate the AngD, AngS, and AngR axes of each Final Module by Arctangent(YorgFM / XorgFM). This points the x-axis of each Final Module directly away from the absolute z-axis.

- **Card 6040 (Optional)**

(a) Syntax:

6040, FMNameIn, GeomFileSyn

(b) Variables:

Variable	# Words	Type	Description
FMNameIn	1	8 character	The name of the section in an input geometry file containing the final module descriptions.
GeomFileSyn	1	8 character	The synonym of the input geometry file (type 261) containing section FMNameIn.

(c) Notes:

If GeomFileSyn is not specified, the type 261 file present earliest on the list of synonyms on card image 1060 of control input is used.

If GeomFileSyn is specified, the first such file with synonym GeomFileSyn is used.

If card image 1060 is absent, the default synonym RCPGEOM comprises the list scanned.

The presence of card image 6040 causes the description of the final modules to be obtained from the specified file section except as overridden and/or extended by input card images.

- **Card 6050 (Optional)**

(a) Syntax:

6050, FMName

(b) Variables:

Variable	# Words	Type	Description
FMName	1	8 character	Name of Final Modules section in output geometry (type 261) file.

(c) Notes:

If card image 6050 is absent and card image 6040 is present, the default value of FMName is FMNameIn from card image 6040.

If neither card image is present, the default value is FMODS.

The card image is effective only if an output geometry file is being written.

- **Card 65FFMs**

(a) Syntax:

65FFMs, Iim, VCm, XorgFM, YorgFM, ZtransFM, AngD, AngS, AngR, SorcFM

(b) Variables:

Variable	# Words	Type	Description
Iim	1	integer	Initial Module referenced. ($1 \leq Iim \leq NIM$)
VCm	1	integer	Number of the composition variation to be used in Final Module FFM. This Final Module variation is applied after the Final Assembly variation. ($0 \leq VCm \leq NCVR$) = 0 No variation.
XorgFM, YorgFM	2	real	Coordinates in the Module Zero absolute system of the point to which the Initial Module origin is translated. The units of XorgFM and YorgFM are centimeters or inches as determined by card image 013000 in the control input. The initial z coordinate is 0.0.
ZtransFM	1	real	Translation along the Final Module z-axis after applying the rotations specified by AngD, AngS, and AngR. The units of ZtransFM are centimeters or inches as determined by card image 013000 in the control input.
AngD	1	real	The angle of rotation, in degrees, of Final Module FFM about the line in the Module Zero $Z = 0.0$ plane passing through (XorgFM, YorgFM, 0.0) and perpendicular to the projection of the x-axis of the Initial module on the $Z = 0.0$ plane. (Rotate on y-axis)

Variable	# Words	Type	Description
AngS	1	real	The angle of rotation, in degrees, of Final Module FFM about the line passing through (XorgFM, YorgFM, 0.0) and perpendicular to the plane formed by the AngD axis and the z-axis of the Initial Module. (Rotate on x-axis)
AngR	1	real	The angle of rotation, in degrees, of Final Module FFM about its z-axis. The AngD and AngS axes are not altered by this rotation. (Rotate on z-axis) Standard orientation puts the Initial Module axes parallel to the absolute axes. AngD, AngS, and AngR are measured counter-clockwise about their respective axes when looking toward the point of intersection of the Initial Module z-axis and the absolute Z = 0.0 plane.
SorcFM	1	real	Share of source particles for Final Module FFM relative to all Final Modules. (SorcFM $\geq$ 0.0)

(c) Notes:

FFM is the Final Module number. Final Module numbers must be consecutive starting with 001. NFM is the number of Final Modules defined on these card images. The sequence number s takes on values 1, 2, ..., 9. ($1 \leq \text{NFM} \leq 999$)

Final modules must be separated by 0.001 centimeters.

- **Card 64000s (Optional)**

(a) Syntax:

64000s, FACollFile(1), $\pm$ FACollFile(2), ..., $\pm$ FACollFile(n)

(b) Variables:

Variable	# Words	Type	Description
$\pm$ FACollFile(i)	n	integer	Sequential Final Assembly number of a Final Assembly in which collisions (except those occurring in compositions listed on card image 000004) are to be included on the Collision Files. If negative, also include all Final Assemblies whose sequential numbers lie between FACollFile(i-1) and FACollFile(i); in such a case, $0 \leq \text{FACollFile}(i-1) < \text{IFACollFile}(i)$. A negative number with magnitude larger than the total number of Final Assemblies is permitted to signal the inclusion of all beyond FACollFile(i-1). A Final Assembly's sequential number is obtained by adding its number within its Initial Module to the total number of Final Assemblies in lower numbered Initial Modules. If FACollFile(i) = 0, include collisions in Module Zero.

(c) Notes:

In problems with one Initial Module, no Module Zero, and no Final Modules, these card images are included in the final case input with the Initial Module input. The sequence number s takes on values 1, 2, ..., 9.

Defaults: In perturbation jobs, all collisions occurring in any Final Assembly or Module Zero are included in the Collision File. In jobs with region-edits, any collision will be included if it occurs in any Final Assembly, or Module Zero, or is included in any entity in which a region-edit region is defined. In other jobs, Collision Files will not be written unless card image series 64000s appears.

Card image series 64000s need not (and should not) be included unless Collision File post-processing other than RCP01 perturbation or Region-Edit re-editing is intended.

- **Card 8FFArr (Optional)**

(a) Syntax:

8FFArr, RegionName, Xmin, Xmax, Ymin, Ymax, Zmin, Zmax, IPorS

(b) Variables:

Variable	# Words	Type	Description
RegionName	1	character	Optional region name, up to 8 alphanumeric characters, of region-edit region rr of Final Assembly FFA. Default = REGNxxxx where xxxx is the region's sequential region number.
Xmin, Xmax	2	real	Left and right x-boundaries in the Initial Assembly coordinate system of region-edit region rr of Final Assembly FFA. $Xmin < Xmax$.
Ymin, Ymax	2	real	Lower and upper y-boundaries in the Initial Assembly coordinate system of region-edit region rr of Final Assembly FFA. $Ymin < Ymax$.
Zmin, Zmax	2	real	Bottom and top z-boundaries in the Initial Assembly coordinate system of region-edit region rr of Final Assembly FFA. $Zmin < Zmax$. The units of Xmin, Xmax, Ymin, Ymax, Zmin, and Zmax are centimeters or inches as determined by card image 013000 in the control input.
IPorS	1	integer	Optional Primary or Secondary Final Assembly indicator. = 0 Primary. (default) ≥ 1 Secondary.

(c) Notes:

In a Composite Final Assembly, if IPorS = 0, the region is defined in the Primary Final Assembly FFA exclusive of the Secondary Final Assembly. Similarly, if IPorS $\geq$ 1, the region is limited to the selected Secondary Final Assembly.

Each of these card images defines a region-edit region in the Final Assembly sequentially numbered FFA where a Final Assembly's sequential number is obtained by adding its number within its Initial Module to the total number of Final Assemblies in lower numbered Initial Modules. Each Final Assembly region of this type consists of all copies of it that occur in Final Modules that are instances of the Initial Module in which Final Assembly FFA is defined.

Each of these card images may contain 6, 7, or 8 items. RegionName and/or IPorS may be omitted, in which case their respective default values will be used. The region number rr takes on arbitrary values, 00, 01, ..., 99.

If FFA = 000, the regions are in Module Zero. Their coordinates are measured in the global right angle coordinate system. These regions may span Final Modules; however, only that portion of the region in Module Zero but not in any Final Module will be edited.

In problems with one Initial Module, no Module Zero, and no Final Modules, these card images are included in the final case input with the Initial Module input. The definition of a region-edit region in Final Assembly FFA (or Module Zero) causes all collisions in that Final Assembly (or Module Zero) to be recorded on Collision Files (except those occurring in compositions listed on card image 000004).

- **Card 9rrrrr (Optional)**

(a) Syntax:

9rrrrr, RegionName, JFM, JFA, Xmin, Xmax, Ymin, Ymax, Zmin, Zmax,
IPorS

(b) Variables:

Variable	# Words	Type	Description
RegionName	1	character	Optional region name, up to 8 alphanumeric characters, of general region-edit region rrr. Default = REGNxxxx where xxxx is the region's sequential region number.
JFM	1	integer	Final module in which general region-edit region rrrr is located. If JFM = 0, then the region is in Module Zero and includes any Final Module, or parts thereof, included within the region boundaries.
JFA	1	integer	Final Assembly within Final Module JFM in which general region-edit region rrrr is located. If JFM = 0, then JFA = 0 is required.

Variable	# Words	Type	Description
Xmin, Xmax	2	real	Left and right x-boundaries in the appropriate coordinate system of general region-edit region rrrr. $Xmin < Xmax$.
Ymin, Ymax	2	real	Lower and upper y-boundaries in the appropriate coordinate system of general region-edit region rrrr. $Ymin < Ymax$.
Zmin, Zmax	2	real	Bottom and top z-boundaries in the appropriate coordinate system of general region-edit region rrrr. $Zmin < Zmax$. The units of Xmin, Xmax, Ymin, Ymax, Zmin, and Zmax are centimeters or inches as determined by card image 013000 in the control input.
IPorS	1	integer	Optional Primary or Secondary Final Assembly indicator. = 0 Primary. (default) ≥ 1 Secondary.

(c) Notes:

In a Composite Final Assembly, if $IPorS = 0$, the region is defined in the Primary Final Assembly FFA exclusive of Secondary Final Assemblies. Similarly, if $IPorS \geq 1$, the region is limited to the selected Secondary Final Assembly.

Each of these card images defines a general region-edit region. Each card image may contain 8, 9, or 10 items. RegionName and/or IPorS may be omitted, in which case their respective default values will be used. The region number rrrr takes on arbitrary values 00000, 00001, ..., 99999.

If $JFM = 0$ and $JFA = 0$, the region is in Module Zero. Its coordinates are measured in the global right angle coordinate system. These regions may span Final Modules; the edit includes both Module Zero and any Final Module, or any parts thereof, within the region boundaries. The definition of such a region-edit region causes all collisions in any Final Module or in Module Zero to be recorded on Collision Files (except those occurring in compositions listed on card image 000004).

If $JFM > 0$ and $JFA = 0$, the region is in Final Module JFM. Its coordinates are measured in the corresponding Initial Module coordinate system (60° or 90°). If the region coordinates span any part of Module Zero, Module Zero is not included in the region. The definition of such a region-edit region causes all collisions in that Final Module or any other Final Module referencing the same Initial Module to be recorded in Collision Files (except those occurring in compositions listed on card image 000004).

If $JFM > 0$ and $JFA > 0$, the region is in Final Assembly JFA of Final Module JFM and is defined in either the Primary or selected Secondary Final Assembly but not both. Its coordinates are measured in the corresponding Initial Assembly coordinate system (60° or 90°). The definition of such a region-edit region causes all collisions in that Final Module or any other Final Module referencing the same Initial Module to be recorded in Collision Files (except those occurring in compositions listed on card image 000004).

In problems with one Initial Module, no Module Zero, and no Final Modules, these card images have JFM = 1. They are included in the final case input with the Initial Module input.

- **Card 7rrrrns (Optional)**

(a) Syntax:

7rrrr0s, Regname, $Z_{\min}$, $Z_{\max}$, X_1 , Y_1 , X_2 , Y_2 , ..., X_{No} , Y_{No}

7rrrrns, X_1 , Y_1 , ..., X_{Nn} , Y_{Nn}

(b) Variables:

Variable	# Words	Type	Description
Regname	1	8 character	Optional name of polygonal region rrrr. Default is REGNxxxx where xxxx is the sequential region number.
$Z_{\min}$, $Z_{\max}$	2	real	Minimum and maximum z-values for the polygonal cylinder's bounding region rrrr. Units are centimeters or inches as determined by card image 13000 in control input.
X_i , Y_i	$2 \cdot N_n$	real	Coordinates of the i th corner of polygon n of region rrrr. Units are centimeters or inches as determined by card image 13000 in control input.

(c) Notes:

The sequence number s takes on values 0, 1, ..., 9. The polygon number n takes on values 0, 1, ..., 9. The region number rrrr takes on values 0000, 0001, ..., 9999. Each polygonal region rrrr can comprise up to 10 polygons.

- **Card 800000s (Optional)**

(a) Syntax:

800000s, $Z_{\min}$, $Z_{\max}$, R_1 , R_2 , W , C_1 , C_2

(b) Variables:

Variable	# Words	Type	Description
$Z_{\min}$, $Z_{\max}$	2	real	Minimum, maximum z boundaries of regions. ($Z_{\min} < Z_{\max}$)
R_1 , R_2 , W , C_1 , C_2	5	real	Transformation variables. (defaults = 1, -1, 0, 0, 0)

(c) Notes:

This card image causes the definition of regions based on a PDQ08/REGPLT (type 262) file. The units of $Z_{\min}$, $Z_{\max}$, C_1 , and C_2 are centimeters or inches as determined by card image 13000 in control input. The units of W are radians.

The x, y coordinates in the file are transformed as follows:

$$x' = R_1 \cdot (x \cdot \cos(W) + y \cdot \sin(W)) + C_1$$

$$y' = R_2 \cdot (y \cdot \cos(W) - x \cdot \sin(W)) + C_2$$

- **Card 65FMM0 (Optional - depletion only)**

(a) Syntax:

65FMM0, TRBiasM, CHBiasM

(b) Variables:

Variable	# Words	Type	Description
TRBiasM, CHBiasM	2	integer	Bias values added, respectively, to all the TR and CH label values for all the fineblocks in the initial module referenced by final module FFM. (default = 0)

- **Card 610000 (Optional)**

(a) Syntax:

610000, IFluxEst

(b) Variables:

Variable	# Words	Type	Description
IFluxEst	1	integer	Estimator to be used for flux-at-a-point option. = 0 Gast estimator. (default) = 1 Pacer estimator. = 2 Hybrid estimator.

(c) Notes:

See Appendix P for a discussion of the flux-at-a-point feature.

- **Card 610sss**

(a) Syntax:

610sss, R_i , X_i , Y_i , Z_i , Δ_i (Gast estimator)
 610sss, R_i , X_i , Y_i , Z_i (Pacer estimator)
 610sss, R_i , X_i , Y_i , Z_i , $Frac_i$ (Hybrid estimator)

(b) Variables:

Variable	# Words	Type	Description
R_i	NDET	real	Radius of i th detector sphere. For Gast and PACER estimators this defines the sphere over which the volume averaged flux estimate is used. For the Hybrid estimator, it defines the sphere that separates the region of detailed tracking from the region where roulette is played to determine the contribution. Units are centimeters or inches as determined by card image 13000 in control input.
X_i, Y_i, Z_i	3-NDET	real	Coordinates of point detector i in module zero coordinates. Units are centimeters or inches as determined by card image 13000 in control input.
Δ_i	NDET	real	Number of mean free paths beyond R_i over which the Russian roulette survival probability declines by a factor of 2. If $\Delta_i < 0$, the roulette weight is set to 1.0.
$Frac_i$	NDET	real	$Frac_i \cdot R_i$ is the radius of an inner sphere inside of which the Gast volume averaged flux estimate is used.

(c) Notes:

The presence of any of these card images causes the flux-at-a-point option to be performed. (See Appendix P.) The sequence number sss takes on values 001, 002, ..., 999.

End of input indicator - A . is placed in column 1 of the input card image to indicate end of input.

10.9 Special Source Starts

These special source start options apply only to the energy and directional components of source particles in fixed source problems. They are specified by selecting a value of LOPT (item 3 of card image 1) and including the appropriate 071mms and 072mms card images in the input control card image (first case input). In all of these cases, the angular distribution of the source will be relative to the axis chosen using LOPT and applies to the Initial Assembly coordinate system. For each value of LOPT, 071mms card images not required are forbidden. These options do not apply to linked calculations.

a. Slab P-3 Source Spectrum

- LOPT = 1 - Source axis is parallel to the Initial Assembly x-axis (along $\mu = 1.0$)
- LOPT = 2 - Source axis is parallel to the Initial Assembly y-axis (along $\gamma = 1.0$) perpendicular to the Initial Assembly x-z plane even for 60° parallelogram problems.
- LOPT = 3 - Source axis is parallel to the Initial Assembly z-axis (along $\eta = 1.0$)

- **Card 71mms**

(a) Syntax:

071mms, P0(mm), P1(mm), P2(mm), P3(mm)

(b) Variables:

Variable	# Words	Type	Description
P0(mm), P1(mm), P2(mm), P3(mm)	4	real	The first four Legendre components of the flux per unit lethargy in multigroup mm. (P0(mm) $\geq$ 0.0.)

(c) Notes:

For neutron jobs, these card images may be included for each multigroup mm = 1, 2, ..., MUFT+1 where group MUFT+1 is the thermal neutron group. For photon jobs, they may be included for groups mm = 1, 2, ..., MUFT. Any group for which these card images are absent will use default values of 0.0. A card image must be present for at least one group. MUFT $\leq$ 57.

RCP01 computes a normalization factor which is the J+ current computed from the input flux components. The angular distribution of the source will be relative to the axis chosen using LOPT and applies to the Initial Assembly coordinate system. The sequence number s takes on values 1, 2, 3.

b. Monodirectional - Arbitrary Spectrum

- LOPT = 4 - Source axis is parallel to the Initial Assembly x-axis (along $\mu = 1.0$)
- LOPT = 5 - Source axis is parallel to the Initial Assembly y-axis (along $\gamma = 1.0$) perpendicular to the Initial Assembly x-z plane even for 60° parallelogram problems.
- LOPT = 6 - Source axis is parallel to the Initial Assembly z-axis (along $\eta = 1.0$)
- Card image 077001 can be used to override the axis selection.

- **Card 71mm1**

(a) Syntax:

071mm1, S0(mm)

(b) Variables:

Variable	# Words	Type	Description
S0(mm)	1	real	The source density per unit lethargy in multigroup mm. (S0(mm) $\geq$ 0.0).

(c) Notes:

For neutron jobs, this datum may be included for each multigroup mm = 1, 2, ..., MUFT+1 where group MUFT+1 is the thermal neutron group. For photon jobs, they may be included for groups mm = 1, 2, ..., MUFT. Any group for which this datum is absent will use a default value of 0.0. A card image must be present for at least one group. The value for group MUFT+1 (thermal) is the integral of the source density over thermal energies. MUFT $\leq$ 57.

- **Card 72mm1 (Neutron only)**

(a) Syntax:

072mm1, Sth(mm)

(b) Variables:

Variable	# Words	Type	Description
Sth(mm)	1	real	The source density per unit energy in thermal subgroup mm. (Sth(mm) $\geq$ 0.0). This datum may be included for each thermal subgroup mm = 1, 2, ..., MPT. Any subgroup for which this datum is absent will use a default value of 0.0. MPT $\leq$ 25.

(c) Notes:

The total thermal source is specified by S0(MUFT+1). The Sth(mm) further subdivide that source into the thermal subgroups. If no values of Sth(mm) are provided, the thermal source is flat over the entire thermal group.

c. **Monodirectional - Monoenergetic or flat**

LOPT = 7 - Source axis is parallel to the Initial Assembly x-axis (along $\mu = 1.0$)

LOPT = 8 - Source axis is parallel to the Initial Assembly y-axis (along $\gamma = 1.0$) perpendicular to the Initial Assembly x-z plane even for 60° parallelogram problems.

LOPT = 9 - Source axis is parallel to the Initial Assembly z-axis (along $\eta = 1.0$)

Card image 077001 can be used to override the axis selection.

- **Card 71011, 71021**

(a) Syntax:

071011, Es

071021, E_{min}

(b) Variables:

Variable	# Words	Type	Description
Es	1	real	Starting energy in electron volts. ($E_s \geq 0.0$).
E _{min}	1	real	Minimum energy for flat spectrum in E_s to E_{min} . $E_{min} \leq E_s$. (default = E_s)

(c) Notes:

All particles will be assigned energy E_s and direction as specified by LOPT. For a flat spectrum, energies will be selected uniformly in $E_s \geq E \geq E_{min}$.

d. **Conical Shell - Arbitrary Spectrum**

LOPT = 10 - Source axis is parallel to the Initial Assembly x-axis (along $\mu = 1.0$)

LOPT = 11 - Source axis is parallel to the Initial Assembly y-axis (along $\gamma = 1.0$) perpendicular to the Initial Assembly x-z plane even for 60° parallelogram problems.

LOPT = 12 - Source axis is parallel to the Initial Assembly z-axis (along $\eta = 1.0$)

Card image 077001 can be used to override the axis selection.

- **Card 71mm1**

(a) Syntax:

071011, S0(1), $\mu 0$, $\mu 1$

071mm1, S0(mm)

(b) Variables:

Variable	# Words	Type	Description
S0(mm)	1	real	The source density per unit lethargy in multigroup mm. ($S0(mm) \geq 0.0$). This datum must be provided for group 1 and may be included for each multigroup $mm = 2, 3, \dots$, MUFT+1 for neutron jobs or $mm = 2, 3, \dots$, MUFT for photon jobs. Any group for which this datum is absent will use a default value of 0.0. The value for group MUFT+1 (thermal) is the integral of the source density over thermal energies. $MUFT \leq 57$.
$\mu 0$	1	real	The cosine of the angle from the axis of the cone to the outer surface of the cone. ($-1.0 \leq \mu 0 \leq 1.0$).
$\mu 1$	1	real	The cosine of the angle from the axis of the cone to the inner surface of the cone. (default = 1.0 which represents a full conical source.) If only two items appear on this card image, the default value of $\mu 1$ is used. ($\mu 0 \leq \mu 1 \leq 1.0$).

(c) Notes:

The directions of source particles are selected with cosines between $\mu 1$ and $\mu 0$ relative to the selected source axis. The axis of the cone will be parallel to the axis chosen using LOPT. An isotropic source can be selected by setting $\mu 0 = -1.0$ and $\mu 1 = +1.0$.

- **Card 72mm1 (Neutron only)**

(a) Syntax:

072mm1, Sth(mm)

(b) Variables:

Variable	# Words	Type	Description
Sth(mm)	1	real	The source density per unit energy in thermal subgroup mm. ($Sth(mm) \geq 0.0$). This datum may be included for each thermal subgroup $mm = 1, 2, \dots$, MPT. Any subgroup for which this datum is absent will use a default value of 0.0. $MPT \leq 25$.

(c) Notes:

The total thermal source is specified by S0(MUFT+1). The Sth(mm) further subdivide that source into the thermal subgroups. If no values of Sth(mm) are provided, the thermal source is flat over the entire thermal group.

e. **Conical Shell - Monoenergetic or flat**

LOPT = 13 - Source axis is parallel to the Initial Assembly x-axis (along $\mu = 1.0$)

LOPT = 14 - Source axis is parallel to the Initial Assembly y-axis (along $\gamma = 1.0$) perpendicular to the Initial Assembly x-z plane even for 60° parallelogram problems.

LOPT = 15 - Source axis is parallel to the Initial Assembly z-axis (along $\eta = 1.0$)

Card image 077001 can be used to override the axis selection.

• **Card 71011, 71021**

(a) Syntax:

071011, Es, μ_0 , μ_1

071021, $E_{\min}$

(b) Variables:

Variable	# Words	Type	Description
Es	1	real	Starting energy in electron volts. $E_s > 0.0$.
μ_0	1	real	The cosine of the angle from the axis of the cone to the outer surface of the cone. $(-1.0 \leq \mu_0 \leq 1.0)$
μ_1	1	real	The cosine of the angle from the axis of the cone to the inner surface of the cone. (default = 1.0 which represents a full conical source.) If only two items appear on this card image, the default value of μ_1 is used. $(\mu_0 \leq \mu_1 \leq 1.0)$
$E_{\min}$	1	real	Minimum energy for flat spectrum in E_s to $E_{\min}$. $E_{\min} \leq E_s$. (default = E_s)

(c) Notes:

All particles will be assigned energy E_s . For a flat spectrum, energies will be selected uniformly in $E_s \geq E \geq E_{\min}$. The directions of source particles are selected with cosines between μ_1 and μ_0 relative to the selected source axis. An isotropic source can be selected by setting $\mu_0 = -1.0$ and $\mu_1 = +1.0$.

11 OUTPUT DESCRIPTION

11.1 Neutron Iteration Edits

For these edits, all results edited by composition are also edited by region if edit regions are defined as described in Section 11.3.3.

RCP can produce a short edit after each iteration k is complete. An input parameter determines the iteration frequency with which this edit is generated. The edited quantities for neutron fixed source and eigenfunction calculations are defined as follows:

1. Composition Absorption:

$$\bar{A}_j^k = \frac{1}{k} \sum_{c_j} \varphi_{c_j} \Sigma_{aj} \sum_{k'=0}^k N^{k'}$$

where the summation over c_j is over all collisions in composition j in iteration 0 to k inclusive, where Σ_{aj} is the total absorption cross section for composition j at the neutron incident energy for collision c_j , and where $\sum_{k'=0}^k N^{k'}$ is the total number of histories in iterations 0 to k inclusive. (In the eigenfunction calculation, all quantities involving $\sum_{k'=0}^k N^{k'}$ will be replaced by $\sum_{k'=1}^k N^{k'}$ since iteration 0 results are not included in the sum.)

2. Composition Absorption Error:

A discussion of total probable errors is in Section 7.1. In fixed source calculations, this quantity is labeled as STAT P.E. For eigenfunction calculations, the estimate of serial correlation ρ_k is included, and this quantity is labeled TOT P.E. RCP allows the option to edit either the 50% confidence interval, i.e., P.E., or a standard deviation, i.e., SIG, or a 95% confidence interval, i.e., 0.95E. The option defaults to P.E. .

3. Composition Production Fraction:

$$\overline{PF}_j^k = \frac{PF_j^k}{\sum_j PF_j^k}, \text{ where}$$

$$PF_j^k = \frac{1}{\sum_{k'=0}^k N^{k'} c_j} \sum_{c_j} \Phi_{c_j} \left(\sum_i v^i \Sigma_{ff}^i \right).$$

Here the summation over c_j is over all collisions in composition j in iterations 0 to k inclusive, while $\sum_i (v^i \Sigma_{ff}^i)$ is a summation over all nuclides i in composition j of the product of neutrons produced per fission for nuclide i , v^i , and the fission cross section for nuclide i in composition j , Σ_{ff}^i . (Again, v^i and Σ_{ff}^i are values at the neutron incident energy for collision c).

4. Composition Production Fraction Error:

This error is computed for fixed source and eigenfunction calculations according to the procedures described in Section 7.1. Again the choice of interval is under user control as discussed in 2 above.

5. Volume Density of the Neutron Production:

Using the PF_j^k defined in 3 above and using the volume of composition j , V_j , the neutron production per cubic centimeter is calculated and edited as:

$$(\text{PROD/CC})_j^k = \frac{PF_j^k}{V_j}$$

6. Composition Fission:

$$\overline{F}_j^k = \frac{1}{\sum_{k'=0}^k N^{k'} c_j} \sum_{c_j} \Phi_{c_j} \Sigma_{ff}$$

where the summation over c_j is over all collisions in composition j in iterations 0 to k inclusive, and where Σ_{ff} is the total fission cross section in composition j evaluated at the neutron incident energy.

7. Composition Fission Fraction:

$$\bar{F}_j^k = \frac{F_j^k}{\sum_j F_j^k}$$

8. Composition Error Factors:

EFAC-A and EFAC-P are the factors by which the absorption and production uncertainties are expanded to produce "total errors" as explained in Section 7.1.

Other quantities edited for iteration k include:

9. Total Multiplication Factor:

$$\overline{MF}^k = \sum_j PF_j^k$$

where PF_j^k is given in 3 above.

10. Total Multiplication Factor Error:

This error is calculated according to the procedures described in Section 7.1. Again the choice of the interval is under user control. In an eigenfunction problem the multiplication factor serial correlation coefficient ρ_k and error factor are additionally edited.

11. Iteration Multiplication Factor:

The contribution by composition j is given by $\overline{mf}_j^k = \frac{1}{N^k} \sum_{c_j} \varphi_{c_j} \sum_i (v^i \Sigma_{jj}^i)$ where the summation over collisions c_j in composition j is in iteration k only.

The iteration multiplication factor is given by

$$\overline{mf}^k = \sum_j \overline{mf}_j^k$$

12. Total Fissions:

$$\bar{F}^k = \sum_j \bar{F}_j^k$$

13. Nu Bar:

$$\bar{\nu}^k = \frac{\overline{MF}^k}{\bar{F}^k}$$

14. Total Leakage:

L^k is an estimate of the neutrons which escape the system either radially or axially. The error on the leakage is additionally edited.

15. Total Absorption:

$$TA^k = \sum_j \bar{A}_j^k$$

In addition to the above accumulative counters over iterations 0 to k inclusive, quantities involving the neutron starts for iteration $k+1$ and the total source over iterations 0 to $k+1$ inclusive are edited. These quantities which are edited by composition j for iteration $k+1$ are summarized next:

16. Neutron starts (for iteration $k+1$):

N_j^{k+1} for an eigenfunction calculation is obtained using the semi-systematic sampling procedure defined in Chapter 6, where the value of the composition neutron production in iteration k , i.e., $\bar{mf}_j^k$ is the source to iteration $k+1$. In Chapter 6 set $SP_j^{k+1} = \bar{mf}_j^k$, where $\bar{mf}_j^k$ is given in 10. above. In a fixed source problem, the iterations are not connected in this manner and a random sampling is used for source starts by composition, i.e., $S_j^{k+1} = S_j^0$, where S_j^0 is the input source density by composition.

17. Total Source:

Starts for iteration $k+1$, i.e., $\sum_j N_j^{k+1}$, is edited. Total starts over iterations 1 to k inclusive is additionally edited.

18. Site Counts:

The counts of sites recorded on fission, fission/capture, trapping surface, or collision files are also edited.

11.2 Neutron Group and Few Group Edits

Few group edits are optional in RCP. The most detailed edit consists of the absorption and neutron production per nuclide i , per composition j , and per few group f where a few group is an integral number of RCP groups. Arbitrary few groups above thermal are permitted where the RCP group numbers to use as break points are described in the input. The thermal group is always edited separately and an additional edit is a total collection over all few groups fast and thermal. Few group f extends from RCP group $g^{f-1}+1$ to g^f . Users may select separately for

fast few groups, the thermal group, and for the edit over all groups whether to generate the edits by nuclide and by composition.

The fundamental quantities for neutron fixed source and eigenfunction calculations which are edited per few group f are the absorption and neutron production per nuclide i per composition j as well as the flux for composition j . These quantities are obtained by accumulating the contribution of each neutron collision as all neutron histories in the iterations are followed through few group f . This accumulation is given by

$$\begin{aligned} A_j^{ig} &= A_j^{ig} + \varphi_{c_j} \Sigma_a^i \\ P_j^{ig} &= P_j^{ig} + \varphi_{c_j} (v^i \Sigma_f^i) \\ \varphi_j^g &= \varphi_j^g + \varphi_{c_j} \end{aligned}$$

where Σ_a^i and Σ_f^i are the macroscopic absorption and fission cross sections per nuclide i in composition j , respectively. v^i is the neutrons produced per fission event in nuclide i ; and φ_{c_j} is the neutron flux estimate at collision c_j in few group f .

$$\varphi_{c_j} = \frac{W_t}{\Sigma_T} \text{ for } \frac{\Sigma_a}{\Sigma_T} \text{ estimators (terminating or non-terminating)}$$

and

$$\varphi_{c_j} = \frac{W_t}{\Sigma_a} \text{ for binomial estimator}$$

where w_t is the neutron weight at the incident energy, Σ_T^j is the total cross section for composition j , i.e.,

$$\Sigma_T = \Sigma_a + \sum_i \Sigma_s^i, \text{ where } \Sigma_s^i \text{ is the scattering cross section for nuclide } i$$

and

$$\Sigma_a = \sum_i \Sigma_a^i \text{ is the total absorption cross section.}$$

(Values of all cross sections are, of course, at the neutron incident energy E_0 for collision c_j .) There are two other quantities which are accumulated and are used later in the RCP estimates of the diffusion coefficient. These two quantities are given in terms of the collision density as:

$$C_j^f = C_j^f + \Sigma_j^T \varphi_{c_j}$$

and

$$T_j^f = T_j^f + \varphi_{c_j}(\Sigma_j^T - \Sigma_{sj}^T \mu^{i(c_j)})$$

where $i(c_j)$ is the scattering nuclide for collision c_j , Σ_{sj}^T is the total scattering cross section for composition j , and $\mu^{i(c_j)}$ is the cosine of the scattering angle in the lab system resulting from scattering with nuclide $i(c_j)$. Again values used above are at the neutron incident energy for collision c_j .

All edited quantities are normalized by the total number of histories as follows:

$$\begin{aligned}\bar{A}_j^{if} &= \frac{A_j^{if}}{\sum_{k'=0}^k N^{k'}} \\ \bar{P}_j^{if} &= \frac{P_j^{if}}{\sum_{k'=0}^k N^{k'}} \\ \bar{\varphi}_j^f &= \frac{\varphi_j^f}{\sum_{k'=0}^k N^{k'}}\end{aligned}$$

The denominator is the total of all histories from 0 to k inclusive. (In an eigenfunction problem, this summation is replaced by $\sum_{k'=1}^k N^{k'}$ since iteration 0 is dropped in the accumulative sum.)

Associated with each edited quantity are counters which accumulate the “squares” of the contributions to the absorption rates per history. These “square” counters are needed to obtain the error estimates as described in Section 7.1. This is the only direct calculation of uncertainties in RCP. If absorption rates are to be accumulated over few groups, over compositions, over nuclides, or over any combination of these, the assumption is made that the quantities being accumulated are statistically independent. Hence, the uncertainty on the accumulation is the square root of the sum of the squares of individual uncertainties.

In addition to $\bar{A}_j^{if}$, $\bar{P}_j^{if}$, and their error estimates, macroscopic cross sections per nuclide per composition j are edited using the following relations:

$$\bar{\Sigma}_{aj}^{if} = \frac{\bar{A}_j^{if}}{\bar{\varphi}_j^f}$$

$$\bar{\nu}\bar{\Sigma}_{fj}^{if} = \frac{\bar{P}_j^{if}}{\bar{\varphi}_j^f}$$

where $\bar{\varphi}_j^f$ is the detailed integrated flux per composition j in few group f .

Following the nuclide edits per composition, there is an edit over all nuclides i in the composition. This edit consists of

$$\bar{A}_j^f = \sum_i \bar{A}_j^{if}$$

$$\bar{P}_j^f = \sum_i \bar{P}_j^{if}$$

Along with these, slowing down per composition j per few group f , $\bar{Q}_j^f$, is edited. In terms of the neutron parameters available at collision c_j , $\bar{Q}_j^f$ is obtained by the following process. Let E^f be the lower energy cutpoint of few group f . Define per collision c_j in composition j ,

$$Q_j^f = Q_j^f + W$$

where $W = W_i$ if $E_0 > E^f$ and $E < E^f$, = 0 otherwise. Q_j^f is also normalized by the total number of neutrons in iteration 0 to k inclusive. Thus,

$$\bar{Q}_j^f = \frac{Q_j^f}{\sum_{k'=0}^k N^{k'}}$$

The last edit per few group is a macroscopic cross section edit per composition j . The macroscopic cross sections are defined as follows:

$$\bar{\Sigma}_{aj}^f = \frac{\bar{A}_j^f}{\bar{\varphi}_j^f}$$

$$\bar{\nu}\bar{\Sigma}_j^f = \frac{\bar{P}_j^f}{\bar{\varphi}_j^f}$$

$$\bar{\Sigma}_{R_i}^f = \frac{\bar{Q}_j^f}{\bar{\varphi}_j^f}$$

Two estimates of the diffusion coefficient are calculated and edited. These are

$$\bar{D}_j^f (\text{free flight}) = \frac{1}{3\bar{\Sigma}_{T,j}^f}$$

where

$$\bar{\Sigma}_{T,j}^f = \frac{C_j^f / \sum_{k'=0}^k N^{k'}}{\bar{\varphi}_j^f}$$

and

$$\bar{D}_j^f (\text{transport}) = \frac{1}{3\bar{\Sigma}_{tr,j}^f}$$

where

$$\bar{\Sigma}_{tr,j}^f = \frac{T_j^f / \sum_{k=0}^k N^k}{\bar{\varphi}_j^f}$$

A nuclide absorption edit over all compositions and over all few groups is also edited by RCP; that is,

$$\begin{aligned}\bar{A}^i &= \sum_{j,f} \bar{A}_j^{if} \\ \bar{P}^i &= \sum_{j,f} \bar{P}_j^{if}\end{aligned}$$

Following the neutron few group edits are the local energy depositions from neutron reactions over all RCP groups. These optional edits are per nuclide per composition and are very useful in determining local neutron heating rates.

Three quantities are accumulated at each collision c as all neutrons in the iteration are followed through all RCP groups. These quantities represent the neutron heating resulting from elastic scattering and absorption, $H_{ea,j}^i$; inelastic scattering events, $H_{ig,j}^i$; and the heating associated if nuclide i is fissionable, $H_{\beta,j}^i$. This latter term is the heating due to fission fragments and beta decay. The accumulation per collision is performed as follows

$$\begin{aligned}
 H_{ea,j}^i &= H_{ea,j}^i + (\Sigma_a \phi) c_j E_0 && \text{for } i = i_a \text{ in } j, \\
 H_{ea,j}^i &= H_{ea,j}^i + (1 - \delta_s) W_t (E_0 - E) && \text{for } i = i_s \text{ in } j, \\
 H_{ig,j}^i &= H_{ig,j}^i + \delta_s [2(W_{t_0} - (\Sigma_a \phi)_{c_j}) - W_t] (E_0 - E) && \text{for } i = i_s \text{ in } j, \\
 H_{f\beta,j}^i &= H_{f\beta,j}^i + \delta_a (\Sigma_a \phi)_{c_j} 1.7562(10^8) && \text{for } i = i_a \text{ in } j,
 \end{aligned}$$

where all quantities have been defined in the description of the neutron collision file (Section 8.6.1).

The edited quantities are, of course, normalized by the number of histories from iterations 0 to k inclusive to yield neutron heating rates in e.v. per neutron born in fission. That is,

$$\begin{aligned}
 \bar{H}_{ea,j}^i &= \frac{H_{ea,j}^i}{\sum_{k'=0}^k N^{k'}}, \\
 \bar{H}_{ig,j}^i &= \frac{H_{ig,j}^i}{\sum_{k'=0}^k N^{k'}}, \\
 \bar{H}_{f\beta,j}^i &= \frac{H_{f\beta,j}^i}{\sum_{k'=0}^k N^{k'}}.
 \end{aligned}$$

Following the nuclide edits per composition, there is an edit over all nuclides in the composition. That is

$$\begin{aligned}
 \bar{H}_{ea,j} &= \sum_i \bar{H}_{ea,j}^i \\
 \bar{H}_{ig,j} &= \sum_i \bar{H}_{ig,j}^i
 \end{aligned}$$

and

$$\bar{H}_{f\beta,j} = \sum_i \bar{H}_{f\beta,j}^i$$

Then an additional edit which is the energy deposition per nuclide summed over all compositions is printed. That is

$$\begin{aligned}\bar{H}_{ea}^i &= \sum_j \bar{H}_{ea,j}^i \\ \bar{H}_{ig}^i &= \sum_j \bar{H}_{ig,j}^i \\ H_{f\beta}^i &= \sum_j \bar{H}_{f\beta,j}^i\end{aligned}$$

and

$$\bar{H}^i = \bar{H}_{ea}^i + \bar{H}_{ig}^i + \bar{H}_{f\beta}^i$$

11.3 Additional Optional Neutron Edits in RCP01

Other edits available in RCP01 include: 1) Calculation of the heterogeneous resonance integral by nuclide i and by few group f ; 2) a nuclide absorption edit by few group; 3) region-wise edits; and 4) a special edit involving ratios of reaction types. Each of these edits is described below.

11.3.1 Heterogeneous Resonance Integral Edit

This edit is provided on option per nuclide i and per few group g . These resonance integrals are a result of nuclide resonance absorption over the entire RCP calculation (normally these integrals would be of interest only when the RCP calculation is of a lattice type geometry, but the procedure used is relatively simple and integrals are edited independently of the geometry). The heterogeneous resonance integrals obtained in RCP are absorption rate resonance integrals; the means of converting these integrals, when computed for a lattice, to the more usual heterogeneous resonance integrals in barns is described later. The absorption rate heterogeneous resonance integral for nuclide i in group g , $RI_{(het)}^i$, is defined here as the group g absorption for nuclide i with all the effects of lethargy dipping in the slowing-in-source removed. This removal is approximately accomplished through the assumption that, within group g , the smooth and resonance absorptions are statistically intermingled, i.e., the smooth and resonance absorptions interfere with each other as though they had constant absorption cross sections. Under this assumption the ratio of the $RI_{(het)}^i$'s, in group g , for any two nuclides, is given by the ratio of the corresponding absorption rates. Also, under this assumption, the lethargy dipping of the slowing-in-source is removed in a manner made evident by the following argument. Let group g be composed of h sub-groups. Let each sub-group be of such a size that ΔA neutrons would be absorbed if there were no lethargy dipping prior to the top of the sub-group. Thus the total escape probability without the effect of dipping, say p_0 , is given by

$$p_0 = 1 - h\Delta A = 1 - A$$

The escape probability including the effect of lethargy dipping, say p , is given by

$$p = (1 - \Delta A)^h = (1 - \Delta A)^{\frac{A}{\Delta A}}$$

Upon taking the limit as $\Delta A \rightarrow 0$, we have $p = e^{-A}$.

Hence if A is the absorption without lethargy dipping, then $1 - e^{-A}$ is the absorption with lethargy dipping. The details of this method of accounting for lethargy dipping to obtain $RI^{ig}(\text{het})$ are as follows: Define,

$$\begin{aligned}\bar{A}^{ig}(\text{sm}) &= \sum_j \bar{A}_j^{ig}(\text{sm}) \\ \bar{A}^{ig}(\text{res}) &= \sum_j \bar{A}_j^{ig}(\text{res}) \\ \bar{A}^{ig} &= \bar{A}^{ig}(\text{sm}) + \bar{A}^{ig}(\text{res})\end{aligned}$$

that is, $\bar{A}^{ig}(\text{res})$ and $\bar{A}^{ig}$ are the resonance and total absorption, respectively, for nuclide i in group g . Let the overall escape probability to the top of group g be p^g , thus

$$p^g = 1 - \sum_{g=1}^{g-1} \sum_i \bar{A}^{ig}.$$

We may define a quantity R^g such that

$$\sum_i \bar{A}^{ig} = p^g (1 - e^{-R^g})$$

or

$$R^g = -\ln \left(1 - \frac{\sum_i \bar{A}^{ig}}{p^g} \right).$$

The edited absorption rate heterogeneous resonance integral for nuclide i in RCP group g follows, i.e., $RI^{ig}(\text{het})$ becomes

$$RI^{ig}(\text{het}) = R^g \frac{\bar{A}^{ig}(\text{res})}{\sum_i \bar{A}^{ig}}$$

Total heterogeneous resonance integrals, i.e., sum over all groups, is also edited for nuclide i using

$$RI^i(\text{het}) = \sum_g RI^{ig}(\text{het})$$

If the RCP calculation is for a lattice geometry, and if it is desired to convert the absorption rate resonance integral to barns, then the following applies. The heterogeneous resonance integral in barns is defined as the lethargy integrated absorption cross section required to produce in a homogenized medium the same amount of absorption as actually takes place in the resonances. The absorption rate heterogeneous resonance integral per nuclide i in RCP01 is a lethargy integrated absorption rate with all effects of lethargy dipping removed including that due to smooth absorption. Thus if we divide this integral by the flux level per unit lethargy that would exist in the absence of all absorption, and further divide this integral by the homogenized atom density ($\frac{\text{atoms}}{\text{barn-cm}}$) for nuclide i , N^i , then we obtain the desired heterogeneous resonance integral in barns. The flux level per unit lethargy in the absence of all absorption is the “asymptotic” flux over the resonance energy range which is a constant per unit lethargy of magnitude, $\frac{1}{\bar{\xi}\Sigma_s}$, where Σ_s is an energy independent homogenized total scattering cross section and $\bar{\xi}$ is an effective lethargy gain per collision given by

$$\bar{\xi} = \frac{\sum_i \xi^i \Sigma_s^i}{\sum_i \Sigma_s^i}$$

where ξ^i is the mean lethargy gain per collision with nuclide i . That is we may write

$$RI^i(\text{het})_{\text{barns}} = \frac{RI^i(\text{het})\bar{\xi}\Sigma_s}{N^i}.$$

11.3.2 Nuclide Absorption Rate Edit by Few Groups

This edit is optional and is similar to the usual few group edit discussed previously in Section 11.2 with the exception that absorption rates per nuclide i are summed over all compositions for each few group f . For each f RCP will edit total absorption by nuclide i , and neutron production by nuclide i as follows:

$$\begin{aligned}\bar{A}^{if} &= \sum_j \bar{A}_j^{if} \\ \bar{P}^{if} &= \sum_j \bar{P}_j^{if}\end{aligned}$$

Additionally RCP edits a summation over all groups except thermal, i.e.,

$$\begin{aligned}\bar{A}^i &= \sum_{f' \neq \text{thermal}} \bar{A}^{if'} \\ \bar{P}^i &= \sum_{f' \neq \text{thermal}} \bar{P}^{if'}\end{aligned}$$

The thermal group is edited separately and the last edit is a summation of all groups including thermal, i.e.,

$$\begin{aligned}\bar{A}^i &= \sum_f \bar{A}^{if} \\ \bar{P}^i &= \sum_f \bar{P}^{if}\end{aligned}$$

11.3.3 Regionwise Edits

All edits previously described were obtained by composition and therefore limited to the maximum number of compositions one can fit into allowable core storage. In many nuclear design calculations, particularly those of a three dimensional full core geometry, more editing in addition to compositions is required. The region edit capability permits the user, on option, to construct region edits without the need for more compositions.

The basic geometry input to RCP remains unchanged, i.e., the initial assembly, the initial module obtained through final assemblies, module zero, and final modules described earlier are used. The only additional input for the region edit option is a definition of the edit regions. Several types of edit regions are permissible. They include: 1) regions by final assembly, 2) module zero regions, 3) regions in particular final modules, 4) regions in the initial module coordinate system, and 5) regions in the absolute right angle coordinate system. All these edit regions are parallelepipeds with each side parallel to one pair of the particular coordinate axes, i.e., x - y , x - z , or y - z . Thus an edit region is uniquely defined by

$$X_1, X_2, Y_1, Y_2, Z_1, Z_2$$

where x_1, x_2 , etc. for regions by final assembly are measured in the local coordinate system of the particular initial assembly; x_1, x_2 , etc. for module zero regions are in the absolute right angle coordinate system. Similarly, for 3) above, if the region is defined for a particular final assembly in a particular final module, the coordinates of that region are in the local coordinate system of the particular initial assembly; for a particular final module region edit, i.e., collection over all final assemblies cut by the region, the coordinates are in the initial module coordinate system; and regions defined in the absolute right angle system, i.e., collections over all final modules and module zero cut by the region, the coordinates are in the absolute right angle system.

General polygonal regions are also available where arbitrary line segments define regions in the x - y plane with z -values in a selected range.

The complete input for types of region edits is described in Section 10.8 of this report since this input is normally included with the final module input.

Each collision occurs with coordinates x, y, z which are, with the exception of module zero collisions, in the local coordinate system of the initial assembly. As collisions occur, each set of coordinates x, y, z are checked by inequalities for each region edit defined. (Of course, the local coordinates must be transformed to the appropriate coordinate system of the region before checking). When the inequalities indicate that a collision site is interior to an edit region, then by use of the collision flux estimate, i.e., $\phi_{c_R} = \phi_{c_j}$, the microscopic cross sections at the incident energy E_0 , and the atom densities for composition j , all the desired edit quantities (with region numbers R taking the place of composition number j) are obtained. In terms of accumulative quantities (similar to that in Section 11.2) these are

$$\begin{aligned} A_R^{ig} &= A_R^{ig} + \phi_{c_R} \Sigma_a^i \\ P_R^{ig}(\text{tot}) &= P_R^{ig}(\text{tot}) + \phi_{c_R} (v^i \Sigma_f^i) \cdot \\ \phi_R^g &= \phi_R^g + \phi_{c_R} \end{aligned}$$

Similarly the collision densities needed to yield estimates of the diffusion coefficients are

$$\begin{aligned} C_R^g &= C_R^g + \Sigma_T \phi_{c_R} \\ T_R^g &= T_R^g \phi_{c_R} (\Sigma_T - \Sigma_s \mu^{i(c)}) \cdot \end{aligned}$$

All edited quantities based on the above accumulative quantities follow as defined in the few group edits by composition. The slowing down density by region is obtained in a manner analogous to that used previously, i.e., by use of E_0 , E , and w_i when a collision is identified as being in some edit region. In an analogous manner to the few group composition edits, the basic quantities for which uncertainties are directly calculated are the absorption and production fraction per nuclide, per few group, per edit region. If absorption rate edits are accumulated over nuclides, over few groups, over edit regions, or over any combination of these, the approximation is made that the quantities being accumulated are statistically independent and hence the uncertainty on the accumulation is the square root of the sum of the squares of the individual uncertainties.

11.3.4 Special Edit Involving Ratios of Reaction Types

An edit representing sums over nuclides of one type is available on option. The list of nuclide ID's, say i , are input for each type t . Up to ten types are permitted and each nuclide ID can appear in only one type. RCP performs the following summations:

$$\bar{A}_t = \sum_{f, j, i(t)} \bar{A}_j^{if}$$

$$\bar{P}_t = \sum_{f, j, i(t)} \bar{P}_j^{if}$$

where $\bar{A}_t$ is the total absorption, $\bar{P}_t$ is the total neutron production, and the summations are over nuclides i of type t only.

Additionally if the types input are specifically the following complete list, i.e., fertile nuclides capture, F_{ec} ; fertile nuclides fission, F_{ef} ; fissile nuclides capture, F_{fc} ; fissile nuclides fission, F_{ff} ; structure nuclides capture, S_c ; moderator nuclides capture, M_c ; and oxygen nuclides capture O_c , ratios will be computed and edited by RCP. These ratios are defined as:

$$\eta = \frac{\bar{P}_{F_{ff}}}{\bar{A}_{F_{fc}} + \bar{A}_{F_{ff}}}$$

$$\varepsilon = \frac{MF}{\bar{P}_{F_{ff}}}$$

$$\alpha = \frac{\bar{A}_{F_{fc}}}{\bar{A}_{F_{ff}}}$$

$$\bar{\nu}_{F_{ef}} = \frac{\bar{P}_{F_{ef}}}{\bar{A}_{ef}}$$

and

$$\bar{\nu}_{F_{ff}} = \frac{\bar{P}_{F_{ff}}}{\bar{A}_{F_{ff}}}.$$

The product $\eta \cdot \varepsilon$ is also edited. All of the above will be edited at the problem neutron production given by MF . Optionally the above quantities will be adjusted to a corrected neutron balance in a critical system, i.e., $MF = 1.0$. This additional edit is triggered by an input value of the enrichment factor E , which is defined as the ratio of fissile atoms to fissile + fertile atoms. To obtain the corrected values, the following procedure developed by G. H. Conley of Bettis is used in RCP. First, we

$$\text{set } X = (1 - E)/(1 - E \cdot \varepsilon)$$

$$\text{and } G = 1 + (1 - MF)X\sqrt{\bar{P}_{F_{ff}}}.$$

The value of G is the correction factor used to modify the fissile fission and fissile capture types as follows:

$$\bar{A}_{F_{ff}}^c = G\bar{A}_{F_{ff}}$$

$$\bar{A}_{F_{fc}}^c = G\bar{A}_{F_{fc}}$$

A correction factor which modifies the fertile nuclide fission type is given by Y , where

$$Y = (1 - GE)/(1 - E).$$

Thus

$$\bar{A}_{F_{cf}}^c = Y\bar{A}_{F_{cf}}$$

Similarly we need a correction factor which will apply to structure nuclide captures, moderator nuclide captures, and fertile nuclide captures. This single correction factor is obtained through the following auxiliary calculations based on the total absorptions in the system. First we note that the total absorptions in the system is $1.0 + \text{fertile } (n, 2n)$ where fertile $(n, 2n)$ goes as fertile loading. Therefore

$$\sum_i \bar{A}_i^c = 1 + Y\left(\sum_i \bar{A}_i - 1\right).$$

Thus setting $\bar{A}_{0_c}^c = \bar{A}_{0_c}$, the correction factor R becomes

$$R = \frac{C_{AB}}{T_{AB}},$$

$$\text{where } C_{AB} = \sum_i \bar{A}_i^c - \bar{A}_{F_{ff}}^c - \bar{A}_{F_{fc}}^c - \bar{A}_{F_{cf}}^c - \bar{A}_{0_c}^c,$$

$$\text{and } T_{AB} = \bar{A}_{S_c} + \bar{A}_{M_c} + \bar{A}_{F_{ec}} \cdot Y.$$

Thus

$$\bar{A}_{S_c}^c = R\bar{A}_{S_c}$$

$$\bar{A}_{M_c}^c = R\bar{A}_{M_c}$$

$$\bar{A}_{F_{ec}}^c = YR\bar{A}_{F_{ec}}.$$

Similarly the neutron production corrected to the critical system follows. That is

$$\bar{P}_{F_{ef}}^c = \bar{P}_{F_{ef}} \frac{\bar{A}_{F_{ef}}^c}{\bar{A}_{F_{ef}}},$$

$$\text{and } \bar{P}_{F_{ff}}^c = \bar{P}_{F_{ff}} \frac{\bar{A}_{F_{ff}}^c}{\bar{A}_{F_{ff}}}.$$

Uncertainties on all of the above quantities are also edited.

Other operations on the corrected quantities are performed. These additional edits include the total conversion ratio and the change in conversion ratio due to parasitic captures in structure, moderator, oxygen, and fertile capture types. The total conversion ratio is given by

$$CR_1 = \frac{\bar{A}_{F_{ec}}^c}{(\bar{A}_{F_{fc}}^c + \bar{A}_{F_{ff}}^c)},$$

and

$$\delta CR_{S_c} = \frac{\bar{A}_{S_c}^c}{(\bar{A}_{F_{fc}}^c + \bar{A}_{F_{ff}}^c)}$$

$$\delta CR_{M_c} = \frac{\bar{A}_{M_c}^c}{(\bar{A}_{F_{fc}}^c + \bar{A}_{F_{ff}}^c)}$$

$$\delta CR_{O_c} = \frac{\bar{A}_{O_c}^c}{(\bar{A}_{F_{fc}}^c + \bar{A}_{F_{ff}}^c)}$$

$$\delta CR_{F_{ef}} = \frac{\bar{A}_{F_{ef}}^c}{(\bar{A}_{F_{fc}}^c + \bar{A}_{F_{ff}}^c)}$$

The ratios using the corrected quantities are computed and edited by RCP. The ratios are:

$$(\eta\varepsilon)^c = \frac{1}{(\bar{A}_{F_{fc}}^c + \bar{A}_{F_{ff}}^c)}$$

$$\varepsilon^c = \frac{1}{\bar{P}_{F_{ff}}^c}$$

and a second estimate of the conversion ratio is given by

$$CR_2 = \frac{\bar{A}_{F_{ec}}}{\bar{A}_{F_{fc}} + \bar{A}_{F_{ff}}} + 0.5((\eta\varepsilon)^c + \eta\varepsilon) \cdot [MF - 1.0].$$

11.4 Photon Iteration Edits

As described previously in Chapter 8, RCP will record energy depositions (eV) due to gammas produced as a result of neutron capture or neutron fission. Edits of the gamma energy deposition are split into these two types, i.e., capture or fission, for linked calculations only. (A linked calculation is one spliced to a previously run neutron problem). For fixed source photon calculations all edits are identified as resulting from neutron fission only. Of course, any photoneutron production resulting from (γ, n) type reactions are additionally recorded and edited by RCP.

Before we can describe the photon iteration edits completely, we must review the results of a photon collision as discussed in Chapter 8. At each collision site RCP adds to a flux counter ϕ_j the contribution from the collision c_j as follows:

$$\phi_j = \phi_j + \phi_{c_j}$$

where $\phi_{c_j} = \frac{W_{t_0}}{\Sigma_{T_j}}$. Here W_{t_0} is the incident photon weight and Σ_{T_j} is the total reaction cross section for composition j evaluated at the incident energy E_0 , i.e.,

$$\Sigma_{T_j} = \Sigma_{c_j} + \Sigma_{pp_j} + \Sigma_{pe_j}$$

where the cross section components are Σ_{c_j} , compton scattering; Σ_{pp_j} , pair production; and Σ_{pe_j} , photoelectric cross sections respectively. The heating contributions at the collision site are recorded in counters in the following manner. First, the heating contribution is based on the type of photon reaction. Secondly, we distinguish between capture and fission gammas by $t = cg$ or $t = fg$. Thus,

$$H_{t_j} = H_{t_j} + W_{t_0}(E_0 - E) \text{ for compton scattering events;}$$

$$H_{t_j} = H_{t_j} + W_{t_0}(E_0 - 1.022(10^6)) \text{ for pair production events;}$$

$$\text{and } H_{t_j} = H_{t_j} + W_{t_0}(E_0) \text{ for photoelectric events;}$$

Any photoneutron production, P_{n_j} , is based solely on the presence of a (γ, n) cross section, σ_{pn}^i , in composition j . The photoneutron production tallied by RCP is

$$P_{n_j} = P_{n_j} + \sum_i N_j^i \sigma_{pn}^i \phi_{c_j}$$

After iteration k is completed, i.e., all photon collisions in all RCP groups are processed, the following normalized accumulated quantities are edited:

1. Fission Gamma Energy Deposition:

$$\bar{H}_{fg_j}^k = \frac{H_{fg_j}}{\sum_{k'=0}^k N^{k'}}$$

where the summation over k is the total number of photon histories run from iterations 0 to k inclusive.

2. Fission Gamma Energy Deposition Error: This error is computed by the procedure discussed in Section 7.1.
3. Total Gamma Energy Deposition:

$$\bar{H}_{T_j}^k = \bar{H}_{fg_j}^k + \bar{H}_{cg_j}^k$$

where the capture contribution is given by

$$\bar{H}_{cg_j}^k = \frac{H_{cg_j}}{\sum_{k'=0}^k N^{k'}}$$

4. Total Gamma Energy Deposition Error: This error is computed by the procedure discussed in Section 7.1.
5. Volume Density of the Total Energy Deposition: Using $\bar{H}_{T_j}^k$ and the volume (cm^3) of composition j , V_j , the density is

$$(\text{Gamma/cc})_j^k = \frac{\bar{H}_{T_j}^k}{V_j}$$

6. Photoneutron Production:

$$\bar{P}_{n_j}^k = \frac{P_{n_j}}{\sum_{k'=0}^k N^{k'}}$$

7. Energy Deposition Fraction:

$$\bar{F}_{T_j}^k = \frac{\bar{H}_{T_j}^k}{\sum_j \bar{H}_{T_j}^k}$$

where the summation over all compositions j is the total energy deposition, and is additionally edited by RCP. Two other quantities produced as output by RCP are the gamma leakage, $\bar{L}^k$, which is an estimate of the gammas which escape the system either radially or axially, and the total neutron production, $\sum_j \bar{P}_n^k$,

Quantities involving photon starts for iteration $k+1$ and the total source over iterations 0 to $k+1$ which are edited by RCP are summarized next.

8. Photon starts (for iteration $k+1$): N_j^{k+1} for a linked calculation is obtained using a semi-systematic sampling procedure discussed earlier for neutrons in Chapter 6, where values of the composition neutron absorption $\sum_{c_j} (\Sigma_a \phi)_{c_j}$ obtained from a previously run neutron problem determine the gamma source distribution by composition. (The value of $\sum_{c_j} (\Sigma_a \phi)_{c_j}$ is obtained only from collisions in iterations k_1 to k_2 of the neutron problem where k_1 and k_2 are input).

The semi-systematic sampling discussed in Chapter 6 applies once we set

$$SP_j = \sum_{c_j} (\Sigma_a \phi)_{c_j}$$

that is we replace P_{c_j} with $(\Sigma_a \phi)_{c_j}$. This will produce N_j^{k+1} .

To obtain photon reaction or heating edits normalized to one neutron born in fission, we set the photon starting weight, w_i , as

$$w_i = \left(\frac{\sum_j SP_j}{N_H} \right) s^{ia, G}$$

where N_H is the total number of histories in the neutron calculation used in the linked

calculation ($\frac{\sum_j SP_j}{N_H}$ is the total neutron absorption per neutron born in fission), and

where $s^{ia, G}$ is the total number of photons emitted per absorption event (capture or fission) with nuclide ia ($G \leq 57$). For a fixed source gamma problem, the source per iteration is not linked to a previously run neutron problem. Rather, the source is produced

in composition j using the composition input source density S_j as described in Section 2.2. For this case the photon starting weight is set to unity.

11.5 Photon Few Group Edits

Three counters per nuclide i , per composition j , and per few group f are used to record the energy deposition and photoneutron production resulting from a photon reaction. These counters are: H_{fg} , for fission gamma heating; H_{cg} for capture gamma heating; and P_n , for photoneutron production. An additional counter per composition ϕ_{c_j} is used to record the photon flux. In the manner described previously, the subscript $t = cg$ or fg will be used to distinguish between capture gammas and fission gammas, respectively. At each photon collision RCP stores for compton scattering events

$$H_{t_j}^{if} = H_{t_j}^{if} + W_{t_0}(E_0 - E) \frac{N_j^i \sigma_c^i}{\Sigma_{c_j}}$$

for pair production reactions

$$H_{t_j}^{if} = H_{t_j}^{if} + W_{t_0}(E_0 - 1.022(10^6)) \frac{N_j^i \sigma_{pp}^i}{\Sigma_{pp_j}}$$

and for photoelectric events

$$H_{t_j}^{if} = H_{t_j}^{if} + W_{t_0}(E_0) \frac{N_j^i \sigma_{pe}^i}{\Sigma_{pe_j}}$$

The photoneutron production is

$$P_{n_j}^{if} = P_{n_j}^{if} + N_j^i \sigma_{pn}^i \phi_{c_j}$$

The photon flux contribution ϕ_{c_j} is added to the flux counter, i.e.,

$$\phi_j^f = \phi_j^f + \phi_{c_j}$$

Few group edits are produced by RCP on option. The above quantities are normalized by the total number of photon histories run as follows:

$$\bar{H}_{t_j}^{if} = \frac{H_{t_j}^{if}}{\sum_{k'=0}^k N^{k'}}$$

$$\bar{P}_{n_j}^{if} = \frac{P_{n_j}^{if}}{\sum_{k'=0}^k N^{k'}}$$

$$\bar{\Phi}_j^f = \frac{\Phi_j^f}{\sum_{k'=0}^k N^{k'}}$$

where the denominator is the sum of all histories contained in iterations 0 to k inclusive. Associated with each quantity are counters which accumulate the “squares” of the contributions to the heating per history. These “square” counters are of course, needed to produce the appropriate error estimates as described in Section 7.1.

The most detailed edit is a few group edit where f , the few group, is used to designate the result obtained over an integral number of RCP groups. The few group breakpoints are described in the input. Thus for each few group f which extends from group $g^{f-1} + 1$ to g , the following quantities are edited by RCP:

$$\bar{H}_{t_j}^{if} \text{ and } \bar{P}_{n_j}^{if}.$$

These nuclide edits per few group f are followed by an edit over all nuclides i in composition j . This edit consists of

$$\bar{H}_{t_j}^f = \sum_i \bar{H}_{t_j}^{if}, \quad \bar{P}_{n_j}^f = \sum_i \bar{P}_{n_j}^{if}, \quad \bar{\Phi}_j^f$$

and slowing down $\bar{Q}_j^f$ which is the total energy remaining to be deposited below E^f , the lower energy cutpoint of few group f . $\bar{Q}_j^f$ for photons is obtained as follows. Record per collision c_j in composition j

$$Q_j^f = Q_j^l + W$$

where for compton scattering $W = w_{t_0}(E)$ if $E_0 > E^f$ and $E < E^f$ and for pair production $W = w_{t_0}(1.022(10^6))$ for $E_0 > E^f$ and $.511(10^6)\text{eV} < E^f$. Otherwise $W = 0$ is used. Thus, the edited quantity $\bar{Q}_j^f$, is

$$\bar{Q}_j^f = \frac{Q_j^f}{\sum_{k'=0}^k N^{k'}}.$$

The final collection for photon editing is a nuclide edit summed over all compositions and over all few groups.

$$\begin{aligned}\bar{H}_t^i &= \sum_{j,f} \bar{H}_{t_j}^{if} \\ \bar{P}_n^i &= \sum_{j,f} \bar{P}_{n_j}^{if}.\end{aligned}$$

11.6 Optional Photon Edits in RCP01

Optional edits for photon calculations include: 1) a nuclide edit of energy deposition by few group and 2) regionwise edits by few group.

11.6.1 Nuclide Heating Edit by Few Group

This edit is similar to the usual few group edit discussed previously in Section 11.5 except that the heating rates per nuclide are summed over all compositions j for few group f . For each f RCP will produce the following edit:

$$\bar{H}_T^{if} = \sum_j (\bar{H}_{fg_j}^{if} + \bar{H}_{cg_j}^{if})$$

$$\text{and } \bar{P}_n^{if} = \sum_j \bar{P}_{n_j}^{if}.$$

Error estimates on the above are also edited. Following this edit is a total edit over all few groups f obtained using

$$\bar{H}_T^i = \sum_f \bar{H}_T^{if}$$

and

$$\bar{P}_n^i = \sum_f \bar{P}_n^{if}.$$

11.6.2 Regionwise Edits

Photon region edits are available exactly as described for neutrons in Section 11.3.3.

12 FILE MANAGER FILES

12.1 Introduction

RCP01 can write (store) several different file types as output File Manager (Reference 14) files: accumulated result data, fission/capture link files, trapping surface link files, collision files, concentration files, channel-track files, and geometry files.

Standard accumulated result data files are written at the end of every normal job and also following selected intermediate iterations. The frequency of writing these files can be controlled by the user and can be based on machine time, on iteration number, or both. A single file of this type is read to continue a job after a recoverable machine error or to perform additional iterations in a subsequent job. These files can also be used by post-processing programs.

Special accumulated result data files are written after completing a perturbation reedit or a collision-file composition or region-edit reedit. A single file of this type is read to continue a job after a recoverable machine error or to perform additional iterations in a subsequent job. These files can also be used by post-processing programs.

Fission/capture link data files are written following each iteration when requested by a user and, for eigenvalue jobs, are written following the selected intermediate iterations. In neutron jobs, these files contain records of all neutron fission events or all neutron fission and capture events. In photon jobs, they record the sites of all events producing neutron emission. A fission or fission/capture file is used as the source to continue a neutron eigenvalue job. Such files may also be used to provide a source guess to another eigenvalue job or as the source to a fixed source neutron calculation. Fission-capture files are used to provide sites of neutron events generating photons as the source to a photon job. Files containing sites of neutrons emitted by photon collisions are used as the source in a photon subcritical calculation.

Trapping surface files are written following each iteration when requested. These files contain records of all particles crossing a user specified module zero surface. Such files may be used to provide a source to a related fixed source calculation.

File Manager Collision files, when required, are written following each iteration. They can be read in subsequent jobs to perform region-edits, or for collision-file composition reedit or

perturbation reedits. They can also be used by post-processing programs as a source of raw data.

Permanent files are stored and retrieved through the File Manager system described in Reference 14. This system permits a program to process files in terms of their logical structure, with no knowledge of the physical format of the files required. File processing is also independent of the physical device used for the permanent retention of the file.

Four significant levels of identification are associated with each file: an alphanumeric SYNONYM of up to eight characters, an integer VERSION number, an integer DATA TYPE number, and an alphanumeric GENERATION. In RCP01, VERSION numbers always refer to the iteration following which the file is written. Files written following iteration zero have VERSION = 999; all others have VERSION = iteration number. DATA TYPES are also supplied by the program and distinguish between different kinds of files generated following a single iteration. The SYNONYM is a temporary identifier which replaces the collection of additional identifiers required by the File Management system; in RCP01, they are used to distinguish between similar files used for different purposes.

Fission/capture link files, trapping surface files, and standard accumulated result files to be written on any iteration are grouped into a single SECTIONED file for that iteration with DATA TYPE = 250.

The sections of such a sectioned file are structured as if they were stand-alone files, but combined to simplify file management. The content of each section in a sectioned file is written exactly as if it were a stand-alone file, including header set(s), for the appropriate file type. Each section is a "named" section whose section name is the three character alphanumeric equivalent of the particular data type.

Collision files, special accumulated result data files, concentration files, channel-track files, and geometry files are written as stand-alone files.

When File Manager files are read by RCP01, they are required to pass certain compatibility checks with respect to the current problem description. These checks are made to assure that the files will be at least mechanically correct.

12.2 Accessing File Manager Files

To facilitate the processing of data contained in the output File Manager files, the following sections contain detailed descriptions of the files. This section contains general information required for the processing of any of these files.

A single routine, called FMG (Reference 14), is used by the program for all communications with the File Manager, both for reading and writing these files. File Manager files are subdivided into sets of data, and the set structure of a file is fundamental to its processing. Two different set structures are provided by the File Manager and each is used for one or more of the output files. In the first structure, the set size is constant and the total number of sets is known in advance. The set size and number of sets are then given to the File Manager before the file is written and are returned by the File Manager before the file is read. In the second

structure, the set size is variable in which case it is assumed the number of sets is not known. Here, the size of each set must be given to the File Manager as the set is written and is returned by the File Manager as the set is read. In this case the number of sets given to the File Manager and returned by the File Manager is zero. The writing program must indicate when it has written the last set and the File Manager will indicate to the reading program when the last set has been read.

The first set in every file is a HEADER set. This set contains important parameters relating to the contents of the file and, in particular, is used by the program to check for problem-file compatibility when the file is used as an input file. In all of the files, the first word of the header set is a numeric version identifier. This should not be confused with the File Manager VERSION number mentioned previously; it is simply an internal indicator used to maintain compatibility when the file structure changes and previously generated files must still be used.

The data in files written by the program are compressed by two different techniques, called PACK and SQOZ. PACK refers to the storing of several (non-negative) integer items in a single computer word, each item occupying a fixed set of bit positions. SQOZ refers to the storing of two real quantities in a single word by decreasing the number of significant digits and the exponent range of each. A set of FORTRAN CALLable subroutines is available (Reference 14) to PACK and SQOZ and perform the inverse operations. The statements:

CALL PACK (WORD, NOITMS, NOBITS, ITEMS)

CALL UNPACK (WORD, NOITMS, NOBITS, ITEMS)

are used to PACK (UNPACK) items into (from) a single computer word. Here WORD is the PACKed word, NOITMS is the number of items to PACK (UNPACK), NOBITS is an array giving the number of bits for each item, and ITEMS is an array containing (to be filled with) data items. Vector routines equivalent to multiple uses of these routines are also used.

Similarly, the statements:

CALL SQOZ (SQZWDS, FPTWDS, NWORDS)

CALL UNSQOZ (SQZWDS, FPTWDS, NWORDS)

are used to compress (expand) an array of real words into (from) an array of SQOZ words. Here SQZWDS is the array of SQOZ words, FPTWDS the array of real words, and NWORDS the number of real words.

12.3 Standard Accumulated Result Data File

The standard accumulated result data file is always written as section 281 of a file with data type 250 and default synonym RESTART. There are two structures possible. In one case,

the nuclide concentrations are included in the file; in the other, they are written in a separate, stand-alone Concentration file.

12.3.1 Complete Standard Accumulated Result Data File

The complete standard accumulated result data file is described below.

Data Type - 281

Set Size - Variable

Number of Sets - Variable

Set 1 (Header) - 17 integer words

Word - Value

1 - 19990706 (Version Identifier)

2 - ITHIST = total number of histories

3 - MR = number of compositions

4 - INCABS = sum of the numbers of nuclides in all compositions

5 - MAXNUC = number of distinct nuclides used

6 - NTEDR = number of region edits

7 - INCTOT = $INCABS + (NTEDR * MAXNUC)$

8 - NFA = number of final assemblies

9 - NFM = number of final modules

10 - MRX = number of compositions with distinct sets of nuclide IDs

11 - INCABX = total number of nuclides in distinct nuclide sets

12 - MROLD = number of original (input) compositions = MR if not a depletion file

13 - MRNOND = number of non-depletable compositions

14 - ISV284 = RCP01 concentration file switch

= 0 full restart file

= 1 separate type 284 concentration file created and section 281 file does not include concentration sets 7, 8, 9, 10

15 - DEplete = depletion switch

= 0 file created in non-depletion problem

= 1 file created in depletion problem

= -1 file created in depletion problem without automatic composition augmentation

16 - INCONC = concentration sets switch

= 0 no concentration sets in this file

= 1 this file has concentration sets

17 - FILETYPE

= 1 normal

= 2 short depletion continuation

= 3 short statistical post-processing

Set 2 contains 18+ NFEWGP integer words

Word - Value

1 - KITE - Iteration Number

2 - NGST = first RCP energy group in job

3 - NLAST = last RCP energy group in job

4 - NFEWGP = number of few groups

5 - NGSPSC = number of energy intervals in source spectrum

6 - IPART = particle type (= 0 - photon, = 1 - neutron)

7 - NTOTG = number of RCP energy groups in RCPL1 library

8 - ITOABS = type of calculation

= 1 fixed source neutron

= 2 neutron eigenvalue

= 3 photon

9 - ITOFLT = neutron time of flight option (= 0 - no, = 1 - yes)

10 - NDLOOP = depletion time step number (0 if not depletion)

11 - IPHOTO = photon scintillator option (= 0 - no, = 1 - yes)

12 - NEDSUM = number of generalized edits

13 - NRATED = number of generalized edit ratios

14 - FLUXPT = flux at a point option (= 0 - no, = 1 - yes)

15 - MUFT = number of fast multigroups

16 - MPT = number of thermal sub-groups

17 - NDET = number of point detectors for flux at a point option (otherwise = 0)

18 - JREGFL = number of the composition selected for the optional edit of results for each MUFT group and thermal subgroup

19 through 18+ NFEWGP - NGRPCT(NFEWGP) = RCP group numbers defining the few groups

Set 3 contains 2 + NFEWGP real words

Word - Value

1 - TIMINL = time in life (hours)

2 - EE(NGST) = maximum energy (ev) of first RCP group used

3 through 2+ NFEWGP - EE(NGRPCT(I)) = remaining few group energy cut-points (ev)

Set 4 contains NFEWGP real words, the values of CHI(1) through CHI(NFEWGP). They are the accumulated starting weights in each few group for all histories.

Set 5 contains MR real words, the values of TS(M). They are the accumulated starting weights in each composition for all histories.

Set 6 contains MTOT real words, the values of PJ(M). They are the accumulated neutron production in each composition and each edit region for all histories.

Set 7 contains MAXNUC integer words, the values of INN(I). They are the nuclide numbers (as used in input and referring to the RCPL1 library) of the nuclides actually used in the job. All references subsequently to nuclides refer to their sequential positions in this list.

Set 8 contains MRX integer words, the values of ISOT(M). They are, for each distinct nuclide list M, the number of nuclides used in its definition.

Set 9 contains INCABX words, the values of II(M,J). They are, in order, the numbers of the nuclides appearing in the definition of each distinct nuclide list. The first ISOT(1) are those for list 1; the next ISOT(2) are those for list 2; etc. This structure, a row-wise ragged matrix, is used as the shape of arrays in which data are stored by nuclide by composition.

Set 10 contains INCABS words, the values of DEN(M,J). They are, in order, the number densities (concentrations) of the nuclides appearing in the definition of each composition.

Sets 7, 8, 9, and 10 are the concentration sets. They are not included in type 281 files when a separate type 284 concentration file is being written.

Each of the next $6 \times (\text{NFEWGP} + 1)$ sets contains the SQOZ values of INCTOT, MTOT+1, or MTOT+2 data together with, for each set, a full-word real normalizer by which the data, after being UNSQOZ, must be multiplied to reconstruct the data. The SQOZ data are normalized to a maximum value of 10^{38} . The first six of these sets correspond to few group 1, the second six to few group 2, etc. The six sets for each group are ARIG(M,J), YRIG(M,J), SDD(M), SDDE(M), AFIG(M,J), and YFIG(M,J). Each of the sets containing SDD and SDDE has data corresponding to the SQOZ values of MTOT+1 values if there are no region edits, MTOT+2 if there are region edits. The other sets contain data corresponding to the SQOZ values of INCTOT data in the order of set 10. The final 6 sets of this collection are heating data. For all these sets, for N initial data, the SQOZ sets have length $\text{INT}((N+1)/2) + 1$.

Each of the next $6 \times \text{NFEWGP}$ sets contains MTOT words. The first six of these sets correspond to few group 1, the second six to few group 2, etc. The six sets for each few group are FLUX(M), FLUXSQ(M), COLL(M), COLLSQ(M), TRANS(M), and TRANSQ(M). These data are, for each composition M, the accumulated values of flux, its sum of squares per iteration, collision density, its sum of squares per iteration, the transport cross section, and its sum of squares per iteration. As for almost all data in this file, these data must be divided by the total number of histories to produce the normal results.

Each of the next 4 sets (absent if NFM=0) contains NFEWGP real words. The sets are RADLEAK(N), RADLKSQ(N), AXLEAK(N), and AXLKSQ(N). These arrays contain, respectively, the values for each few group of the radial leakage, its sum of squares, the axial leakage, and its sum of squares.

The next set contains NFA+1 real words which are CURFA(JFA), the unnormalized net currents for each final assembly followed by the total final assembly current.

The next set (absent if NFM=0) contains NFM+1 real words which are CURFM(JFM), the unnormalized net currents for each final module followed by the module zero net current.

The next set contains NGPSPC real words which are FMUFT(K), the unnormalized counts of starting particles in each multigroup or source interval. They are used in the quota sampling of the fission source spectrum.

The next set contains MTOT real words which are TOTABS(M), the unnormalized sums of the total absorption for each composition and region.

Next Set: - 23 words

Word - Value

- 1 - DIVHST (the inverse of ITHIST) - real
- 2 - NSITES (the total number of fission sites) - integer
- 3 - 0.0
- 4 - PEMDST (the sum of the squares of iteration multiplication rates each divided by its history count)
- 5 - PPJSUM
- 6 - TOTPJ
- 7 - TOTMF
- 8 - XBAR = unnormalized first moment of x-coordinate of fission sites
- 9 - XBAR2 = unnormalized second moment of x-coordinate of fission sites
- 10 - XBAR4 = unnormalized fourth moment of x-coordinate of fission sites
- 11 - YBAR = unnormalized first moment of y-coordinate of fission sites
- 12 - YBAR2 = unnormalized second moment of y-coordinate of fission sites
- 13 - YBAR4 = unnormalized fourth moment of y-coordinate of fission sites
- 14 - ZBAR = unnormalized first moment of z-coordinate of fission sites
- 15 - ZBAR2 = unnormalized second moment of z-coordinate of fission sites
- 16 - ZBAR4 = unnormalized fourth moment of z-coordinate of fission sites
- 17 - TLEAK = total leakage
- 18 - TLKSQ = sum of squares of iteration values of total leakage
- 19 - LHIST (possibly reduced in photon jobs) = number of histories in iteration zero

20 - ITHIST = total histories represented by file

21 - NSUBCR = subcritical option

22 - EPHOTO = energy for photon scintillator option

23 - TOFMAX = time cutoff for time-of-flight option

The next set contains MTOT words which are PPJ(M), the unnormalized sums of the squares of the contributions, per iteration, to the neutron production for each composition and region.

Next Set: - 2 words

Word - Value

1 - IHO (one-half of the increment in history count per iteration)

2 - IRCOR (the continuation value for the pseudo-random number generator)

The next set contains MROLD words which are WDAV(M), the thermal Russian roulette remainders in each composition.

The next set contains MAXNUC words which are NME(I), the alphanumeric identifiers of the nuclides actually used in the job. These identifiers are saved from the RCPL1 job library.

The next set contains MAXNUC words which are RXLOAD(I), the masses of the nuclides. These masses are used to calculate total loadings in kilograms and may be different from the masses used to determine scattering patterns. These masses are also saved from the RCPL1 job library.

The next set contains MROLD+NTEDR (= MTOT when there is no depletion subdivision) real words which are VOLUME(M), the total volume, summed over all final modules, for each composition M and each region.

The next set (absent when not depletion) contains MR-MRNOND real words which are DVOLUME(M), the volumes of subdivided depletion compositions.

The next set contains MTOT real words which are PFIS(M), the unnormalized sums of the neutron fission for each composition and region.

The next set contains MTOT real words which are PFCUM(M), the unnormalized sums of the squares of the contributions, per iteration, to the neutron fission for each composition and region.

The next set contains MTOT real words which are ABCUM(M), the unnormalized sums of the squares of the contributions, per iteration, to the neutron absorption for each composition and region.

The next set contains MR integer words which are NJT(M), the counts of starting particles in each composition.

Each of the next 6 sets contains MTOT real words. The sets are HT1(M), HT1SQ(M), HT2(M), HT2SQ(M), HT(M), and HTSQ(M). These arrays contain, respectively, the values for each composition of the two kinds of neutron heating data, their total, and their respective squares. These data are totals over all nuclides.

Each of the next 6 sets contains MAXNUC real words. The sets are H1(I), H1SQ(I), H2(I), H2SQ(I), HI(I), and HISQ(I). These arrays contain, respectively, the values for each nuclide of the two kinds of neutron heating data, their total, and their respective squares. These data are totals over all compositions.

The next set contains MTOT real words which are ABSI(M), the unnormalized contributions to total absorption for the current iteration, for each composition and region.

Next Set: (12 words)

Word - Value

1 - ABC (the real sum of the square roots of the numbers of histories per iteration times their immediate predecessors)

2 - N1 (iteration 1 history count) - integer

3 - Nk - iteration k (current) history count - integer

4 - 0 - fixed source; 1 - eigenvalue calculation - integer

5 - CLEAK(1) = Iteration 1 total leakage

6 - CLEAK(k) = Iteration k total leakage

7 - Sum of total leakage correlation terms

8 - Correlation coefficient for total leakage

9 - PPJSUM(1) = Iteration 1 neutron leakage

10 - PPJSUM(k) = Iteration k neutron leakage

11 - Sum of total neutron production correlation terms

12 - Correlation coefficient for total neutron production

The next set contains MTOT words which are PPJ1(M), the unnormalized contributions, for iteration 1, to the neutron production for each composition and region.

The next set contains MTOT words which are APPJ(M), the unnormalized sums of the square roots of the contributions, per iteration, to the neutron production for each composition and region.

The next set contains MTOT words which are $\rho(PJ(M))$, the correlation coefficients of the neutron production for each composition and region.

The next set contains MTOT words which are ABSI1(M), the unnormalized contributions, for iteration 1, to the neutron absorption for each composition and region.

The next set contains MTOT words which are AABS(M), the unnormalized sums of the square roots of the contributions, per iteration, to the neutron absorption for each composition and region.

The next set contains MTOT words which are $\rho(ABS(M))$, the correlation coefficients of the neutron absorption for each composition and region.

The next set contains MR words which are CFP(M), the unnormalized sums of the values needed to calculate the xenon number densities for the next iteration.

If and only if a composition has been selected for the edit by multigroup and thermal subgroup, the next 8 sets are included in the file. These sets contain FLUXJ(K), FLUXJSQ(K), ABSJ(K), ABSJSQ(K), FLTHJ(K), FLTHSQ(K), ABSTHJ(K), and ABTHSQ(K) respectively. The first four of these sets have MUFT data. The second four have MPT data. The four thermal sets are absent for photon jobs.

For eigenvalue jobs, the next set has MR values of PPJF, the amount of fission in the fission file per composition.

For neutron jobs which include the thermal group, the next two sets have MTOT values of neutron density (DNUT) and its sum of squares (DNSQ) for each composition and region.

If the job has generalized edits, the next three sets have NEDSUM values of iteration values, sums of iteration values, and sum of squares (EDSM, EDST, EDSQ).

If the job has ratios of generalized edits, the next three sets have NRATED values of iteration ratios, sums of iteration ratios, and sums of squares (EDRT,ERTT,ERSQ).

If the job has the flux at a point option, the next NDET sets have $2 + 2 * (\text{MUFT} + \text{MPT} + \text{NLAST})$ FLUXPT data for editing flux at a point results.

The next set has MR integer values of IIXF, the unique set numbers for each composition.

The next set has MRX integer values of IIPT, the pointers to the unique sets in II.

If NTEDR is nonzero, the next set contains NTEDR words of NMEREG which are the region names.

The next set has MAXNUC values of FMLD; the total loadings per nuclide over all final modules (Initial Module one if NFM = 0).

If NFM is nonzero, the next set has MAXNUC values of MZLD, the total loadings per nuclide over module zero.

The next two sets have MAXNUC values of ABNC and PDNC data, accumulated absorption and production per nuclide.

The next set contains MR integer words of SRTC, the sorted composition numbers. The first MRNOND values are the nondepletable composition numbers.

The next two sets contain variables used in the warmup, rampup, iterate iteration strategy.

The next set contains three integers KWARMUP, LHIST_TGT, and ITHIST01, the number of fixed batch size warmup iterations, the number of histories in iterations after rampup, and total histories since rampup.

The next set contains one real word, RAMPFACTOR, the rate of history growth during rampup.

The next set contains KITE+1 iteration eigenvalues.

The next set contains KITE+1 real values of the batch sizes, the numbers of histories in each iteration.

12.3.2 Reduced Standard Accumulated Result Data File

Reduced files are written when a separate concentration file is being written. Reduced files differ from complete files in that certain sets are absent from reduced files. Differences in file structure are as follows:

In set 1, word 14 = 1 indicating a reduced file and word 16 = 0 indicating absence of concentrations.

Sets 7, 8, 9, 10 containing the INN, ISOT, II, and DEN arrays are absent.

12.3.3 Concentration Files

Concentration files are non-sectioned files of type 284. They contain selected sets normally included in results files. The default synonym is DEPLCONC.

Data Type = 284

Set Size - Variable

Number of Sets - Variable

We describe the file structure in terms of the Complete Standard Accumulated Result Data file.

In set 1, word 14 = 1 indicating existence of a separate concentration file and word 16 = 1 indicating concentrations in this file.

Sets included are sets 1, 2, 3, 6, 7, 8, 9, 10, the set containing the VOLUME array, the IIXF and IIPT sets, the SRTC set, and the final four sets describing iteration strategy and providing eigenvalues and batch sizes.

12.3.4 Summary

The following tabulation summarizes the arrangements of sets when the concentration sets are included or separate from the accumulated result data file in terms of complete file structure:

	Complete Standard Accumulated Result Data File	Reduced Standard Accumulated Result Data File (without concentrations)	Concentration File
Type	250	250	284
Section	281	281	Unsectioned
Default Synonym	RESTART	RESTART	DEPLCONC

	Complete Standard Accumulated Result Data File	Reduced Standard Accumulated Result Data File (without concentrations)	Concentration File
<u>Sets</u>			
1, 2, 3	Yes	Yes	Yes
4, 5	Yes	Yes	No
6	Yes	Yes	Yes
7, 8, 9, 10 (concentration sets)	Yes	No	Yes
ARIG through RXLOAD	Yes	Yes	No
VOLUME	Yes	Yes	Yes
DVOLUME through FLUXPT	Yes	Yes	No
IIXF and IIPT	Yes	Yes	Yes
NMERE (if NTEDR > 0) through PDNC	Yes	Yes	No
SRTC to end	Yes	Yes	Yes

12.4 Special Accumulated Result Data Files

There are three kinds of special accumulated result data files, all containing the results of collision-file re-edit jobs. The three kinds result from perturbation re-edits, composition collision-file re-edits, and region-edit collision file re-edits. A perturbation re-edit job containing region-edit region definitions produces region-edit files based on the perturbed problem.

All of these files are written as stand-alone files, not sectioned, and have data type 281. Perturbation and composition files have default Synonym PERTURB. Region-edit files have default Synonym REGEDIT.

Each of these files has the same number of sets and, generally, the same set sizes as the standard accumulated result data file of the job that generated the collision files processed. In fact, the set sizes are identical except that different regions or even a different number of regions may occur in the region-edit restart file. Also, for many sets, even the data are those from the original problem.

12.5 Collision Files

Collision files are always written as stand-alone files with data type 285 and default synonym COLLIDE. Their structure is described below.

Data Type - 285

Number of Sections - 2

Section 1:

Set Size - Variable

Number of Sets - 1

Set 1 (Header)

Word -- Value

1 - 19990507 (Version Identifier)

2 - Iteration Number

3 - $\pm$ ICOLCT = Number of collisions recorded in the file (Negative if perturbation job)

4 - $\pm$ LHIST = Number of histories in iteration (Negative if EDR01/PACER format)

5 - ITHIST = Total histories through this iteration

Section 2:

Set Size - Variable

Number of Sets - Variable

Set 1 (Header)

Word -- Value

1 - 19990507 (Version Identifier)

2 - Iteration Number

3 - $\pm$ 1000000 (Negative if perturbation job)

4 - $\pm$ LHIST (Negative if EDR01/PACER format)

5 - ITHIST

All remaining sets have 504 words per set. In standard files, each set contains 7 words of data from each of 72 collisions. In EDR01/PACER format or perturbation files, each set contains 9 words of data from each of 56 collisions. In all cases, the last set also contains 504 words; it is filled with meaningless data.

In all files, the first word of each collision record is a PACKed word of the following structure:

Word 1- PACKED data

BITS DATA

10 KSCAT

2 LCM

8 KGP

13 JFA

10 JFM

3 IADELT

1 IEDFISS

12.5.1 Standard Collision Files

In standard files, words 2-5 of each collision record are SQOZ words containing the following 8 data:

μ_0 (Cosine of the laboratory system scattering angle); RFLUX if photon.

X

Y

Z

W_t/Σ_t

Exit Energy

W_t

Incident Energy

Words 6 and 7 of each collision record are full-word integer values of the History Number within the current iteration and the composition number.

12.5.2 EDR01/PACER Format Collision Files

In EDR01/PACER format files, words 2-5 of each collision record are SQOZ words containing the following 8 data:

μ_0 (Cosine of the laboratory system scattering angle); RFLUX if photon.

X

Y

Z

W_t/Σ_t

Exit Energy

W_t

Incident Energy

Word 6 of each collision record is the full-word integer value of the History Number within the current iteration. Words 7-8 of each collision record are SQOZ words containing the following 4 data:

Absorption deposited on the collision

Neutron Production deposited on the collision

$\Sigma^T(\text{JREG})$ without delta-scattering

$\Sigma^T + \Sigma^\delta$ including delta-scattering

Word 9 is the full word integer value of JREG, the composition number.

12.5.3 Perturbation Collision Files

In perturbation files, words 2-6 of each collision record are SQOZ words containing the following 10 data:

μ_0 (Cosine of the laboratory system scattering angle)

X

Y

Z

W_t/Σ_t

Exit Energy

W_t

Σ_t (composition 1)

Distance travelled in composition 1 since previous collision by this particle

$\Sigma_t(\text{JREG})$

Word 7 of each collision record is the full-word value of Incident Energy. Words 8 and 9 of each collision record are the full-word integer values of the History Number within the current iteration and JREG, the composition number.

12.6 Fission/Capture Link Files

A FISSION/CAPTURE LINK file is always written as section 280 of a file with data type 250 and default synonym RESTART. Its structure is described below.

Data Type - 280

Set Size - Variable

Number of Sets - Variable

Set 1 (Header)

Word - Value

1 - 19990507 (Version Identifier)

2 - LHIST

3 - NSITES (Number of sites recorded in the file)

4 - 0

The remaining sets have 500 words per set except for the final set which contains 4 words for each of the remaining sites (≤ 125).

In these files, each set contains data for 125 sites or for the remainder sites of the last set.

Let NSITST = the number of sites in the set (125 or remainder). Each set consists of 3 blocks.

Block 1 of each set contains $2 * \text{NSITST}$ SQOZ words, the first NSITST each containing the X and Y coordinates of a site and the second NSITST each containing the Z-coordinate and, for neutrons, the absorption at the site. For photon jobs, the absorption is replaced by the incident photon energy.

Block 2 of each set contains NSITST PACKed words of the following structure:

<u>BITS</u>	<u>DATA</u>
10	IGNI (absorbing nuclide)
1	IFISS
27	JREG
13	JFA
10	JFM
3	IADELT

Block 3 of each set contains NSITST full word values of Neutron Production deposited at the corresponding collision sites.

12.7 Trapping Surface Files

A TRAPPING SURFACE file is always written as section 282 of a file with data type 250 and default synonym RESTART. Its structure is described below.

Data Type - 282

Set Size - Variable

Number of Sets - Variable

Set 1 (Header)

Word - Value

1 - 19990507 (Version Identifier)

2 - L HIST

3 - ICNTPS (Number of sites recorded in the file)

4 - 0

5 - 0

The remaining sets have 500 words per set except for the final set which contains 5 words for each of the remaining sites (≤ 100).

In these files, each set comprises 5 blocks of data. Each block contains data for 100 sites or for the remainder sites of the last set.

Let NSITST = the number of sites in the set (100 or remainder). Block 1 of each set contains $2 * \text{NSITST}$ SQOZ words, the first NSITST each containing the X and Y coordinates of a site and the second NSITST each containing the Z coordinate and Energy value of a site. Block 2 contains NSITST packed words containing the 11 bit value of IEDFIS (0 if neutron job, 0 if photon originated from neutron capture, 1 if photon from fission) and the 40 bit value of the module zero trapping surface radius number. Block 3 of each set contains $2 * \text{NSITST}$ SQOZ words, the first NSITST each containing the μ and γ values at a site (cosines of angles relative to the x and y axes) and the second NSITST containing the η (cosine relative to z -axis) and W_t of a neutron or photon.

The final set of each of these files has the data for the remaining sites (≤ 100) and has correspondingly reduced block sizes.

12.8 Channel-Track File

A channel-track file is written, when requested, in depletion jobs. It is written as a stand-alone file with data type 300 and default synonym CHANTRCK. Its structure is described below.

12.8.1 Set Descriptions

Let MRD = number of depletable compositions

FZ = axial finezone number

(In an RCP01 job the axis is divided into zones, and in a depletion job each zone may be subdivided by the user into depletion zones. The finezone is defined as the depletion zone number plus the total number of depletion zones in the lower zones.)

Channel = channel number

Track = track number

PorS = primary (=1), or secondary (=2)

FA = final assembly number

FM = final module number

$VOL(i)$ = volume of depletable composition i

Set 1 contains one integer (MRD). Sets 2 through MRD+1 contain six integers each (FZ, Channel, Track, PorS, FA, FM), which give the correspondence between RCP01 depletable compositions and PDQ08 planes and fineblocks. The depletable composition number is the set number minus 1. The RCP01 finezones match the PDQ08 planes. The five integers from RCP01 (Channel, Track, PorS, FA, FM) match the four integers that PDQ08 uses to label fineblocks (Channel, Track, Planar Region, Final Figure) Set MRD+2 contains MRD reals, which are the volumes of the depletable compositions. PorS is 0 for primary final assemblies and the secondary number for secondaries.

set 1 : MRD

set 2 : FZ, Channel, Track, PorS, FA, FM

set 3 : FZ, Channel, Track, PorS, FA, FM

. .

. .

. .

set MRD+1: FZ, Channel, Track, PorS, FA, FM

set MRD+2: $VOL(1)$, $VOL(2)$, ..., $VOL(MRD)$

13 DEPLETION CAPABILITY

13.1 Introduction

RCP01 has the capability to carry out a time dependent depletion calculation. The user has the choice of letting RCP01 automatically subdivide the input compositions into depletable compositions, or supplying the depletable compositions as input. The depletion calculation used in RCP01 was adapted from the calculation used in the PACER program (Reference 17).

To use the depletion option, the user must provide additional store card images, input control card images, and initial assembly input card images. These card images are described in Sections 13.2, 13.3, and 13.4. Some of the card images are optional. The depletion chain input card images have the same form as they do in the PACER program (Reference 17). Other card images give the user control over various options. RCP01 also has the capability to produce initial module and z-slice plots that contain labels to show the locations of depletable compositions in order to assist users in verifying their geometric input. This plotting capability is described in Chapter 14.

In addition, RCP01 can write a file that gives a correspondence between RCP01 depletable compositions and PDQ08 fineblocks and planes. The system of identifiers used for the fineblocks is similar to the channel-track system used in PDQ08 in order to facilitate comparisons of the depletion results from RCP01 and PDQ08. This is described in Section 13.5. See Section 12.8 for a description of the channel-track file.

13.2 Store Card Images

An RCP01 restart file in a non-depletion job contains concentration sets. Concentration sets are the set of nuclide numbers, the set of numbers of nuclides used for each composition, the set of the nuclide numbers appearing in the definition of each composition, and the set of concentrations. When the depletion capability is used, the amount of data in the concentration sets increases. Hence, the user is given the option of keeping the concentration sets in the restart file, or of writing the concentration sets to a separate concentration file. This option is controlled by the fourth data item on card image 18000. See Chapter 10. Since the concentration data does not change until after the last iteration in a depletion time step, a concentration file only needs to be written once per depletion time step, whereas a restart file may be written more frequently.

Restart files (type 250), and concentration files (type 284) use the generation field to distinguish between files produced during different depletion time steps. The generation field is of the form 'STEPNNN', where NNN is an integer between 000 and 999. Files written during the first spatial calculation (BOL) are labeled 'STEP000'. Type 250 files are written during each spatial calculation. A type 284 file is written immediately after each spatial calculation, and one additional type 284 file is written after the last depletion. Also, after the last depletion, a type 250 file with version number 999 is written, which corresponds to iteration zero. If the user fetches this type 250, version 999 file along with a type 284 file, RCP01 will start up from iteration zero of the next depletion time step reading the concentrations in from the type 284 file.

Here is an example of the store card images that are needed for a job that goes through 2 depletion time steps, each having 100 iterations.

```
STORE,I=RCP-DEPL,T=250,V=999,F=I,S=RESTART,D=1N,M=MSET,G=STEP000
STORE,I=RCP-DEPL,T=250,V=1-100,F=I,S=RESTART,D=1N,M=MSET,G=STEP000
STORE,I=RCP-DEPL,T=250,V=999,F=I,S=RESTART,D=1N,M=MSET,G=STEP001
STORE,I=RCP-DEPL,T=250,V=1-100,F=I,S=RESTART,D=1N,M=MSET,G=STEP001
STORE,I=RCP-DEPL,T=250,V=999,F=I,S=RESTART,D=1N,M=MSET,G=STEP002
STORE,I=RCP-DEPL,T=284,V=1,F=I,S=DEPLCONC,D=1N,M=MSET,G=STEP000
STORE,I=RCP-DEPL,T=284,V=1,F=I,S=DEPLCONC,D=1N,M=MSET,G=STEP001
STORE,I=RCP-DEPL,T=284,V=1,F=I,S=DEPLCONC,D=1N,M=MSET,G=STEP002
```

13.3 Input Control Card Images

Card images for control of depletion input are described in detail in Chapter 10. These card images include the following.

- **Card 300 (optional)** - Controls the frequency of edits.
- **Card 18000** - Controls the depletion mode and selected printing, editing, and automated generation of depletable composition.
- **Card 1800s (optional)** - Permits the specification of compositions which will not be depleted. ($1 \leq s \leq 9$)
- **Card 18100** - Controls the depletion power level.
- **Card 1810s** - Controls the length of each depletion time step. ($1 \leq s \leq 9$)
- **Card 1811s** - Selects edit regions for flux normalization. ($1 \leq s \leq 9$)

- **Card 182ss** - Defines the nuclides in a depletion chain. ($1 \leq ss \leq 99$)
- **Card 1900ss or 19ssssss** - Defines the relationships between composition and the depletion chain list. ($1 \leq ss \leq 99$), ($1 \leq ssssss \leq 999999$)
- **Card 19LLss** - Defines chain list LL. ($1 \leq LL \leq 99$), ($1 \leq ss \leq 99$)
- **Card 3CC000** - Defines chain CC. ($1 \leq CC \leq 99$)
- **Card 3CCNN1** - Defines nuclide NN in chain CC. ($1 \leq CC \leq 99$), ($1 \leq NN \leq 99$)
- **Card 3CCNNs** - Defines the coupling of nuclide NN in chain CC. ($1 \leq CC \leq 99$), ($1 \leq NN \leq 99$)
- **Cards 3CCC000, 3CCCN1, and 3CCCNs** - Can replace the above card images with $1 \leq CCC \leq 999$.

13.4 Initial Assembly Input Card Images

Card images for describing depletion regions are described in detail in Chapter 10.

- **Card 450000 (optional)** - Defines relationship between z-zone boundaries and depletion zone boundaries.
- **Card 45ZZZs (optional)** - Defines depletion zone boundaries. ($1 \leq ZZZ \leq 999$), ($1 \leq s \leq 9$)
- **Card 7PSSs (optional)** - Defines the width of depletion blocks in the x-direction. PSS is the P-list number. ($1 \leq s \leq 9$)
- **Card 8PSSs (optional)** - Defines the height of depletion blocks in the y-direction. PSS is the P-list number. ($1 \leq s \leq 9$)
- **Card 9PSS1 (optional)** - Can modify the number of depletable compositions in sub-cell copies. PSS is the P-list number.

13.5 Channel-Track File

13.5.1 Control Card Image Input

Card input images for control of channel-track file description are described in detail in Chapter 10.

- **Card 18500 (optional)** - Determines if the file is written.

13.5.2 Initial Assembly Input

- **Card 70PSS0 (optional)** - Determines the orientation of channels in the x-y plane. PSS is the P-list number.
- **Card 70PSSs (optional)** - Defines track numbers. PSS is the P-list number. ($1 \leq s \leq 9$)
- **Card 80PSSs (optional)** - Defines channel numbers. PSS is the P-list number. ($1 \leq s \leq 9$)
- **Card 9PSS1 (optional)** - This card was described in Section 13.4. It can also be used to set channel-track biases for subcell repeats. PSS is the P-list number.
- **Card 50PSSs (optional)** - Can be used to set channel-track biases for repeats of a P-list in the final laydown. PSS is the P-list number. ($1 \leq s \leq 9$)

13.5.3 Initial Module Input

- **Card 63FFA0 (optional)** - Defines channel-track biases for final assembly number FFA.

13.5.4 Final Module Input

- **Card 65FFM0 (optional)** - Defines channel-track biases for final module number FFM.

14 PLOTting OVERVIEW

14.1 Introduction

RCP01 has the capability to produce initial assembly, initial module, and z-slice plots in black and white or color with detailed geometry to assist users in verifying their geometric input. The user has the option of assigning colors to compositions. If the user does not select a color for a certain composition, an arbitrary default color will be assigned to that composition. These color plots can be displayed on workstations or printed.

RCP01 has the capability to produce a file that describes the 3-D geometry of final assemblies and the elliptical cylinders they contain. This file can be read by AVS (Reference 18), and the 3-D geometry can then be displayed on a workstation. The user can assign colors to the compositions that appear in the elliptical cylinders on input card images, and RCP01 will color the geometry accordingly. Once the geometry is read by AVS, the user can, for example, rotate and translate the image, change colors and opacities, or take a slice through the object by adjusting the front clipping plane. RCP01 can also produce black and white 3-D perspective plots which do not require AVS.

A summary of all the plot options in RCP01 follows.

14.2 2-D Plots With Internal Details

Card image 14000 has the form:

14000, plotunit, IMDETAIL, implotsize, IADETAIL, iaplotsize, SLICEDetail, sliceplotsize

IADETAIL refers to initial assembly plots, IMDETAIL refers to initial module plots, and SLICEDetail refers to slice plots. The initial assemblies to be plotted are listed on card images 14011 to 14019. The initial modules to be plotted are listed on card images 14001 to 14009. The x-y plots are listed on card image 47001. The x-z plots are listed on card image 48001. The y-z plots are listed on card image 49001.

Basic plots showing minimal detail can be requested by setting the integer parameters IADETAIL, IMDETAIL, and/or SLICEDetail equal to 0 on card image 14000.

Setting IADETAIL equal to 1 will add mesh line numbers and composition stack numbers to initial assembly plots. Setting IMDETAIL equal to 1 will add final assembly numbers to

initial module plots. Setting SLICEDetail equal to 1 will add final module and final assembly numbers to slice plots.

Setting IMDETAIL and/or SLICEDetail equal to 2 will cause initial assembly details to appear in plots.

Setting IADetail, IMDETAIL, and/or SLICEDetail equal to 3 requests plots with color filling the initial assembly details. The colors can be selected using the card images described below.

Setting IMDETAIL or SLICEDetail equal to 4 requests plots with labels showing the locations of depletable compositions. For cell geometry use IMDETAIL=4. The z value is set on card image 42000, described below. For modular geometry use SLICEDetail=4. In the case of P-lists, one label is inserted in the center of the area, and the output contains a table that lists the compositions represented by that label.

The card images described below can be optionally added to the input control card images in order to select the colors used on the plots.

In order to assign colors to compositions, a color model must first be selected. Section 14.6 contains descriptions of the two color models available and some examples. On card image 40000, set ICOLORMODEL equal to 1 for RGB (red, green, blue), or equal to 2 for HSV (hue, saturation, value). The default color model is HSV.

40000, ICOLORMODEL

The user can assign colors to compositions with card images of the following form.

40NNN, X, Y, Z, C1, C2, C3, ...

$001 \leq \text{NNN} \leq 248$

$0.0 \leq X, Y, Z \leq 1.0$

X, Y, and Z are real numbers. (Either X=red, Y=green, and Z=blue, or X=hue, Y=saturation, and Z=value.)

C1, C2, C3, ... is a list of integer composition numbers. Any number of compositions may be listed on a given card image. Use a + to continue the card image if necessary. Only one color number NNN may be associated with a composition Ci.

For initial assembly plots the z-zone that is displayed can be selected by specifying the integer parameter IAZONE on card image 41000. Although RCP may reduce the number of zones by eliminating redundant z-boundaries, the zones referred to on these card images are the input zones. The default zone is 1.

41000, IAZONE

Initial modules may contain assemblies with different numbers of z-zones. Therefore, for initial module plots the user has the option of specifying a real z value on card image 42000, and RCP01 will determine which zone that z lies in for each assembly in the initial module. The default z value is 0.0.

42000, ZIM

There is also a zoom option for z-slice plots. Insert the following card image in the module zero input.

50000, XMIN, XMAX, YMIN, YMAX

This allows the user to specify the minimum and maximum X and Y values for slice plots in the X-Y plane. This gives the effect of zooming.

These card images are described further in Chapter 10.

14.3 Summary of Plot Options on Card Image 14000

IADETAIL = 0 , basic plot

IADETAIL = 1 , add mesh line numbers and composition stack numbers

IADETAIL = 2 , same as 1

IADETAIL = 3 , color fill, no numbers

IADETAIL = 4 , undefined

IMDETAIL = 0 , basic plot

IMDETAIL = 1 , add final assembly numbers

IMDETAIL = 2 , black and white IA details, no numbers

IMDETAIL = 3 , color fill with IA details, no numbers

IMDETAIL = 4 , depletable composition labels in cell geometry case

SLICEDTL = 0 , basic plot

SLICEDTL = 1 , add final module numbers and final assembly numbers

SLICEDTL = 2 , black and white IA details, no numbers

SLICEDTL = 3 , color fill with IA details, no numbers

SLICEDTL = 4 , depletable composition labels in modular geometry case

14.4 Color 3-D AVS Plots With Internal Details

In the module zero input include the following card image:

47000,0

This causes RCP01 to write a file called "movie.byu". This file must then be transferred to a workstation to use AVS. The filename should have an extension ".byu". In the AVS applications menu there is a button labeled "Color BYU Visualization". Once this application is started, the user must supply a directory and a filename. The colored object will then appear on the screen. The following input card images are needed for RCP01 to know what colors are to be used.

In order to assign colors to compositions, a color model must first be selected. Section 14.6 contains descriptions of the two color models available and some examples. In the input control card images, include a card image 40000 to select the color model for both 3-D and 2-D plots. On this card image, set ICOLORMODEL equal to 1 for RGB (red, green, blue), or equal to 2 for HSV (hue, saturation, value). The default color model is HSV.

40000, ICOLORMODEL

In addition, AVS allows the user to define an opacity. An opacity of 1.0 means that the object is completely opaque, and an opacity of 0.0 means that the object is completely transparent. The user can assign colors to the compositions that fill elliptical cylinders with card images of the following form in the module zero input.

57NNN, X, Y, Z, OPACITY, C1, C2, C3, ...

$001 \leq \text{NNN} \leq 256$

$0.0 \leq X, Y, Z, \text{OPACITY} \leq 1.0$

X, Y, and Z are real numbers. (Either X=red, Y=green, and Z=blue, or X=hue, Y=saturation, and Z=value.)

C1, C2, C3, ... is a list of integer composition numbers. Any number of compositions may be listed on a given card image. Use a + to continue the card image if necessary. Only one color number NNN may be associated with a composition C_i . A list of consecutive composition numbers $C_m, C_{m+1}, C_{m+2}, \dots, C_n$ may be entered using the notation $C_m, 0, C_n$, provided that $n > m$.

These card images are described further in Chapter 10.

14.5 Black and White 3-D Perspective Plots

For an overall picture of the core showing final assemblies without details include the following card image in the module zero input.

47000,M,N1,N2,EPS

M is an integer multiplication factor. $M > 1$ means magnify by M. $M < 0$ means reduce by $1/\text{abs}(M)$. $M=1$ is the normal plot. N1, N2 are optional integers (defaults = 1). N1 is the first module 0 cylinder to plot. N2 is the last. EPS is an optional real number (default = 0.0). If the difference between successive radii is less than EPS, the second cylinder is not drawn.

This card image is described further in Chapter 10.

14.6 Color Models

14.6.1 RGB Model

This model uses a Cartesian coordinate system. This may be visualized as a cube with one corner at the origin of the red, green, and blue axes, extending from 0.0 to 1.0 along each axis. Color selection is achieved by specifying a percentage of red, green, and blue that will be added together to form a result.

Examples

- 1) Red of 1.0, green of 1.0, and blue of 1.0 will give bright white.
- 2) Red of 0.5, green of 0.5, and blue of 0.0 will give a dull yellow.
- 3) Red of 0.0, green of 0.0, and blue of 0.3 will give a low intensity blue.

14.6.2 HSV Model

This model uses the hue, saturation, value coordinate system. This may be visualized as a cone with its apex at the bottom and its base at the top. The value axis runs vertically through the center of the cone, with 1.0 at the top (maximum intensity), and 0.0 at the bottom (lowest intensity, or black). The angle around the value axis is hue, with red at 0.0. The hue angle runs from 0.0 to 1.0. The saturation axis extends outward horizontally from the value axis. The center of the cone corresponds to a saturation of 0.0, and the edge of the cone corresponds to a saturation of 1.0. A saturation of 0.0 results in a shade of grey, and a saturation of 1.0 results in the most vivid color possible.

Examples

- 1) Hue of 0.0, saturation of 1.0, and value of 1.0 will give pure red.
- 2) Hue of 0.5, saturation of 0.5, and value of 0.5 will give a greyish cyan.
- 3) Typical hues:
 - 0.00 = red
 - 0.16 = yellow
 - 0.33 = green
 - 0.50 = cyan
 - 0.66 = blue
 - 0.83 = magenta

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A. SLOWING DOWN START

A.1 Slowing Down Start

The slowing-down start is used in RCP01 when the starting group of the problem is not an inelastic group. If composition source densities are not specified in the input, the number of neutrons starting per composition is proportional to the calculated composition slowing-down power times the composition volume; if source densities are specified, then they are used as the composition slowing-down power.

A.1.1 Determination of the Composition, j

First consider the case where the source density is not specified in the input. Let E^1 be the upper energy cutpoint of the starting RCP group treated in RCP01. Let q_j be the slowing-down density in composition j due to scattering reactions above E^1 . The nature of the scattering reactions above E^1 is set by the following assumptions: a) the flux spectrum is given by $1/E$, b) the flux is spatially flat and isotropic, and c) nuclide scattering cross sections above E^1 are energy independent. Thus, the relative number of neutrons per unit volume with energy $E < E^1$ produced from scattering reactions above E^1 in composition j is

$$q_j = \sum_i (\xi^i \Sigma_s^i)_j$$

where the summation is over all nuclides in composition j . The term $\xi^i \Sigma_s^i$ is the nuclide contribution to the asymptotic slowing-down density, ξ^i is the mean lethargy gain per collision for nuclide i , and Σ_s^i is the macroscopic smooth scattering cross section for nuclide i above energy E^1 (taken as the value at E^1 from the RCPL1 job library). Relative to all other compositions, the number of neutrons that degrade in energy below E^1 is proportional to the volume integral of q_j over the volume occupied by composition j . Since q_j is constant due to the spa-

tially flat flux assumption, this integral is equal to $q_j v_j$ where v_j is the composition volume. To choose a starting composition using a random number ρ , where $0 < \rho < 1.0$, the integral of the slowing-down density over all space is first normalized. Let Q_j be the normalized integrated slowing-down density at E^1 for composition j . Then,

$$Q_j = \frac{q_j v_j}{\sum_j q_j v_j}.$$

Using Q_j as a distribution function in histogram form and using a random number ρ , the composition j in which the neutron starts is obtained by solving for j in the following inequality:

$$\sum_{i=1}^{j-1} Q_i < \rho \leq \sum_{i=1}^j Q_i.$$

Note: It will be understood throughout this report that any ρ without an asterisk is a different random number than the ρ previously used. Also, random numbers in separate RCP01 calculations are correlated in the sense that corresponding neutron histories start with the same random number provided the user elects to "skip" the same number of random numbers (see Appendix L for further details).

For the case where the source density, s_j , is specified by composition in the problem input, Q_j becomes

$$Q_j = \frac{s_j v_j}{\sum_j s_j v_j}.$$

A.1.2 Determination of the Energy, E

The neutron energy is determined by first selecting the nuclide in composition j with which a collision above E^1 degraded the neutron in energy below E^1 (the procedure for obtaining E is the same with and without an input source density). The probability that this collision occurred with nuclide i in composition j is proportional to its macroscopic slowing-down contribution $(\xi^i \Sigma'_s)_j$. Thus, the scattering nuclide i is determined by solving the inequality

$$\frac{1}{q_j} \sum_{k=1}^{i-1} (\xi^k \Sigma_s^k)_j < \rho \leq \frac{1}{q_j} \sum_{k=1}^i (\xi^k \Sigma_s^k)_j$$

for i . The exit energy E resulting from such a scattering event (target at rest) must lie in the range $\alpha^i E^1 \leq E \leq E^1$ where $\alpha^i = ((1-\gamma^i)/(1+\gamma^i))^2$, and γ^i is the ratio of the neutron mass to the mass of nuclide i .

The neutron slowing-in source per unit energy due to nuclide i alone, $\eta(E)$, is defined over the range $\alpha^i E^1 \leq E \leq E^1$ by

$$\eta(E) = \Sigma_s^i \frac{(1+\gamma^i)}{4\gamma^i} \left[\frac{1}{E^1} - \frac{\alpha^i}{E} \right].$$

The total number of neutrons slowing down past E^1 due to scattering reactions above E^1 with nuclide i alone integrates to the slowing-down power of nuclide i , $\xi^i \Sigma_s^i$, that is,

$$\xi^i \Sigma_s^i = \int_{\alpha^i E^1}^{E^1} \eta(E) dE$$

where

$$\xi^i = 1 + \frac{\alpha^i}{1 - \alpha^i} \ln \alpha^i.$$

Thus, the distribution function, $f(E)$, for the neutron exit energy due to an isotropic scattering event with nuclide i above energy E^1 is given by

$$f(E) = \frac{(1+\gamma^i)^2}{4\xi^i \gamma^i} \left[\frac{1}{E^1} - \frac{\alpha^i}{E} \right].$$

We now obtain the neutron starting energy, E , by a rejection technique using $f(E)$. That is, set $E = E^1(1 - \alpha^i)\rho + E^1\alpha^i$

The maximum value of $f(E)$ occurs for $E = E^1$, i.e.,

$$f_{\max} = \frac{(1+\gamma^i)^2}{4\xi^i \gamma^i} \frac{1}{E^1} [1 - \alpha^i].$$

Thus, if

$$\rho < \frac{f(E)}{f_{\max}} = \frac{1}{1 - \alpha^i} \left[1 - \alpha^i \frac{E^1}{E} \right],$$

then accept E . Otherwise, repeat the entire process with new pairs of random numbers until E is acceptable.

For the case where the nuclide which degrades the neutron in energy below E^1 is hydrogen and where the exit energy falls in the epithermal binding range or in the thermal group, the exit energy given above has a correct flat distribution function from E^1 to $E = 0$ if the hydrogen velocity is zero (i.e., its temperature is 0°K). However, this distribution is further altered to account for the fact that a collision above E^1 with hydrogen at some “effective” temperature $T^*(^\circ\text{K})$ produces an exit spectrum per unit energy proportional to $\text{Erf}(\sqrt{E/(kT^*)})$, where k is Boltzmann's constant ($\approx 8.61(10^{-5})$ eV/ $^\circ\text{K}$) and where

$$\text{Erf}(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-y^2} dy.$$

This error function spectrum is the result of assuming that the hydrogen velocity is negligible compared to the velocity of a neutron above E^1 , and that in general the hydrogen velocity is not negligible compared to the velocity of an exit neutron resulting from a hydrogen collision above E^1 (the velocities of all heavy nuclides, i.e., those heavier than hydrogen, are assumed to be negligible relative to the velocities of exit neutrons resulting from heavy nuclide collisions above E^1). Accordingly, RCP01 produces the desired neutron slowing-in spectrum in the epithermal binding range and in the thermal group resulting from hydrogen collisions above E^1 by the vectorial addition of a hydrogen velocity vector, drawn randomly, to the neutron velocity vector drawn using the flat distribution in energy. The magnitude of the hydrogen velocity vector has a Maxwellian distribution at T^* . The angular distribution of the hydrogen velocity vector is isotropic in the lab system.

For the special case of a thermal group only calculation, the slowing-in source spectrum due to neutron scattering with nuclide i above E^1 is still obtained using only the above rejection techniques provided nuclide i is not hydrogen (this technique for hydrogen produces a flat energy distribution between E^1 and 0, i.e., $f(E) = 1/E^1$ and E is immediately obtained as $E = E^1\rho$). To produce the thermal slowing-in source spectrum proportional to $\text{Erf}(\sqrt{E/(kT^*)})$ that results from neutron scattering above E^1 with bound hydrogen, then the following rejection technique is used.

$$\text{Set } E = E^1\rho,$$

$$\text{and if } \rho < \text{Erf}\left(\sqrt{\frac{E}{kT^*}}\right),$$

then accept E ; otherwise repeat the entire process with new pairs of random numbers until E is acceptable.

A.1.3 Determination of the Starting Weight, W

The neutron starting weight is set to unity.

A.1.4 Determination of the Basic Region Indices, n, m

The basic region indices are determined as follows: Assuming that the axial zone index, l , is known, denote the total volume of region n, m, l , which may be subdivided by subcells, by $V_{(n, m, l)}$. Let $f_{(n, m), j}^s (s = 1, \dots, G + 1)$ each be a volume fraction of one of the possible $G + 1$ compositions in n, m, l , assigned to one of the $G + 1$ subcell regions s if the composition is j , and let each $f_{(n, m), j}^s = 0$ if the composition is not j (because of the use of cylindrical surfaces with axes parallel to the z -axis, the RCP01 volume fractions are independent of l ; see Appendix H for description of initial assembly volumes). Then, in general, $V_{n, m, l}(f_{(n, m), j}^1 + \dots + f_{(n, m), j}^{G+1})$ is the volume of composition j in n, m, l . An ordering index t is assigned to each basic region n, m . The total volume of composition j in axial zone l , $V_{l, j}$, is

$$V_{l, j} = \sum_{t=1}^T [V_{n, m, l}(f_{(n, m), j}^1 + \dots + f_{(n, m), j}^{G+1})]_t.$$

The desired value of t , and thus (n, m) , is determined by use of random number ρ and solving the inequality for t :

$$\frac{1}{V_{l, j}} \sum_{k=1}^{t-1} [V_{n, m, l}(f_{(n, m), j}^1 + \dots + f_{(n, m), j}^{G+1})]_k < \rho \leq \frac{1}{V_{l, j}} \sum_{k=1}^t [V_{n, m, l}(f_{(n, m), j}^1 + \dots + f_{(n, m), j}^{G+1})]_k$$

A.1.5 Determination of the Axial Zone Index, l

The axial zone index is determined by use of random number ρ and solving the inequality,

$$\frac{1}{V_j} \sum_{i=1}^{l-1} V_{i, j} < \rho \leq \frac{1}{V_j} \sum_{i=1}^l V_{i, j} \text{ for } l.$$

A.1.6 Determination of the Direction Cosines, μ, γ, η

The direction cosines of the neutron velocity vector relative to the cartesian x , y , and z axes, respectively, are determined to be those for an isotropic source as follows (the possible addition to the neutron velocity vector of a randomly drawn hydrogen velocity vector with an isotropic angular distribution as discussed in A.1.2 does not alter the isotropic nature of the source): First observe that $d\mu \, d\theta$ represents a constant elementary area on the surface of a unit

sphere where μ is the projection of a sphere radius on the x -axis and θ is the azimuthal angle of the sphere radius projected on the y - z plane. Thus we choose both μ and θ from flat distributions, That is,

$$\theta = \rho\pi,$$

$$\mu = 2\rho - 1.$$

γ and η are then determined by

$$\gamma = \sqrt{1 - \mu^2} \cos \theta,$$

and

$$\eta = \frac{2\rho - 1}{|2\rho^* - 1|} \sqrt{|1 - \mu^2 - \gamma^2|},$$

where the asterisk on the random number ρ is used to indicate that the same random number is used in numerator and denominator. Observe that θ was drawn from only its half range, but this is sufficient to determine γ . Knowing μ and γ , the magnitude of η is given by $|\eta| = \sqrt{|1 - \mu^2 - \gamma^2|}$. Since the sign of η is equally likely to be positive or negative, the term $(2\rho - 1)/|2\rho^* - 1|$ determines its sign. The absolute value under the square root in the expression for η is to avoid possible round-off difficulties.

B. RANDOM LINEAR SAMPLING

In this case, the probability density $f(E)$ is specified as a set of $N+1$ points $(E_i, f(E_i)), i = 1, 2, \dots, N+1$. The density is the continuous function comprising the line segments connecting the points. We require that $E_{i+1} < E_i$ for all i .

The function in the interval $E_{i+1} \leq E \leq E_i$ is

$$f(E) = f(E_{i+1}) + (f(E_i) - f(E_{i+1})) \cdot \frac{E - E_{i+1}}{E_i - E_{i+1}}.$$

Its integral over the interval $F_i = \frac{1}{2}(E_i - E_{i+1}) \cdot (f(E_i) + f(E_{i+1}))$

An interval is selected by finding i such that

$$\sum_{i'=1}^{i-1} F_{i'} \leq \rho \leq \sum_{i'=1}^i F_{i'}.$$

A second random number ρ is selected and E is determined by solving the equation

$$\int_{E_{i+1}}^E f(E') dE' = \rho \cdot F_i \text{ for } E.$$

C. EQUIPROBABILITY INTERVAL HISTOGRAM SCATTERING

Equiprobability interval histogram scattering is used optionally in RCP01 to define elastic scattering patterns in the inelastic scattering range.

It is specified by a set of N energies E_i , $i = 1, 2, \dots, N$ defining energy intervals over each of which $n + 1$ cosines of scattering angles μ_{ij} ($j = 0, 1, \dots, n$) are provided. For each energy interval, the scattering probability density is uniform between each pair of μ 's. The μ 's are selected so that the probabilities of scattering by an amount μ in each interval $\mu_{ij} \leq \mu \leq \mu_{i,j+1}$ are equal.

Selection of scattering angle, μ , is simply done as follows:

- 1) Find i such that $E_{i-1} > E \geq E_i$.
- 2) Select a random number ρ , calculate $R = n\rho$, $j = \text{int}(R)$, and $f = \text{frac}(R)$.
- 3) Calculate $\mu_c = \mu_{ij} + f \cdot (\mu_{i,j+1} - \mu_{ij})$.

In RCP01, an improved optional model consists of replacing μ_{ij} and $\mu_{i,j+1}$ in the above equation by interpolated values

$$\hat{\mu}_{ij} = \mu_{ij} + \frac{(E - E_i)}{(E_{i-1} - E_i)} \cdot (\mu_{i-1,j} - \mu_{ij})$$

and

$$\hat{\mu}_{i,j+1} = \mu_{i,j+1} + \frac{(E - E_i)}{(E_{i-1} - E_i)} \cdot (\mu_{i-1,j+1} - \mu_{i,j+1})$$

D. A NEUTRON CONSERVING RUSSIAN ROULETTE

Russian Roulette is a commonly used device in neutron reaction rate Monte Carlo calculations. It is used to avoid tracking a large fraction of those neutrons which are not likely to contribute significantly to reaction rates of interest. In particular it is frequently applied to neutrons undergoing thermal collisions in certain compositions, for example H_2O or D_2O in core reflectors. Without Russian Roulette, such neutrons could experience hundreds of collisions before absorption causing an inordinate amount of computer time for such relatively unimportant neutrons. For example if the ratio of $\frac{\Sigma_a}{\Sigma_T}$ is energy independent in the thermal group, then the mean number of collisions before absorption without Russian Roulette can be obtained as follows. Let $\frac{\Sigma_a}{\Sigma_T} = p$. Then the probability of having precisely one collision is p ; the probability of having precisely two collisions is $(1-p)p$; and in general the probability of having precisely n collisions is $(1-p)^{n-1}p$. Thus the mean number of collisions, say m , is given by

$$m = \frac{\sum_{n=1}^{\infty} n(1-p)^{n-1}p}{\sum_{n=1}^{\infty} (1-p)^{n-1}p} = \frac{1}{p} = \frac{\Sigma_T}{\Sigma_a}.$$

Using 0.0253 eV values of $\frac{\Sigma_a}{\Sigma_T}$, the value of m for H_2O is 120 and the value of m for D_2O is 19,000. While conventional Russian Roulette can arbitrarily reduce the mean number of collisions in such compositions by simply adjusting the kill-off probability, there is a serious drawback in that such Russian Roulette is not neutron conserving. This lack of conservation is especially disturbing in Monte Carlo eigenvalue calculations.

The purpose of this appendix is to present a new type of Russian Roulette that is very nearly neutron conserving and to prove that it is a fair game. A fair game in neutron reaction

rate Monte Carlo calculations means that, if A is the transport theory neutron reaction rate, and if A_N is the estimate of this rate after N histories, then it must follow that

$$\lim_{N \rightarrow \infty} [P\{|A_N - A| < \varepsilon\}] = 1$$

for any arbitrarily chosen positive ε . Since, however, Russian Roulette is only a very small part of the total Monte Carlo calculation, the proof of a fair game for a new Russian Roulette strategy need only involve a demonstration that the neutron reaction rates are the same with or without the new Russian Roulette as $N \rightarrow \infty$.

That conventional Russian Roulette in neutron reaction rate Monte Carlo calculations is not neutron conserving is easily seen as follows. We will view the Russian Roulette game as being played on the neutron free flight just prior to a collision site since in this case we do not need to concern ourselves with the details of the neutron reaction rate estimator. If the kill-off probability in composition j is K_j , and if a random number ρ ($0 < \rho < 1$) meets the condition $\rho > K_j$ then survival has occurred on the free flight prior to a collision in composition j and the neutron weight, w_{t_0} , is altered to $w_{t_0} \left[\frac{1}{1-K_j} \right]$. Otherwise the history is terminated. If we consider a Monte Carlo calculation where all neutrons are born and tracked with equal weight w_{t_0} , and further if we permit Russian Roulette to be played only once per history then the following is clear. For a finite number of histories the fraction of total neutrons surviving Russian Roulette, say F , is not, in general, equal to $1 - K_j$. Thus the average neutron surviving weight $F w_{t_0} \left[\frac{1}{1-K_j} \right]$ does not equal the average incident weight w_{t_0} . That is, the condition for neutron conservation is not met.

A new type of Russian Roulette may be defined that is neutron conserving to within some very small epsilon for a reasonable number of histories. To meet the condition for a fair game, this Russian Roulette may be applied only once per neutron history and the histories must be independent up to the Russian Roulette game. We introduce here a weight defect counter for composition j , w_{dj} . This quantity determines survival or kill-off (w_{dj} is initialized to 0). If $w_{dj} \leq 0$ then survival occurs and the new values of w_{t_0} and w_{dj} , say w'_{t_0} and w'_{dj} , are

$$w'_{dj} = w_{dj} + \left[\frac{K_j}{1-K_j} \right] w_{t_0}$$

$$w'_{t_0} = w_{t_0} \left[\frac{1}{1-K_j} \right].$$

If $w_{dj} > 0$ then kill-off occurs and the values of w'_{t_0} and w'_{dj} are:

$$w'_{dj} = w_{dj} - w_{t_0}$$

$$w'_{t_0} = 0.$$

E. DETERMINATION OF FINAL ASSEMBLIES IN CONTACT

The determination of final assemblies in contact with side SN of final assembly FA' , i.e., $FA^1, FA^2, \dots, FA^{C_{SN}}$ (C_{SN} is the number of final assemblies in contact with side SN), as well as determination of the four external corner points of a final assembly in the absolute x - y plane, i.e., $(X_1, Y_1), (X_2, Y_2), (X_3, Y_3), (X_4, Y_4)$, is required to complete the expanded input for a final assembly as discussed in Section 4.3.2.

The process for obtaining the final assemblies in contact is as follows:

1. For final assembly FA' in initial module IM (starting with $FA' = 1$), we check all other final assemblies in initial module IM , $FA=1, \dots, (FA' - 1), (FA' + 1), \dots, N_{IM}$, for contact (i.e., parallel sides within 10^{-4} cm).
2. Define the four corner points of FA in its initial assembly coordinate system using V_g, X_N, Y_{n, M_n} from the expanded input for FA .

Point (1)		$(0, 0)$
Point (2)		$(0, Y_{n, M_n})$
Point (3)	If $V_g = 1$ and if $X_N \geq Y_{n, M_n}$;	$(Y_{n, M_n}, 0)$
	If $V_g = 1$ and if $X_N < Y_{n, M_n}$;	$(X_N, Y_{n, M_n} - X_N)$
	Otherwise;	(X_N, Y_{n, M_n})
Point (4)	(If $V_g = 1$ and if $X_N > Y_{n, M_n}$;	$(Y_{n, M_n}, 0)$
	Otherwise;	$(X_N, 0)$

3. Obtain each of the four corner points of FA in the initial assembly coordinate system for FA' .
4. Define a side SN of FA using corner points n and m defined in the initial assembly coordinate system for FA' by

SN	n	m
Side (1)	1	4
Side (2)	1	2
Side (3)	2	3
Side (4)	3	4

We will denote the pair of points n and m by $(X_n, Y_n), (X_m, Y_m)$.

5. Starting with side 1 (SN) = 1 :

If $|X_m - X_n| < 10^{-4}$ and if $|Y_m - Y_n| < 10^{-4}$ Set $SN = SN + 1$, go to 4).

If $|X_m - X_n| < 10^{-4}$ go to 6).

If $|Y_m - Y_n| < 10^{-4}$ go to 7).

If $|X_m - X_n + Y_m - Y_n| < 10^{-4}$ go to 8).

6. If both $Y_m, Y_n > Y'_{n, M_n} - 10^{-4}$ set $SN = SN + 1$, go to 4).

If both $Y_m, Y_n < 10^{-4}$ set $SN = SN + 1$, go to 4).

Set $A = \frac{1}{Y_m - Y_n} [X_n Y_m - Y_n X_m]$.

If $|A| < 10^{-4}$ list FA as being in contact with side (2) of FA', set $C_2 = C_2 + 1$ and go to next FA at 2).

If $|A - X'_N| > 10^{-4}$ set $SN = SN + 1$, go to 4).

If both $Y_m, Y_n > Y'_{n, M_n} - V'_g X'_N - 10^{-4}$, set $SN = SN + 1$, go to 4).

List FA as being in contact with side (4) of FA', set $C_4 = C_4 + 1$ and go to next FA at 2).

7. Set $D = Y'_{n, M_n}$, but if $X'_N < D$ or if $V'_g = 0$, set $D = X'_N$.

If both $X_m, X_n > D - 10^{-4}$, set $SN = SN + 1$, go to 4).

If both $X_m, X_n < 10^{-4}$, set $SN = SN + 1$, go to 4).

Set $B = \frac{1}{X_m - X_n} [Y_n X_m - X_n Y_m]$.

If $|B| < 10^{-4}$ list FA as being in contact with side (1) of FA', set $C_1 = C_1 + 1$ and go to next FA at 2).

If $V'_g = 1$, set $SN = SN + 1$, go to 4)

If $|B - Y'_{n, M_n}| < 10^{-4}$ list FA as being in contact with side (3) of FA', set $C_3 = C_3 + 1$ and go to next FA at 2).

Set $SN = SN + 1$ and go to 4).

8. If $v'_g = 0$, set $SN = SN + 1$, go to 4).

If both $Y_m, Y_n > Y'_{n, M_n} - 10^{-4}$, set $SN = SN + 1$, go to 4).

Set $D = 0$ but if $X'_N < Y'_{n, M_n}$ set $D = Y'_{n, M_n} - X'_N$

If both $Y_m, Y_n < D + Y'_{n, M_n}$, set $SN = SN + 1$, go to 4)

Set $B = \frac{1}{X_m - X_n} [Y_n X_m - X_n Y_m]$.

If $|B - Y'_{n, M_n}| > 10^{-4}$ list FA as being in contact with side (3) of FA', set $C_3 = C_3 + 1$ and go to next FA at 2).

Set $SN = SN + 1$ and go to 4).

Continue the above process through side 4, $SN = 4$, for FA. Then go to next FA at item 2 and continue through all FA, and finally repeat the whole process for all FA' starting at item 1. When completed, we will have for each final assembly FA', the list of final assemblies in contact with sides 1, 2, 3, and 4 of FA' and also four counters, C_{SN} , that give the number of final assemblies in contact with each side SN .

The process for obtaining the four external corner points of a final assembly FA in the initial module x, y plane, i.e., $(X_n, Y_n), n = 1, \dots, 4$ is defined by item 2 which yields say x, y together with the value of x', y' , i.e., (X_n, Y_n) where x', y' is given by (see Section 4.3)

$$\begin{aligned} x' &= c_1 x + c_2 y + x_{FA} \\ y' &= d_1 x + d_2 y + y_{FA} \end{aligned}$$

F. FINAL MODULE INPUT CHECKS

If two or more final modules intersect in RCP01, then input checks will cause the calculation to abort (RCP01 requires a minimum separation distance between modules of 10^{-4} cm). If two final modules intersect, then some final assembly FA in final module FM intersects some final assembly FA'' in final module FM'. This intersection is detected by treating the twelve edges that form the exterior boundary of FA in FM as neutron paths. These paths are transformed to the initial assembly coordinate system corresponding to FA'' in FM'. Distances along these paths to the six faces of FA'', computed as in module zero tracking, will determine final assembly intersection. This however excludes the type of intersection where FA in FM is completely contained within FA'' in FM' (or vice versa); additional checks determine this possibility. The details of the procedure are as follows:

1. Set $FM = 1$, $FA = 1$
2. Determine starting point x_n, y_n, z_n , direction cosines μ_n, γ_n, η_n , and length R_n of each of the twelve edges of FA in FM (when the distance to any of the six faces of FA'' in FM' from x_n, y_n, z_n along the direction μ_n, γ_n, η_n , say R , is such that $0 < R < R_n$, then an intersection has occurred).

First determine the four corner points in the x - y plane of FA in the initial assembly coordinate system, i.e., $x'_n, y'_n, n = 1, 2, 3, 4$ which accounts for an added zone of 10^{-4} cm thickness. That is

$$\begin{aligned} (x'_1, y'_1) &= (-10^{-4}, -10^{-4}). \\ (x'_2, y'_2) &= (-10^{-4}, Y_{n, M_n} + 2(10^{-4})) ; \text{ if } V_g = 1, \\ &= (-10^{-4}, Y_{n, M_n} + 10^{-4}) \quad ; \text{ otherwise.} \end{aligned}$$

$$\begin{aligned}
(x'_3, y'_3) &= (Y_{n, M_n} + 2(10^{-4}), -10^{-4}) \quad ; \text{ if } V_g = 1 \text{ and if } X_N \geq Y_{n, M_n}, \\
&= (X_N + 10^{-4}, Y_{n, M_n} - X_N) \quad ; \text{ if } V_g = 1 \text{ and if } X_N < Y_{n, M_n}, \\
&= (X_N + 10^{-4}, Y_{n, M_n} + 10^{-4}) \quad ; \text{ otherwise.}
\end{aligned}$$

$$\begin{aligned}
(x'_4, y'_4) &= (Y_{n, M_n} + 2(10^{-4}), -10^{-4}) \quad ; \text{ if } V_g = 1 \text{ and if } X_N \geq Y_{n, M_n}, \\
&= (X_N + 10^{-4}, -10^{-4}) \quad ; \text{ otherwise.}
\end{aligned}$$

For $n = 1, 2, 3, 4$ set,

$$\begin{aligned}
x_n &= x'_n, & \mu_n &= 10^{-8}, \\
y_n &= y'_n, & \gamma_n &= 10^{-8}, \\
z_n &= -10^{-4}, & \eta_n &= 1, \\
R_n &= Z_L + 2(10^{-4}).
\end{aligned}$$

For $n = 5, 6$ set

$$\begin{aligned}
x_n &= x'_1, & \mu_n &= 1, \\
y_n &= y'_1, & \gamma_n &= 10^{-8}, \\
z_5 &= 10^{-4}, & \eta_n &= 10^{-8}, \\
z_6 &= Z_L - 10^{-4}, \\
R_n &= X_N + 2(10^{-4}).
\end{aligned}$$

For $n = 7, 8$ set,

$$\begin{aligned}
x_n &= x'_2, & \mu_n &= \frac{1}{2}V_g + (1 - V_g), \\
y_n &= y'_2, & \gamma_n &= \frac{\sqrt{3}}{2}V_g + (1 - V_g)10^{-8}, \\
z_7 &= 10^{-4}, & \eta_n &= 10^{-8}, \\
z_8 &= Z_L - 10^{-4},
\end{aligned}$$

Set $M = \text{minimum value of } (X_N, Y_{n, M_n}) \text{ if } V_g = 1 ; M = X_N \text{ if } V_g = 0 ,$

$$R_n = M + 2(10^{-4}).$$

For $n = 9, 10$ set,

$$x_n = x'_1, \quad \mu_n = \frac{1}{2} \left(1 - \frac{P}{R} \right) + \frac{P}{R} (10^{-8}),$$

$$y_n = y'_1, \quad \gamma_n = \frac{\sqrt{3}}{2} \left(1 - \frac{P}{R} \right) + \frac{P}{R},$$

$$z_9 = 10^{-4}, \quad \eta_n = 10^{-8},$$

$$z_{10} = Z_L - 10^{-4},$$

$$R_n = Y_{n, M_n} + 2(10^{-4}).$$

For $n = 11, 12$ set,

$$x_n = x'_4, \quad \mu_n = \frac{1}{2} \left(1 - \frac{P}{R} \right) + \frac{P}{R} (10^{-8})$$

$$y_n = y'_4, \quad \gamma_n = \frac{\sqrt{3}}{2} \left(1 - \frac{P}{R} \right) + \frac{P}{R}$$

$$z_{11} = 10^{-4}, \quad \eta_n = 10^{-8}$$

$$z_{12} = Z_L - 10^{-4}$$

$$\begin{aligned} R_n &= 2(10^{-4}) && ; \text{ if } V_g = 1 \text{ and if } X_N \geq Y_{n, M_n}, \\ &= Y_{n, M_n} - X_N + 2(10^{-4}) && ; \text{ if } V_g = 1 \text{ and if } X_N < Y_{n, M_n}, \\ &= Y_{n, M_n} + 2(10^{-4}) && ; \text{ if } V_g = 0. \end{aligned}$$

3. Set $n = 1$.
4. Obtain absolute x, y, z corresponding to x_n, y_n, z_n in FA in FM.
5. Obtain absolute μ_n, γ_n, η_n in FA in FM.
6. Set $FM' = 1$.
7. Determine possible intersection of edge n of FA in FM with FM' .
8. Set $FA'' = 1$ in FM' .
9. If $C = 1$ for FA'' , i.e., if FA'' is an interior final assembly, then go to next final assembly in FM' by setting $FA'' = FA'' + 1$ (note that if final module FM and FM' intersect, then some exterior final assembly of FM intersects FM' or some exterior final assembly of FM' intersects FM).
10. Determine possible intersection of edge n of FA in FM with FA'' in FM' .

11. Obtain $x_n, y_n, z_n, \mu_n, \gamma_n, \eta_n$ for edge n of FA in FM in the coordinate system of the initial assembly corresponding to FA'' in FM', say $x''_n, y''_n, z''_n, \mu''_n, \gamma''_n, \eta''_n$. To avoid division by zero, set:

$$\mu'' = 10^{-8} \text{ if } \mu'' = 0,$$

$$\gamma'' = 10^{-8} \text{ if } \gamma'' = 0,$$

$$\eta'' = 10^{-8} \text{ if } \eta'' = 0.$$

The following six items will determine distances to the six faces of FA''; from x'', y'', z'' along the direction μ'', γ'', η'' and will check for intersection of FA with FA''; (note that initial assembly quantities involved in this check for intersection, i.e., $X''_N, Y''_{N,M_n}, V''_g$, and Z''_L are those for FA''; also the geometry distinction of 60° or 90° is for FA'').

12. Face 1)

$$\begin{aligned} \text{For } 60^\circ \text{ geometry, set } R &= -\frac{\sqrt{3}y''}{2\gamma''}, \\ x_p &= x'' + \mu''R + \frac{y''}{2}. \end{aligned}$$

$$\begin{aligned} \text{For } 90^\circ \text{ geometry, set } R &= -\frac{y''}{\gamma''}, \\ x_p &= x'' + \mu''R \end{aligned}$$

Set $z_p = z'' + R\eta''$.

Set $M = \text{minimum value of } (X''_N, Y''_{N,M_n}) \text{ if } V''_g = 1; = X''_N \text{ otherwise. If } 0 < x_p < M \text{ and if } 0 < z_p < Z''_L \text{ and if } 0 < R < R_n \text{ and if } FM' \neq FM, \text{ then list } FM' \text{ as intersecting FM and set } FM' = FM' + 1 \text{ and return to 7). Otherwise go to 13).}$

13. Face 2)

$$\begin{aligned} \text{For } 60^\circ \text{ geometry, set } R &= -\frac{x''}{\mu'' - \frac{\gamma''}{\sqrt{3}} + 10^{-8}}, \\ y_p &= y'' + \frac{2}{\sqrt{3}}\gamma''R. \end{aligned}$$

$$\begin{aligned} \text{For } 90^\circ \text{ geometry, set } R &= -\frac{x''}{\mu''}, \\ y_p &= y'' + \gamma''R. \end{aligned}$$

Set $z_p = z'' + R\eta''$.

If $0 < y_p < Y''_{N, M_n}$ and if $0 < z_p < Z''_L$ and if $0 < R < R_n$ and if $FM' \neq FM$, then list FM' as intersecting FM and set $FM' = FM' + 1$ and return to 7). Otherwise go to 14).

14. Face 3)

$$\text{For } 60^\circ \text{ geometry, set } R = -\frac{Y''_{N, M_n} - y'' - V''_g x''}{V''_g \mu'' + (2 - V''_g) \frac{\gamma''}{\sqrt{3}} + 10^{-8}},$$

$$x_p = x'' + \left(\mu'' - V''_g \frac{\gamma''}{\sqrt{3}} \right) R + \frac{(1 - V''_g)}{2} (y'' - Y''_{N, M_n}).$$

$$\text{For } 90^\circ \text{ geometry, set } R = \frac{Y''_{N, M_n} - y''}{\gamma''},$$

$$x_p = x'' + \mu'' R.$$

Set $z_p = z'' + R\eta''$.

If $0 < y_p < M$ and if $0 < z_p < Z''_L$ and if $0 < R < R_n$ and if $FM' \neq FM$, then list FM' as intersecting FM and set $FM' = FM' + 1$ and return to 7). Otherwise go to 15).

15. Face 4)

$$\text{For } 60^\circ \text{ geometry, set } R = \frac{x''_N - x''}{\mu'' - \frac{\gamma''}{\sqrt{3}} + 10^{-8}},$$

$$y_p = y'' + \frac{2}{\sqrt{3}} \gamma'' R.$$

$$\text{For } 90^\circ \text{ geometry, set } R = -\frac{x''_N - x''}{\mu''},$$

$$y_p = y'' + \gamma'' R.$$

Set $z_p = z'' + R\eta''$.

If $0 < y_p < Y''_{N, M_n} - V''_g X''_N$ and if $0 < z_p < Z''_L$ and if $0 < R < R_n$ and if $FM' \neq FM$, then list FM' as intersecting FM and set $FM' = FM' + 1$ and return to 7). Otherwise go to 16).

16. Face 5)

$$\text{Set } R = \frac{z''}{\eta''}$$

For 60° geometry, set

$$\begin{aligned} x_p &= x'' + R \left[\mu'' - \frac{1}{\sqrt{3}} \gamma'' \right], \\ y_p &= y'' + R \left[\frac{2}{\sqrt{3}} \gamma'' \right]. \end{aligned}$$

For 90° geometry, set

$$\begin{aligned} x_p &= x'' + R\mu'', \\ y_p &= y'' + R\gamma''. \end{aligned}$$

If $0 < x_p < M$ and if $0 < y_p < Y''_{N,M_n} - V''_g x_p$ and if $0 < R < R_n$ and if $FM' \neq FM$, then list FM' as intersecting FM and set $FM' = FM' + 1$ and return to 7). Otherwise go to 17).

17. Face 6)

Set $R = \frac{Z''_L - z''}{\eta''}$.

For 60° geometry, set

$$\begin{aligned} x_p &= x'' + R \left[\mu'' - \frac{1}{\sqrt{3}} \gamma'' \right], \\ y_p &= y'' + R \left[\frac{2}{\sqrt{3}} \gamma'' \right]. \end{aligned}$$

For 90° geometry, set

$$\begin{aligned} x_p &= x'' + R\mu'', \\ y_p &= y'' + R\gamma''. \end{aligned}$$

If $0 < x_p < M$ and if $0 < y_p < Y''_{N,M_n} - V''_g x_p$ and if $0 < R < R_n$ and if $FM' \neq FM$, then list FM' as intersecting FM and set $FM' = FM' + 1$ and return to 7). Otherwise go to 18).

18. This check insures that if FA is completely contained in FA'' , then FM' ; will be listed as intersecting FM. If $0 < x'' < M$ and if $0 < y'' < Y''_{N,M_n} - V''_g x''$ and if $0 < z'' < Z''_L$, then list FM' as intersecting FM and set $FM' = FM' + 1$ and return to 7). Otherwise set $FA'' = FA'' + 1$ in FM' and return to 8). Continue this process, for the value of n , through all FA'' in FM' and through all FM' .
19. Set $n = n + 1$ and return to item 4); continue this process for all 12 edges of FA in FM.
20. Set $FA = FA + 1$ and return to item 2); continue this process for all FA in FM.
21. Set $FM = FM + 1$, $FA = 1$ and return to item 2); continue this process of all FM (this completes final module input checks).

G. COMPOSITE FINAL ASSEMBLY INPUT CHECKS

A composite final assembly comprises a set of up to eight initial assemblies such that all of the up to seven "secondary" (all but the first) initial assemblies are contained within the first "primary" initial assembly.

Each composite final assembly is checked using the algorithm described in this appendix to detect if each secondary initial assembly, I_a^s , is totally inside the primary initial assembly, I_a^p . This check is performed by obtaining the eight corner points of I_a^s , accounting for the addition of a 10^{-4} cm zone, in the coordinate system of I_a^p and checking to see that each corner point is interior to I_a^p .

1. The four corner points of I_a^s in the x - y coordinate system of I_a^s , say (x'_n, y'_n) , $(n = 1, 2, 3, 4)$, are defined as in item 2) of Appendix F (Final Module Input Checks). We now define the eight corner points of I_a^s in the I_a^p coordinate system, say (x''_n, y''_n, z''_n) , $n = 1, \dots, 8$, as:

$$\begin{aligned} x''_n &= x'_n \\ y''_n &= y'_n \quad \text{for } n = 1, 2, 3, 4, \\ z''_n &= -10^{-4} \end{aligned}$$

$$\begin{aligned} x''_n &= x'_{n-4} \\ y''_n &= y'_{n-4} \quad n = 5, 6, 7, 8. \\ z''_n &= Z_L^s + 10^{-4} \end{aligned}$$

2. For all 8 corner points $n = 1, \dots, 8$, transform (x''_n, y''_n, z''_n) to the coordinate system of I_a^p say (x_n, y_n, z_n) .

A corner is outside the primary initial assembly if:

If $x_n < 0$, or $y_n < 0$, or $z_n < 0$, or $z_n > z_L^p$, or $y_n > Y_{n,M_n}^p - V_g^p x_n$.

Set M = minimum value of x_N^p, Y_{n,M_n}^p .

If $x_n > x_N^p(1 - V_g^p) + V_g^p M$ the corner is also outside the primary initial assembly.

For each composite final assembly with an error in its geometrical description, RCP01 prints a comment that the secondary initial assembly is not contained in the primary initial assembly.

If one or more of the composite final assemblies fails to have its secondary initial assemblies contained within its primary initial assembly, then RCP01 aborts the calculation.

H. INITIAL ASSEMBLY VOLUME CALCULATIONS

The calculation of initial assembly volumes requires the calculation of total area fractions in basic region n, m i.e., $f_{n,m}^1, \dots, f_{n,m}^t, \dots, f_{n,m}^{G+1}$ corresponding to the $G+1$ possible compositions defined by the G permitted ellipses per P-list as discussed in Section 4.2.3. These area fractions require the calculation of the area A_t interior to ellipse t in the subcell. Of course, the ellipse may be truncated by the subcell boundaries and, furthermore, may be truncated by the basic region boundaries.

The calculational steps for initial assembly volumes are summarized next.

1. First, we move the anchor point (x_a, y_a) for the P-list to a new anchor point (x'_a, y'_a) which falls below the lower left corner of basic region n, m as illustrated in Figure H-1.

To move to the new anchor point, set

$$k_x^a = \text{integral part of } \frac{x_a - X_{n-1}}{D_x},$$

$$k_y^a = \text{integral part of } \frac{y_a - Y_{n,m-1}}{D_y}.$$

The new anchor point then becomes: $x'_a = x_a - (k_x^a + 1)D_x$, and

$$y'_a = y_a - (k_y^a + 1)D_y.$$

2. We then calculate the total area over region n, m for each ellipse t accounting for all truncations, first by the subcell boundaries D_x, D_y , and secondly, by the basic region boundaries as illustrated in Figure H-1. This is done by calculating area contributions for each subcell repeated along the x -axis first. Repeating continues until the next subcell to be considered along the x -axis lies completely outside the basic region. Then we move up a subcell distance along the y -axis and repeat the process along the x -axis

Figure H-1 Example of RCP Basic Region Filled by Subcells Containing Elliptical Surfaces

again. We continue moving up the y -axis until the next subcell to be considered along the y -axis lies completely outside the basic region. The sum of all contributions obtained by this process yields A_t , the total area of ellipse t in basic region n, m .

3. The total area of basic region n, m , say $A_{n,m}$, is given by

$$A_{n,m} = \left[\frac{\sqrt{3}}{2} (1 - P/R) + P/R \right] [Y_{n,m} - Y_{n,m-1}] [X_n - X_{n-1}].$$

Thus the area fraction corresponding to ellipse t alone is given by

$$f_{n,m}^t = \frac{A_t}{A_{n,m}}.$$

Knowledge of the ellipse arrangement within the subcell then enables the calculations of basic region area fractions from the quantities $f_{n,m}^t$. The calculation of the area interior to ellipse t in a subcell and the deduction of ellipse arrangement from P-List data is given in the remainder of this appendix. This calculation is the area option of the RGM (Reactor Materials and Geometry) system developed by D. J. DiLeonardo and J. R. Popp of Bettis.

H.1 Area Calculation Overview

In this overview we will consider the mathematical concepts used in RCP01 which calculates areas for quadratic surfaces such as circles and ellipses bounded by a convex polygon. Several examples are shown in Figure H-2. Note that the ellipses are truncated at the polygon

Figure H-2 Examples of Quadratic Surfaces in a Convex Polygon Region

boundaries. RCP makes extensive use of ellipses to define the straight and curved detailed structure of a core, core internal components and the pressure vessel.

The approach which is taken in calculating areas is to first determine the orientation of the polygon relative to one or more ellipses. The polygon is transformed into the coordinate system of each ellipse with the center of the ellipse at the origin and its major and minor axes coincident with the coordinate directions. Each side of the convex polygon is tested for intersections or tangency with the ellipse and the result of the test recorded in a status table. The table is then examined to determine the component boundaries forming the ellipse region. When the ellipse is inside the polygon, the ellipse equation completely defines the surface. When the ellipse intersects the polygon, the governing equations for the straight line and for the ellipse define the component boundaries of the ellipse region as shown in Figure H-3. The area and centroid of the ellipse regions are found using line integrals over the component boundaries.

After all ellipses in the polygon have been processed, the ellipse region centroids are utilized to deduce the ellipse configuration in the polygon. When nesting occurs, the inner ellipse area is subtracted from the outer one. Nesting to any depth is permitted. Finally, the area of the

Figure H-3 Examples of Component Boundaries Defining Shaded Ellipse Region

polygon outside an ellipse is obtained by subtracting the ellipse region areas from the polygon area.

In the following sections we will describe the line integral method used to compute the areas and centroids, the details of the status table, the geometric constraints which are imposed on the ellipse configurations in a polygon due to the method used to obtain the areas and finally, the mathematical techniques used to determine if the restraints on the ellipse configurations have been met.

H.2 Equations for Ellipse Region Areas and Centroids

H.2.1 Introduction

The equations used to calculate the ellipse region area and centroid in a convex polygon are derived in the following sections from line integrals taken along plane curves bounding the ellipse region.

H.2.2 Line Integral

Green's theorem for a plane defines the relationship between a line integral along the boundary C of a region R and the area integral taken over the given region. The form of the theorem is

$$\iint_R \left(\frac{\partial V}{\partial x} - \frac{\partial U}{\partial y} \right) dx dy = - \int_C (U dx + V dy) \quad (1)$$

where $U(x, y)$ and $V(x, y)$, $\frac{\partial U}{\partial y}$ and $\frac{\partial V}{\partial x}$ are continuous single valued functions over the closed region R which is bounded by the curve C . For the form of the theorem stated in (1), the boundary is assumed to be described in the negative direction. If one walks along the curve in the direction of the description, the enclosed region is always to the right. Thus for simply connected regions (see Figure H-4), such as those bounded by a circle or ellipse, the negative direction is a traverse of the boundary in the clockwise direction.

Figure H-4 Simply Connected Region

Regions which contain holes are known as multiply connected regions. For this type, both clockwise and counterclockwise movement over the boundary will occur as shown in Figure H-5.

H.2.3 Equations for the Ellipse Region Area

Upon introducing

$$\begin{aligned} U &= \frac{-y}{2} \\ V &= \frac{x}{2} \end{aligned} \quad (2)$$

Figure H-5 Multiply Connected Region

into (1) we have

$$\iint_R dx dy = -\frac{1}{2} \int_C (-y dx + x dy). \quad (3)$$

Equation (3) establishes the relationship between the area of a region and the line integration over the boundary curve of the region. For an ellipse in a polygon the boundary curve is defined by both straight lines

$$\begin{aligned} y &= mx + c & m &\neq \infty \\ x &= x_i & m &= \infty \end{aligned} \quad (4)$$

and ellipse equations given in parametric form (see Figure H-6)

$$\begin{aligned} x &= a \cos t \\ y &= b \cos t \end{aligned} \quad (5)$$

where m is the slope of the line, c is the y intercept, x_i is the x intercept, a is the x semi-axis of the ellipse, b is the y semi-axis and t is the parameter angle measured positive counter-clockwise relative to the positive x axis and related to the polar angle θ by

$$\tan \theta = (b/a) \tan t. \quad (6)$$

Figure H-6 Parameters Defining Ellipse

For a straight line boundary component we substitute (4) into the right-hand side of (3) and integrate from the starting point x_1, y_1 to the end point x_2, y_2 . This gives

$$\begin{aligned} I &= -\frac{1}{2} \int_{x_1, y_1}^{x_2, y_2} [-(mx + c)dx + mxdx] & m \neq \infty \\ I &= -\frac{1}{2} \int_{x_1, y_1}^{x_2, y_2} x_i dy & m = \infty \end{aligned} \quad (7)$$

which reduces to

$$\begin{aligned} I &= \frac{1}{2} c(x_2 - x_1) & m \neq \infty \\ I &= -\frac{1}{2} x_i(y_2 - y_1) & m = \infty. \end{aligned} \quad (8)$$

For the boundary component defined by the ellipse equation we substitute (5) into (3) together with the relations

$$\begin{aligned} dx &= -a \sin t dt \\ dy &= b \cos t dt \end{aligned}$$

to obtain

$$I = -\frac{1}{2} \int_{t_1}^{t_2} (ab \sin^2 t dt + ab \cos^2 t dt) \quad (9)$$

which reduces to

$$I = -\frac{1}{2} ab \Delta t. \quad (10)$$

The integration is again taken in the clockwise direction where t_1 and t_2 are the parameter angles at the start and end of the curve. These angles are obtained from (5) as follows

$$\begin{aligned}x_1 &= a \cos t_1 \\y_1 &= b \sin t_1 \\ \tan t_1 &= \left(\frac{y_1}{x_1}\right)\left(\frac{a}{b}\right) \\ t_1 &= \text{atan}\left[\left(\frac{y_1}{x_1}\right)\left(\frac{a}{b}\right)\right]\end{aligned}\tag{11}$$

and similarly

$$t_2 = \text{atan}\left[\left(\frac{y_2}{x_2}\right)\left(\frac{a}{b}\right)\right].\tag{12}$$

In (10), Δt is given by

$$\Delta t = t_2 - t_1\tag{13}$$

unless the integration path crosses the positive x axis. In this case, 2π is subtracted from the right side of (13) to give the correct total angular change.

$$\Delta t = t_2 - t_1 - 2\pi.\tag{14}$$

The area of the ellipse region is given by the sum of the line integrals of the N boundary components forming the surface of the region.

$$A_t = \sum_{j=1}^N I_j.\tag{15}$$

In RCP, of course, the polygon region is either a parallelogram or a rectangle, e.g., the subcell box is of size D_x by D_y . Similarly the basic region itself is a parallelogram or a rectangle.

H.2.4 Equations for the Ellipse Region Centroids

To obtain the $\bar{x}$ component of the centroid for the ellipse region in the polygon, let

$$\begin{aligned}U &= -\frac{xy}{2} \\ V &= \frac{x^2}{4}\end{aligned}\tag{16}$$

Figure H-7 Centroid of Ellipse Region

and substitute into (1)

$$\iint_R x dx dy = -\int_C \left(\frac{-xy}{2} dx + \frac{x^2}{4} dy \right). \quad (17)$$

Equation (17) defines the line integral form for the product $\bar{x}A_R$ where A_R is the region area.

To obtain the $\bar{y}$ component of the ellipse region area we introduce

$$\begin{aligned} U &= \frac{-y^2}{4} \\ V &= \frac{xy}{2} \end{aligned} \quad (18)$$

into (1) and get

$$\iint_R y dx dy = -\int_C \left(\frac{-y^2}{4} dx + \frac{xy}{2} dy \right). \quad (19)$$

Equation (19) establishes the line integral form for $\bar{y}A_R$.

For a straight line boundary component, (4) is substituted into (17) and (19) to give

$$\begin{aligned} I_x &= -\int_{x_1}^{x_2} \left[\frac{-x(mx+c)}{2} dx + \frac{mx^2}{4} dx \right] & m \neq \infty \\ I_x &= -\int_{y_1}^{y_2} \frac{x_i^2}{4} dy & m = \infty \\ I_y &= -\int_{x_1}^{x_2} \left[\frac{-(mx+c)^2}{4} dx + \frac{x(mx+c)}{2} mx dx \right] & m \neq \infty \\ I_y &= -\int_{y_1}^{y_2} \frac{x_i y}{2} dy & m = \infty. \end{aligned} \quad (20)$$

Upon simplifying (20) we have

$$\begin{aligned}
 I_x &= \frac{m}{12}(x_2^3 - x_1^3) + \frac{c}{4}(x_2^2 - x_1^2) \quad m \neq \infty \\
 I_x &= \frac{x_i^2}{4}(y_2 - y_1) \quad m = \infty \\
 I_y &= -\frac{m^2}{12}(x_2^3 - x_1^3) + \frac{c^2}{4}(x_2 - x_1) \quad m \neq \infty \\
 I_y &= \frac{x_i}{4}(y_2^2 - y_1^2) \quad m = \infty.
 \end{aligned} \tag{21}$$

To evaluate the centroid line integrals for ellipse boundary components, (5) is substituted into (17) and (19). This gives

$$\begin{aligned}
 I_x &= -\int_{t_1}^{t_2} \left[\frac{a^2 b \cos t \sin^2 t}{2} dt + \frac{a^2 b}{4} \cos^3 t dt \right] \\
 I_y &= -\int_{t_1}^{t_2} \left[\frac{ab^2 \sin^3 t dt}{4} + \frac{ab^2}{2} \cos^2 t \sin t dt \right]
 \end{aligned} \tag{22}$$

which reduces to

$$\begin{aligned}
 I_x &= \frac{a^2 b}{4} [(1/3) \sin t_1 (\cos^2 t_1 + 2) - (1/3) \sin t_2 (\cos^2 t_2 + 2) + (2/3)(-\sin^3 t_2 + \sin^3 t_1)] \\
 I_y &= \frac{ab^2}{4} [-(1/3) \cos t_1 (\sin^2 t_1 + 2) + (1/3) \cos t_2 (\sin^2 t_2 + 2) + (2/3)(\cos^3 t_2 - \cos^3 t_1)].
 \end{aligned} \tag{23}$$

When evaluating the centroid line integrals (20) and (22), the integration is performed in the clockwise direction.

The last step in obtaining the centroid of the ellipse region is to sum the centroid line integral components I_x and I_y and divide by the area. We then have

$$\begin{aligned}
 \bar{x} &= \frac{\sum_{j=1}^N I_{x,j}}{A_R} \\
 \bar{y} &= \frac{\sum_{j=1}^N I_{y,j}}{A_R}.
 \end{aligned} \tag{24}$$

H.3 Status Table Construction and Evaluation

H.3.1 Introduction

We wish to use the line integrals described in the previous section to find the area of a region defined by the intersection of a polygon and an ellipse. To do this we need to know the elliptic and straight line components forming the boundary of the region and their end points. A status table, giving the location of polygon-ellipse intersections and the relationship of the polygon's vertices to the ellipse, is constructed to gain this knowledge. The following sections describe methods used to construct the status table and to deduce a description of the region boundary from it.

H.3.2 Construction of the Status Table

For each vertex of the polygon an entry is made in the status table concerning the status of the vertex, either inside, outside, or on the ellipse, and the location of any polygon-ellipse intersections found along the line to the next vertex in the clockwise direction. The first step in obtaining these values is to translate the polygon to the standard coordinate system of the ellipse. Then, using the process described in Section H.4.6 of this Appendix, the status of the vertices of the polygon is determined. Vertices within an ε distance of the ellipse are assumed to be on the ellipse.

To find the intersections on the line connecting the vertices (x_i, y_i) and (x_j, y_j) we substitute the equation of the straight line defined by the points

$$\begin{aligned} y &= x \left(\frac{y_i - y_j}{x_i - x_j} \right) + \left[y_j - x_j \left(\frac{y_i - y_j}{x_i - x_j} \right) \right] \text{ if } x_i \neq x_j \\ x &= x_i \text{ if } x_i = x_j \end{aligned} \quad (25)$$

into the ellipse equation

$$\left(\frac{x}{a} \right)^2 + \left(\frac{y}{b} \right)^2 = 1 \quad (26)$$

forming a quadratic in x (or y if $x_i = x_j$). If the discriminant is less than or equal to zero we have no intersections or just a tangency. Therefore, we only need to solve the equation when the discriminant is positive. If this is the case, we find the two distinct x (or y) values by the quadratic formula and, by substitution into (25), determine the corresponding y (or x) values. These x, y pairs are the intersections of the ellipse with the line. If a (x, y) lies between (x_i, y_i) and (x_j, y_j) then the point is on the polygon boundary. The intersections, thus found, are then listed in the status table in the order they would be encountered when traversing the polygon in a clockwise direction.

Two characteristics of the vertices which make further analysis necessary are:

- (a) The possibility an intersection may be counted twice, once at the vertex and once on the line nearby, because of round off.
- (b) The need to determine if an intersection actually occurs at a vertex lying on the ellipse. For example, in Figure H-8a there is an intersection at the upper left hand corner, while in Figure H-8b there is not.

Figure H-8 Two Possible Occurrences at a Vertex on the Ellipse

To account for these characteristics we first delete from the status table any intersections between two consecutive vertices lying on the ellipse. The side between these vertices is completely within the ellipse, and any intersection on it is the result of inconsistent round off. Next, for any vertex lying on the ellipse we determine the relation of the sides of the polygon to the ellipse near the vertex. For example, if, in Figure H-9 vertex n is on the ellipse, we wish

Figure H-9 Relation of Neighboring Sides and Vertices of Vertex n which is on the Ellipse

to know if sides $n-1$ and n , within a neighborhood of vertex n , lie inside or outside the ellipse. In the following discussion we will refer to side $n-1$ and vertex $n-1$, but the same reasoning applies to side n and vertex $n+1$.

If vertex $n-1$ lies on or inside the ellipse, the entire side $n-1$, and therefore the part within a neighborhood lies inside. Any intersections along this side are deleted. Otherwise, vertex $n-1$ lies outside the ellipse. In this case the neighborhood lies outside if there are an even number of intersections of side $n-1$ and the ellipse, and inside if there are an odd number of intersections.

If we find the same status for the neighborhoods of sides $n-1$ and n , i.e., both inside or both outside, then vertex n is given that status. However, if one is inside and the other outside, then vertex n is listed as a polygon ellipse intersection. Thus, using this procedure, the upper left hand corner of Figure H-8a would be entered as an intersection while the corresponding corner in Figure H-8b would be listed as inside. The status table is now complete and ready to be processed.

H.3.3 Determination of Integrals from the Status Table

From the completed status table the component boundaries of the area common to the ellipse and the polygon region can be deduced. The first step is to check for three special cases.

- (a) If all the vertices of the polygon are in the ellipse, the polygon is completely within the ellipse. In this case the region we are looking for is the entire polygon. Its area and centroid are obtained by integrating around the sides of the polygon.
- (b) If all the vertices of the polygon are outside the ellipse and if there are no polygon-ellipse intersections, and if the center of the ellipse is in the polygon; the ellipse is completely within the polygon. For this case the region is the ellipse with area $ab\pi$ and centroid (x_c, y_c) (See Section H.4.5 for ellipse parameters.)
- (c) If all the vertices are outside the ellipse, if there are no polygon-ellipse intersections, and if the center of the ellipse is outside the polygon; the ellipse and polygon are disjoint. In this case there is no common region. Therefore the area is zero; the centroid does not exist and is set arbitrarily to zero.

If none of the above cases occur, the status table must be analyzed to obtain the component boundaries. A vertex of the polygon outside the ellipse is found. Relative to this vertex, the polygon-ellipse intersections are numbered, from 1 to n , in a clockwise direction. We then integrate between successive intersections forming a closed figure to find the area and centroid of the region. If, when integrating from intersection i to intersection j , i is odd, the integration is done along the polygon border in the clockwise direction as a series of one or more straight lines. If i is even, the integration is done clockwise along the ellipse connecting intersections i and j . After computing the area and centroid, the centroid is translated back to the original coordinate system.

The process is repeated for each ellipse assigned to the polygon region. When we have obtained an area and centroid for each region formed by the polygon and ellipses, we are ready to determine the ellipse configuration in the polygon. This process is described in the following section.

H.4 Determining Ellipse Configurations in a Polygon

H.4.1 Introduction

Several geometric restraints are required on the nesting of ellipses in order that the holes, created by overlaying ellipses, can be found. The method used to determine nesting, the restraints imposed on the ellipse configuration by the procedure and the tests used to determine that the restraints are satisfied are described next. In the discussion, when we refer to the area A , we are speaking of that area bounded by the intersection of the polygon region and ellipse A .

H.4.2 Determine Ellipse Configurations

There are two important aspects to the determination of ellipse configurations:

- (a) The ability to deduce the relative stacking of any two ellipses in a configuration.
- (b) The use of a procedure which can determine any level of stacking working with only two ellipses at a time.

For any two ellipses in the configuration given in order: A, B ; we know, by the geometric restraints described in the next section, that only two valid configurations are possible: area B is completely contained in area A or areas A and B are disjoint. Therefore, we simply determine if the centroid of area B is inside or outside ellipse A (it cannot lie on ellipse A if area B is nonzero) by the procedure described in Section H.4.6. If it is inside, then area B creates a hole in area A and is accordingly subtracted from A . Otherwise, the areas are disjoint and no subtraction is done.

The above process works with two ellipses at a time. However, the following two examples will illustrate that by working with pairs of ellipses in a specific order any level of nesting may be deduced. In Figure H-10a the areas of B and C are subtracted from A and the proper result is obtained. In Figure H-10b, though, we must subtract area C from area B before subtracting area B from area A . Otherwise area C will be subtracted from area A twice, once as area C itself and once as part of area B . In general, all holes in an ellipse area must be accounted for before that area is used to create holes in other areas.

Figure H-10 Two Possible Nestings of Ellipses

H.4.3 Geometric Restrictions on Ellipse Configurations

To ensure that no ambiguity exists in detecting ellipse configurations, two geometric restraints are imposed:

- (a) The areas of any two ellipses, within the region, must either be disjoint or one completely contained within the other.
- (b) The ellipses are in an ordered set such that if area A contains area B , then ellipse A must appear in the set before ellipse B .

These restraints can be restated as four rules which can be tested analytically. In the following discussion we assume ellipse A appears before ellipse B .

- (a) Ellipses A and B are not allowed to intersect within a polygon region. However, intersections outside or on the border of the polygon or tangencies anywhere are allowed. The test for ellipse-ellipse intersections is described in the next section.

Figure H-11 Examples of Violation of Rule a

- (b) Ellipse B cannot contain intersections of the polygon boundary and ellipse A . This would imply that region B is partly inside and partly outside ellipse A . Adherence

Figure H-12 Examples of Configurations Allowed by Rule a

to this rule is determined by testing the points of intersection, between an ellipse and the polygon, given in the status table for that ellipse. These intersection points are checked for containment within a later ellipse by the method described in Section H.4.6.

Figure H-13 Violation of Rule b Marked by x

- (c) Ellipse *B* cannot contain the centroid of area *A* unless ellipse *A* contains the centroid of area *B*. A violation of this rule implies improper order of the set of ellipses. At the time it is determined that centroid *B* is not in ellipse *A* for nesting determination, a check is made to see if the centroid of *A* is in ellipse *B*.
- (d) Ellipse configurations which generate negative areas imply a violation in the input order.

Figure H-14 Example of a Violation of Rule c

Figure H-15 Example of a Violation of Rule d

H.4.4 Testing for Ellipse-Ellipse Intersections

To detect intersections between two ellipses within the region, the following procedure is used. The second ellipse is transformed into the coordinate system of the first by translation of the second's center and subtraction of the first's tilt angle from the second's. (See Section H.4.5 for definition of the standard ellipse parameters.) The second ellipse is now written in the form

$$Ax^2 + Bxy + Cy^2 + Dx + Ey + F = 0 \quad (27)$$

with ellipse parameters as defined in Section H.4.5.

The first ellipse equation in its own coordinate system is

$$\left(\frac{x}{a_1}\right)^2 + \left(\frac{y}{b_1}\right)^2 = 1 \quad (28)$$

Combining (28) with (27) we obtain a polynomial of the form

$$A_4x^4 + A_3x^3 + A_2x^2 + A_1x + A_0 = 0 \quad (29)$$

where

$$\begin{aligned}
 A_4 &= \left(A - \left(\frac{b_1}{a_1}\right)^2 C\right)^2 + \left(\frac{b_1 B}{a_1}\right)^2 \\
 A_3 &= 2\left(A - \left(\frac{b_1}{a_1}\right)^2 C\right)D + 2BE\left(\frac{b_1}{a_1}\right)^2 \\
 A_2 &= D^2 + 2\left(A - \left(\frac{b_1}{a_1}\right)^2 C\right)(F + b_1^2 C) - (Bb_1)^2 + \left(\frac{b_1 E}{a_1}\right)^2 \\
 A_1 &= 2D(F + b_1^2 C) - 2BEb_1^2 \\
 A_0 &= (F + b_1^2 C)^2 - (Eb_1)^2.
 \end{aligned}$$

Some or all the coefficients of (29) may be zero. If all are zero, the two ellipses are the same and intersect at all points. If A_0 is the only nonzero coefficient, we have two concentric non-intersecting ellipses.

The only other possibilities are that (29) reduces to a quadratic or that it remains a quartic. If (29) remains a quartic, we divide through by A_4 and factor it into two quadratics by iteration on their coefficients as

$$(x^2 + B_1x + \gamma_1)(x^2 + B_2x + \gamma_2) = 0. \quad (30)$$

Thus in either case we can find the roots of (29) by the quadratic formula.

The real roots of (29) are possible x intersection values. To determine if there actually is an intersection at any of these values, we first find the corresponding y values (generally two per x value) by substituting x into (28). Each x, y pair thus found is then substituted into (27). If the equation is satisfied we test for tangency at (x, y) by checking the slopes of the two ellipses

$$\begin{aligned}
 \frac{dy}{dx} &= -\frac{xb_1^2}{ya_1^2} && \text{ellipse 1} \\
 \frac{dy}{dx} &= -\frac{2Ax + By + D}{Bx + 2Cy + E} && \text{ellipse 2.}
 \end{aligned} \quad (31) \text{ and } (32)$$

If the slopes are equal, we have a tangency. If not, we check to see if the intersection is inside the polygon region. Any point which is found to be inside is in violation of Rule a.

H.4.5 Ellipse Parameters and Equation Forms

An ellipse in the $x-y$ plane can be completely defined by five parameters:

a, b = semi-axes

θ = the angle the a -axis is tilted from the horizontal in the counterclockwise direction

x_c = x -coordinate of the center

y_c = y -coordinate of the center

Figure H-16 Ellipse Parameters

These ellipse parameters can be used to form a number of useful ellipse equations.

If we are in the standard ellipse coordinate system, i.e., origin at the center of the ellipse and the x -axis co-linear with the a -axis, we can write the ellipse equation as

$$\left(\frac{x}{a}\right)^2 + \left(\frac{y}{b}\right)^2 = 1 \quad (33)$$

or in parametric form

$$\begin{aligned} x &= a \cos t \\ y &= b \sin t. \end{aligned} \quad (34)$$

The most general form of the ellipse equation is

$$Ax^2 + Bxy + Cy^2 + Dx + Ey + F = 0 \quad (35)$$

where

$$\begin{aligned} A &= (b \cos \theta)^2 + (a \sin \theta)^2 \\ B &= 2(b^2 - a^2) \sin \theta \cos \theta \\ C &= (b \sin \theta)^2 + (a \cos \theta)^2 \\ D &= -2x_c A - y_c B \\ E &= -x_c B - 2y_c C \\ F &= x_c^2 A + x_c y_c B + y_c^2 C - a^2 b^2. \end{aligned}$$

H.4.6 Finding the Relation of a Point to an Ellipse

In testing ellipse configuration violations and determining nesting, it is often necessary to know if a point lies inside, outside, or on an ellipse. We first rewrite the ellipse equation

$$\left(\frac{x}{a}\right)^2 + \left(\frac{y}{b}\right)^2 = 1 \quad (36)$$

as a function

$$f(x, y) = \left(\frac{x}{a}\right)^2 + \left(\frac{y}{b}\right)^2 - 1 \quad (37)$$

Next assume that a point (x_0, y_0) is defined relative to the standard ellipse coordinate system by an appropriate transformation. From the value of $f(x_0, y_0)$ we conclude

- If $f(x_0, y_0) < 0$ (x_0, y_0) lies within the ellipse
- $= 0$ (x_0, y_0) lies on the ellipse
- > 0 (x_0, y_0) lies outside the ellipse.

I. MODULE ZERO VOLUMES

The calculation of module zero volumes requires the calculation of volumes of cylindrical or spherical sections cut out by axial planes. The m, l region determined by the planes Z_{l-1}, Z_l and radii R_{m-1}, R_m will have a particular composition j assigned to it. (Recall from the description of module zero input that the first C-List gives the composition arrangement by z -zone interior to the first cylinder (or sphere); the second C-List gives the composition arrangement by z -zone of the domain lying between the first and second cylinders (or spheres) etc.). The composition j has total volume V_j computed as a sum over all m, l regions that contain composition j . Module zero volumes in the RCP edits do not account for any volume displacement resulting from the final module overlay.

For cylindrical module zero, composition volumes are obtained using

$$V_j = \sum_{m,l} \pi(R_m^2 - R_{m-1}^2)(Z_l - Z_{l-1})$$

where $R_0 = 0$, and where m, l defines a region that contains composition j .

For spherical module zero we will make use of an expression for obtaining the volume of a sphere of radius R_m cut by arbitrary planes Z_{l-1} and Z_l . This expression is

$$V_{m,l} = \pi \int_{Z_{l-1}}^{Z_l} (R_m^2 - z^2) dz$$

where the limits Z_l and Z_{l-1} are altered as follows:

if $Z_{l-1} < 0.0$ and $\frac{|Z_{l-1}|}{R} > 1.0$, set $Z_{l-1} = -R$,

if $Z_l < 0.0$ and $\frac{|Z_l|}{R} > 1.0$, set $Z_l = -R$,

if $Z_{l-1} > 0.0$ and $\frac{Z_{l-1}}{R} > 1.0$, set $Z_{l-1} = +R$,

if $Z_l > 0.0$ and $\frac{Z_l}{R} > 1.0$, set $Z_l = +R$.

This yields

$$v_{m,l} = \pi[R_m^2(Z_l - Z_{l-1}) - (Z_l^3 - Z_{l-1}^3)/3].$$

since module zero is made up of concentric spheres, we obtain by subtraction

$$V_{m,l} = v_{m,l} - v_{m-1,l}$$

The sum over all regions m, l that contain composition j is the composition volume, i.e.,

$$V_j = \sum_{m,l} V_{m,l}$$

J. PERTURBATION CALCULATION

A perturbation calculation as proposed by E. M. Gelbard at Bettis is available in RCP01. It permits arbitrary changes of the nuclide atom densities for all nuclides in a specified composition (RCP01 requires that this be composition 1). The perturbation calculation also permits arbitrary cross-section changes per nuclide for all nuclides in the specified composition. However, in this latter case the assumption is made that a perturbed thermal kernel, for a thermal kernel nuclide, is the same as the unperturbed thermal kernel; the thermal scattering cross section for a kernel nuclide is permitted to change with the perturbation. Of course, the perturbation calculation permits any combination of nuclide atom density changes and nuclide cross-section changes for composition 1.

If the perturbation calculation is performed following an eigenfunction calculation, then the perturbation is of first order; that is, the effect of the perturbation on the eigenfunction source is not taken into account. The perturbation calculation for a fixed source problem involves no approximations other than the universal approximation made for the thermal kernel.

The perturbation calculation in RCP01 is simply a special re-edit of special neutron collision files over all collisions in all compositions with the required perturbed microscopic cross sections for composition one being obtained from a new RCPL1 job library (if only atom densities are being perturbed then a new job library is not required).

The parameters from the collision parameter list (this list is described in Section 8.6) used in the perturbation re-edit are:

- j - composition number
- g - RCP group number
- h - history number
- i_s - scattering nuclide
- δ_s - if scattering is elastic, $\delta_s = 0$; if scattering is inelastic, $\delta_s = 1$.
- d - distance traveled in composition 1 since last collision (this quantity is absent unless the requestor specifies a perturbation calculation).

E_0 - incident neutron energy.

ϕ_j^E - neutron flux estimate at collision site.

Σ_s - scattering cross section at E_0 for scattering nuclide i_s : Σ_s is the elastic scattering cross section if $\delta_s = 0$; Σ_s is the inelastic scattering cross section if $\delta_s = 1$. (This quantity is absent unless the requestor specifies a perturbation calculation).

Σ_T - total cross section at E_0 for composition j . (This quantity is absent unless the requestor specifies a perturbation calculation).

The macroscopic cross sections per collision at $E = E_0$ constructed using the new RCPL1 job library in the perturbation re-edit are the perturbed scattering cross section for nuclide i_s , i.e., Σ'_s (this is the elastic scattering cross section if $\delta_s = 0$; it is the inelastic scattering cross section if $\delta_s = 1$), and the perturbed total cross section, i.e., Σ'_T .

The process involved in the perturbation re-edit may be easily visualized by considering a sequence of collisions with a $\frac{\Sigma_a}{\Sigma_T}$ non-terminating (or terminating) estimator. Let superscripts denote collision number. The free flight transmissions through a distance d to the first collision with the unperturbed and perturbed total cross sections are $e^{-\Sigma_T^1 d}$ and $e^{-\Sigma_T^{1'} d}$. Thus, a freeflight weight for the first collision, say g^1 , is given by

$$g^1 = e^{-(\Sigma_T^{1'} - \Sigma_T^1)d}.$$

Since $\frac{W_0^1}{\Sigma_T^1}$ is an estimate of neutron flux at the first collision site, where W_0^1 is the incident neutron weight, then we may write the perturbed neutron weight, $W_0^{1'}$ as

$$W_0^{1'} = g^1 \frac{\Sigma_T^{1'}}{\Sigma_T^1} W_0^1.$$

The perturbed exit neutron weight for the first collision is given by

$$W^{1'} = g^1 \frac{\Sigma_T^{1'}}{\Sigma_T^1} W^1 \frac{\Sigma_s^{1'}}{\Sigma_T^{1'}} \cdot \frac{\Sigma_T^1}{\Sigma_s^1} = g^1 W_0^1 \frac{\Sigma_s^{1'}}{\Sigma_s^1}.$$

(Note that the same expression results for the $\frac{\Sigma_a}{\Sigma_T}$ terminating estimator since $\frac{\Sigma_s^{1'}}{\Sigma_T^{1'}} / \frac{\Sigma_s^1}{\Sigma_T^1}$ is the ratio of survival probabilities with binomial kill-off.)

The perturbed incident weight for the second collision is given by:

$$W_0^{2'} = g^2 \frac{\Sigma_T^{2'}}{\Sigma_T^2} W_0^{1'} = g^1 g^2 \frac{\Sigma_T^{2'} \Sigma_s^{1'}}{\Sigma_T^2 \Sigma_s^1} W_0^2.$$

In general, after n collisions, we obtain

$$W_0^{n'} = g^1 g^2 \dots g^n \frac{\Sigma_T^{n'}}{\Sigma_T^n} \cdot \frac{\Sigma_s^{1'}}{\Sigma_s^1} \cdot \frac{\Sigma_s^{2'}}{\Sigma_s^2} \dots \frac{\Sigma_s^{n-1'}}{\Sigma_s^{n-1}} \cdot W_0^n$$

That is, the relation between the perturbed flux of the n^{th} collision, $\phi^{n'}$, and the unperturbed flux of the n^{th} collision, ϕ^n , is

$$\phi^{n'} = g^1 g^2 \dots g^n \frac{\Sigma_s^{1'}}{\Sigma_s^1} \cdot \frac{\Sigma_s^{2'}}{\Sigma_s^2} \dots \frac{\Sigma_s^{n-1'}}{\Sigma_s^{n-1}} \phi^n.$$

It is clear that the perturbation re-edit at collision n in history h may be obtained by use of the perturbed flux $\phi^{n'} = f \phi^n$ where f is a multiplication factor per collision. The value of f is unity for a source neutron. At the first collision for history h , set

$$f = f e^{-(\Sigma_T^{1'} - \Sigma_T^1)d}.$$

At the second collision for history h , set

$$f = f e^{-(\Sigma_T^{2'} - \Sigma_T^2)d} \left(\frac{\Sigma_s^{1'}}{\Sigma_s^1} \right)$$

where $\frac{\Sigma_s^{1'}}{\Sigma_s^1}$ is the ratio of elastic scattering cross sections if $\delta_s = 0$ and is the ratio of inelastic scattering cross sections if $\delta_s = 1$. At the n^{th} collision of history h , we have

$$f = f e^{-(\Sigma_T^{n'} - \Sigma_T^n)d} \left(\frac{\Sigma_s^{n-1'}}{\Sigma_s^{n-1}} \right).$$

The perturbation re-edit procedure outlined above is valid for any calculation with a combination of the $\frac{\Sigma_a}{\Sigma_T}$ terminating and $\frac{\Sigma_a}{\Sigma_T}$ non-terminating estimators. Recall from the description of the neutron collision parameters list in Section 8.6, that when a binomial estimator is used,

then only collision sites that result in kill-off are recorded. Thus the perturbation re-edit cannot be performed for this case. For problems in which the binomial estimator is normally set automatically by the program, i.e., in fissionable compositions in the thermal group, then this set-up is over-ridden when the requestor specifies a perturbation calculation and the binomial estimator is replaced by the $\frac{\Sigma_a}{\Sigma_T}$ terminating estimator. In a similar manner, if the requestor specifies a binomial estimator in the non-thermal groups and also specifies a perturbation calculation, then the binomial estimator is replaced by the $\frac{\Sigma_a}{\Sigma_T}$ non-terminating estimator.

Probable error estimates for the magnitude of a perturbation are not obtained internally in RCP01; they must be obtained externally using iteration results from the perturbed and unperturbed edits.

K. VARIANCE CALCULATION FOR VARIABLE NUMBER OF HISTORIES PER ITERATION

There are many formulas that can be used for estimating variance; two will be given here and compared for accuracy. To make the analysis convenient for both approaches, we will assume that there is a sequence of experiment types as to number of histories, and each type is designated by an index l ($1 \leq l \leq L$). Thus, for example, A^l will denote the total number of experiments of type l with N^l histories each. If K is the total number of experiments, then $K = \sum_{l=1}^L A^l$. The total number of histories is given by $\sum_{l=1}^L A^l N^l$.

1. The first formula that we will conjecture as reasonable results from viewing an experiment k which yields a neutron reaction rate, say x^k , as being repeated a number of times proportional to the number of histories in experiment k , i.e., N^k . Thus, we write the variance of the initial population of x^k , i.e., $\sigma^2(x^k)$, as:

$$\sigma^2(x^k) = \frac{\sum_{k=1}^K N^k (x^k - \bar{x})^2}{\sum_{k=1}^K N^k}$$

where $\bar{x} = \frac{\sum_{k=1}^K N^k x^k}{\sum_{k=1}^K N^k}$ in order to produce a minimum variance estimate of $\bar{x}$.

We may regroup terms in the numerator of the above expression for $\sigma^2(x^k)$ so that the A^l experiments with N^l histories are together. Then:

$$\sigma^2(X^k) = \frac{\sum_{l=1}^L N^l \sum_{j=1}^{A^l} (X^{lj} - \bar{X})^2}{\sum_{l=1}^L A^l N^l}$$

Observe that $\frac{1}{A^l} \sum_{j=1}^{A^l} (X^{lj} - \bar{X})^2$ is an estimate of the initial population variance, say σ_l^2 , from A^l experiments with N^l histories each. Assume the value of σ_l^2 is known, then we may write $N^l \sigma_l^2 = N^1 \sigma_1^2$ and therefore:

$$\sigma^2(X^k) = \frac{\sum_{l=1}^L A^l N^1 \sigma_1^2}{\sum_{l=1}^L A^l N^l} = \frac{K N^1 \sigma_1^2}{\sum_{l=1}^L A^l N^l}.$$

But if we know the value of σ_1^2 , then the variance of $\bar{X}$, say $\sigma^2(\bar{X})$, is estimated by:

$$\sigma^2(\bar{X}) = \left(\frac{\sigma_1^2}{A^1} \right) \left(\frac{\frac{A^1 N^1}{L}}{\sum_{l=1}^L A^l N^l} \right)$$

where the first factor is the estimate of $\sigma^2(\bar{X})$ based on A^1 experiments only, and the second factor is the ratio of the total number of histories involved in the A^1 experiments to the total number of histories. We may now define an effective number of experiments, say A_{eff} , such that

$$\sigma^2(\bar{X}) = \frac{\sigma^2(X^k)}{A_{eff}}$$

using the above expressions for $\sigma^2(\bar{X})$ and $\sigma^2(X^k)$ we see that $A_{eff} = K$. Thus the first formula becomes:

$$\sigma^2(\bar{X}) = \frac{\sum_{k=1}^K N^k (X^k - \bar{X})^2}{K \cdot \sum_{k=1}^K N^k}$$

2. The second formula for variance that we will obtain starts with the minimum variance estimate of $\bar{X}$, i.e.,

$$\bar{X} = \frac{\sum_{k=1}^K N^k X^k}{\sum_{k=1}^K N^k}$$

Since the X^k are independent random variables, we may make use of the standard formula for obtaining $\sigma^2(\bar{X})$ in terms of the variances of the random variables X^k , say $\sigma^2(X^k)$, where now $\sigma^2(X^k)$ is understood to be the variance resulting from independent repetitions of experiment k with N^k histories. Thus we may write:

$$\sigma^2(\bar{X}) = \frac{\sum_{k=1}^K (N^k)^2 \sigma^2(X^k)}{\left(\sum_{k=1}^K N^k \right)^2}$$

But again there are A^l experiments with N^l histories each, thus we may also write:

$$\sigma^2(\bar{X}) = \frac{\sum_{l=1}^L (N^l)^2 A^l \sigma^2(X^l)}{\left(\sum_{k=1}^K N^k \right)^2}$$

But,

$$\sigma^2(X^l) = \frac{1}{A^l} \sum_{j=1}^{A^l} (X^{lj} - \bar{X})^2$$

(normally a factor of $\frac{A^l}{A^l-1}$ would be applied to this expression, but it is not required

since we will understand that $\bar{X}$ is not the local mean of the A^l experiments, but is the overall mean), so that we obtain the second formula as:

$$\sigma^2(\bar{X}) = \frac{\sum_{l=1}^L (N^l)^2 \sum_{j=1}^{A^l} (X^{lj} - \bar{X})^2}{\left(\sum_{k=1}^K N^k \right)^2} = \frac{\sum_{k=1}^K (N^k)^2 (X^k - \bar{X})^2}{\left(\sum_{k=1}^K N^k \right)^2}$$

3. It is clear that we may formulate any number of weighting schemes to obtain estimates of $\sigma^2(\bar{X})$, However, the first formula derived above used the number of histories per iteration k, N^k , as a linear weight factor and this same approach used in estimating $\bar{X}$ is known to produce minimum variance. Thus one conjectures that the first formula will produce a smaller σ^2 on the value of $\sigma^2(\bar{X})$, i.e., $\sigma^2(\sigma^2(\bar{X}))$. That this is the case may be shown as follows: (We will assume that the underlying frequency distribution function for the sequence of X^k 's with a given number of histories N^k is normal.) We will start by obtaining $\sigma^2(\sigma^2(\bar{X}))$.

$$\text{Let } Z^k = (X^k - \bar{X}) \\ Y^k = (Z^k)^2$$

then $\bar{Z} = 0, \sigma^2(Z^k) = \sigma^2(X^k)$. Let $f(Z^k)$ be a normal frequency distribution function for Z^k with mean 0, then

$$\sigma^2(Z^k) = \int_{-\infty}^{\infty} f(Z^k)(Z^k)^2 dZ^k.$$

The frequency distribution function for $Y^k, f(Y^k)$, will have the property $f(Y^k)dZ^k = f(Z^k)dZ^k$, therefore we may write:

$$\sigma^2(Y^k) = \int_{-\infty}^{\infty} f(Z^k)(Y^k - \bar{Y})^2 dZ^k.$$

Let M_n be the n^{th} moment of the standard normal frequency distribution function, then $M_0 = 1, M_2 = \sigma^2(Z^k)$, and $M_4 = 3\sigma^4(Z^k)$, Since

$$\bar{Y} = \int_{-\infty}^{\infty} f(Z^k)(Z^k)^2 dZ^k = \sigma^2(Z^k)$$

then

$$\sigma^2(Y^k) = \int_{-\infty}^{\infty} f(Z^k)(Z^k)^4 dZ^k - 2\sigma^2(Z^k) \int_{-\infty}^{\infty} f(Z^k)(Z^k)^2 dZ^k + \sigma^4(Z^k) = 2\sigma^4(Z^k).$$

Therefore

$$\sigma^2(\sigma^2(\bar{X})) = \frac{2\sigma^4(\bar{X})}{K}$$

where K is the number of experiments involved in estimating $\sigma^2(\bar{X})$. To obtain $\sigma(\sigma(\bar{X}))$, consider the following argument: Write $Y = X^2 = (\bar{X} + \epsilon)(\bar{X} + \epsilon) \approx \bar{X}^2 + 2\bar{X}\epsilon$ where ϵ is considered a random variable of sufficiently small magnitude that we need keep only first order terms in ϵ . Then,

$$\begin{aligned}\sigma^2(X) &= \sigma^2(\epsilon) \\ \sigma^2(Y) &= 4\bar{X}^2\sigma^2(X) \\ \sigma(Y) &= 2\bar{X}\sigma(X)\end{aligned}$$

and therefore $\sigma(\sigma^2(\bar{X})) = 2\sigma(\bar{X})\sigma(\sigma(\bar{X}))$.

But

$$\sigma(\sigma^2(\bar{X})) = \sqrt{\frac{2}{K}}\sigma^2(\bar{X})$$

resulting in

$$\sigma(\sigma(\bar{X})) = \frac{\sigma(\bar{X})}{\sqrt{2K}}.$$

This result is of direct utility in estimating $\sigma(\sigma(\bar{X}))$ for any $\sigma(\bar{X})$ obtained from RCP01. Now to continue comparing the first and second formulas for estimating variance, we again write $Y^k = (X^k - \bar{X})^2$ and use the previous results to write $\sigma^2(Y^k) = 2\sigma^4(X^k)$. As we consider experiments with different numbers of histories, N^k , then we may write $\sigma^2(X^k) = \frac{A}{N^k}$ where A is a constant and thus $\sigma^2(Y^k) = \frac{2A^2}{(N^k)^2}$. The first formula may be written as

$$\sigma^2(\bar{X}) = \frac{\sum_{k=1}^K N^k Y^k}{K \sum_{k=1}^K N^k}.$$

Therefore,

$$\sigma_1^2(\sigma^2(\bar{X})) = \frac{1}{\left[\frac{K}{K \sum_{k=1}^K N^k} \right]^2} \sum_{k=1}^K 2A^2 = \frac{2A^2 K}{\left[\frac{K}{K \sum_{k=1}^K N^k} \right]^2}.$$

The second formula may be written as

$$\sigma^2(\bar{X}) = \frac{\sum_{k=1}^K (N^k)^2 Y^k}{\left(\sum_{k=1}^K N^k \right)^2}.$$

Therefore

$$\sigma_2^2(\sigma^2(\bar{X})) = \frac{1}{\left[\sum_{k=1}^K N^k \right]^4} \sum_{k=1}^K (N^k)^2 2A^2.$$

We may now verify the conjecture that $\frac{\sigma_1^2(\sigma^2(\bar{X}))}{\sigma_2^2(\sigma^2(\bar{X}))} \leq 1$ by showing that

$$\frac{\left[\sum_{k=1}^K N^k \right]^2}{K \sum_{k=1}^K (N^k)^2} \leq 1$$

or that $\frac{\bar{N}^2}{N^2} \leq 1$, but $\sigma^2(N^k) = \bar{N}^2 - \bar{N}^2 \geq 0$,

therefore the inequality is satisfied. Thus throughout RCP01, formula one will be used to estimate variance, i.e.,

$$\sigma^2(\bar{X}) = \frac{\sum_{k=1}^K N^k (X^k - \bar{X})^2}{K \cdot \sum_{k=1}^K N^k}.$$

L. CORRELATED SAMPLING IN RCP01

Random numbers are generated in RCP01 by a standard pseudo-random number generator of the mixed congruential type, that is if ρ_i is the i^{th} random number, then

$$\rho_{i+1} = (2^9 + 1)\rho_i + \mu \pmod{2^{47}}.$$

where $\mu = 29,741,096,258,473$,

and where $\rho_0 = 762,939,453,125$.

This generator has a periodicity of 2^{47} . The program uses $2^{-47}\rho_i$ as its uniformly distributed "random" number.

Correlated sampling is obtained in RCP01 by insuring that each history in each calculation starts with the same random number provided the requestor skips the same number of random numbers in each calculation.

Thus, for example, if a geometry perturbation is made following a base RCP01 calculation, and if the same number of random numbers are skipped in the base and perturbed calculations, then neutron histories for which the perturbation is not sensed will be identical (e.g., those histories for which the neutron paths do not intersect the domain of the geometry perturbation). This will then produce small standard deviations on differences between the base and perturbed calculation. Independent runs on the same RCP01 problem are obtained by having a different number of random number-skips in each run.

The correlated sampling is obtained in RCP01 by the following procedure. Let $\rho_{h,i}$ be the i^{th} random number used in history h . Set $\rho_{1,0} = \rho_0$, and let the symbol $\rho_{h,i} \rightarrow \rho_{h,i+1}$ denote use of the recursion procedure in the pseudorandom number generator. Then the RCP group one first history sequence of random numbers for k skips (if $k = 0$, set $k = 1$) is given by $\rho_{1,k+1} \dots \rho_{1,N_{1,1}+k}$, where $N_{h,g}$ is the total number of random numbers required for history h through RCP group g . This sequence is extracted from:

$$\rho_0 = \rho_{10} \rightarrow \rho_{11} \rightarrow \rho_{12} \rightarrow \rho_{13} \dots$$

The RCP group one second history sequence of random numbers for k skips (if $k = 0$, set $k = 1$) is given by $\rho_{2,k+1}, \dots, \rho_{2,N_{2,1}+k}$. This sequence is extracted from

$$\rho_{20} = 1 - \rho_{11} \rightarrow \rho_{21} \rightarrow \rho_{22} \rightarrow \rho_{23} \dots$$

An analogous procedure is used for subsequent histories in RCP group one. Here, $1 - \rho$ means $2^{47} - \rho$ in the notation of the generator.

The last random number used in RCP group g for neutron history h , i.e., $\rho_{h,N_{hg}+g \cdot k}$, is recorded on the slowing down file and is used to reset the recursion formula to obtain the random number to start history h in RCP group $g + 1$. At the start of each group, k random numbers are skipped.

If neutron splitting occurs for history h after use of the i^{th} random number, i.e., $\rho_{h,i}$, then the first split neutron uses the regular continuation of the sequence $\rho_{h,i} \rightarrow \rho_{h,i+1} \rightarrow \dots$. The 2nd split particle uses (superscripts denote split particle number)

$$\rho_{h,i}^2 \rightarrow \rho_{h,i+1}^2 \rightarrow \dots \text{ where,}$$

$$\rho_{h,i}^2 \rightarrow 1 - \rho_{h,i+1} \rightarrow \rho_{h,i+1}^2 \rightarrow \dots$$

The 3rd split particle uses

$$\rho_{h,i}^3 \rightarrow \rho_{h,i+1}^3 \rightarrow \dots \text{ where,}$$

$$\rho_{h,i}^3 \rightarrow 1 - \rho_{h,i+1}^2 \rightarrow \rho_{h,i+1}^3 \rightarrow \dots, \text{ etc.}$$

Each split particle, of course, also skips k random numbers at the start of each new group.

M. EQUILIBRIUM XENON POISONING IN RCP01

The number of atoms per cubic centimeter surviving radioactive disintegration of a nuclide is defined by the expression,

$$N(t) = N_0 e^{-\lambda t}$$

where $N(t)$ is the number of atoms per cubic centimeter at time t , N_0 is the number of atoms per cubic centimeter at time zero and λ is the decay constant. The mean time for survival, $\bar{t}$, is given by

$$\bar{t} = \frac{\int_0^{\infty} N_0 e^{-\lambda t} t dt}{\int_0^{\infty} N_0 e^{-\lambda t} dt} = \frac{1}{\lambda}$$

(the half life, $t_{1/2}$, is obtained from $e^{-\lambda t_{1/2}} = 0.5$, or $t_{1/2} = \frac{0.693}{\lambda}$). The number of atoms per cubic centimeter disintegrating in time interval Δt about time t , i.e., ΔN_D , is given by

$$\Delta N_D = N(t) - N(t + \Delta t) = -\frac{dN(t)}{dt} \Delta t = N_0 e^{-\lambda t} \lambda \Delta t = N \lambda \Delta t$$

where $N = N(t)$, i.e., time dependence of N is understood.

The number of atoms per cubic centimeter, ΔN_c , of a given nuclide with yield y , created in time Δt as a result of fissioning is given by

$$\Delta N_c = y \int_E \phi_t \Sigma_f \Delta t$$

where Δt is the neutron flux level at time t , Σ_f is the macroscopic fission cross section and the integration is over all energy (for a given nuclide, the yield y is defined as the reaction of total fissions yielding that nuclide as a direct fission product; the sum of all yields is 2).

^{135}Xe poisoning in an operating reactor is the result of direct fission product yield of ^{135}Xe and of the direct fission product yields of ^{135}Sb , ^{135}Te , and ^{135}I and their subsequent β -decay (^{135}Sb β -decays to ^{135}Te , ^{135}Te β -decays to ^{135}I , and ^{135}I β -decays to ^{135}Xe). No other decay processes are involved in this fission product chain. Also for each of the precursors of ^{135}Xe , i.e., ^{135}Sb , ^{135}Te , and ^{135}I , the value $\int_E \phi_t \sigma N$ is small compared to λN , where σ is the precursor absorption cross section, as N is the precursor atom density, ϕ_t is a flux level typical of an operating reactor, and where the integration is over all energy.

The above discussion leads directly to a sequence of equations to describe the ^{135}Xe fission product chain. Let N^i be the nuclide density of nuclide i in atoms/cm³. Let y^i and λ^i be the direct fission product yield and decay constant for nuclide i , then we may write

$$\begin{aligned}\frac{dN^{Sb}}{dt} &= y^{Sb} \int_E \phi_t \Sigma_f - \lambda^{Sb} N^{Sb} \\ \frac{dN^{Te}}{dt} &= \lambda^{Sb} N^{Sb} + y^{Te} \int_E \phi_t \Sigma_f - \lambda^{Te} N^{Te} \\ \frac{dN^I}{dt} &= \lambda^{Te} N^{Te} + y^I \int_E \phi_t \Sigma_f - \lambda^I N^I \\ \frac{dN^{Xe}}{dt} &= \lambda^I N^I + y^{Xe} \int_E \phi_t \Sigma_f - \lambda^{Xe} N^{Xe} - \int_E \phi_t \sigma^{Xe} N^{Xe}\end{aligned}$$

where σ^{Xe} is the ^{135}Xe absorption cross section; and the integrations are over all energy.

For a reactor in equilibrium, we have

$$\frac{dN^{Sb}}{dt} = \frac{dN^{Te}}{dt} = \frac{dN^I}{dt} = \frac{dN^{Xe}}{dt} = 0.$$

Since ϕ_t is independent of time we will denote the neutron flux by ϕ ; of course the N^i 's are also independent of time. This leads to the equation $(y^{Sb} + y^{Te} + y^I + y^{Xe}) \int_E \phi \Sigma_f = N^{Xe} (\lambda^{Xe} + \int_E \phi \sigma^{Xe})$. If we define a total yield y of ^{135}Xe as the direct plus precursor yields, i.e., $y = y^{Sb} + y^{Te} + y^I + y^{Xe}$, then we have

$$y \int_E \phi \Sigma_f = N^{Xe} \left(\lambda^{Xe} + \int_E \phi \sigma^{Xe} \right)$$

(the value of y for ^{135}Xe is about 0.063).

While we have restricted our discussion to ^{135}Xe poisoning, an equation of the same form as that above holds for any fission product poisoning in equilibrium provided β -decay is the only decay process for the precursors, and provided the value $\int_E \phi_t \sigma N$ is small compared to λN for all precursors where σ is the precursor absorption cross section. RCP01 permits any one such fission product to be treated.

The RCP01 edit of neutron flux required for equilibrium Xenon poisoning is obtained only from the composition edits. Thus, the ^{135}Xe atom density is adjusted only by composition, i.e., the RCP01 compositions will define gross depletion blocks. For this reason we define an average Xe atom density for composition j as

$$N_j^{Xe} = \frac{1}{V_j} \int_{V_j} N^{Xe}$$

where V_j is the volume of composition j .

Upon integrating the equation for N^{Xe} over V_j we obtain

$$y \int_{V_j, E} \phi \Sigma_f = N_j^{Xe} V_j \lambda^{Xe} + \int_{V_j} N^{Xe} \int_E \phi \sigma^{Xe}$$

We now assume in RCP01 that we may set

$$\int_{V_j} N^{Xe} \int_E \phi \sigma^{Xe} = N_j^{Xe} \int_{V_j, E} \phi \sigma^{Xe}$$

that is, we assume gross depletion blocks are acceptable. To obtain N_j^{Xe} in $\frac{\text{atoms}}{\text{barn-cm}}$ and to use σ^{Xe} in barns (σ^{Xe} is available in barns from the RCPL1 job library), we write

$$N_j^{Xe} \frac{\text{atoms}}{\text{barn-cm}} = \frac{y \int_{V_j, E} \phi \Sigma_f (10^{-24})}{V_j \lambda^{Xe} + \int_{V_j, E} \phi \sigma^{Xe} (10^{-24})}$$

The flux level, ϕ , available from RCP01 is the flux level in neutrons/cm²-sec per neutron born in fission per second. To obtain the flux level in an operating reactor that is just critical, we must multiply ϕ by the average number of neutrons born per fission, i.e., $\bar{\nu}$, and further multiply by the number of fission events per second to obtain one watt of power, say f_w , and finally, further multiply by the power level in watts, say $P(\text{watts})$. That is, we replace ϕ in the above equation with

$$\phi \bar{\nu} f_w P(\text{watts}).$$

If the reactor is subcritical or supercritical, then for the concept of equilibrium fission product poisoning to have meaning, we must scale $\bar{v}$ so that the reactor is just critical, i.e., we replace $\bar{v}$ by $\frac{\bar{v}}{MF}$ where MF is the reactor multiplication factor (in the actual RCP01 calculation this will be the best estimate of the multiplication factor after k iterations, i.e., MF^k , see Section 11.1).

Another perspective of the above scaling of $\bar{v}$ comes from considering a cell calculation of a subdomain of a just critical reactor. Because the cell calculation does not treat net leakage into the cell as it actually exists in the reactor, this subdomain may be subcritical or supercritical. The scaling of $\bar{v}$ in this case is equivalent to the assumption that these leakage neutrons contribute to the terms $\int_{V,E} \phi \Sigma_f$ and $\int_{V,E} \phi \sigma^{Xe}$ in the same manner as neutrons born in fission in the cell. This is a highly reasonable assumption, especially for a thermal reactor.

The equation defining equilibrium ^{135}Xe atom density may now be written as

$$N_j^{Xe} \frac{\text{atoms}}{\text{barn-cm}} = \frac{\gamma \int_{V,E} \phi \Sigma_f \bar{v} f_w P(\text{watts}) \left(\frac{1}{MF} \right) (10^{-24})}{V_j \lambda^{Xe} + \int_{V,E} \phi \sigma^{Xe} \bar{v} f_w P(\text{watts}) \left(\frac{1}{MF} \right) (10^{-24})}.$$

The flux level ϕ in the above equation is a function of N_j^{Xe} . In particular if N_j^{Xe} is increased, then ϕ will decrease and will cause N_j^{Xe} , as defined in the above equation, to decrease. This type of behavior will result in rapid convergence to an equilibrium value of N_j^{Xe} in a simple iterative procedure. The RCP01 calculation uses the above equation at the end of each fixed source or eigenfunction iteration to update the estimate of the equilibrium value of N_j^{Xe} .

The quantities directly available from RCP01 at the end of iteration k and which are based on all iterations $\leq k$ are (see Section 8.3):

1. The fission rate in composition j per neutron born in fission, i.e., F_j^k , where

$$F_j^k = \int_{V,E} \phi \Sigma_f$$

2. The ^{135}Xe absorption rate per neutron born in fission, say C_j^k where

$$C_j^k = \int_{V,E} \phi \Sigma^{Xe}$$

3. The multiplication factor MF^k , and

4. an estimate of $\bar{v}$, i.e., $\bar{v}^k$.

Let the atom density of ^{135}Xe used in iteration k in composition j be N_j^k . Then the updated value of this quantity for iteration $k+1$ which is obtained in RCP01 at the end of iteration k is given by

$$N_j^{k+1} = \frac{y\bar{v}^k f_w P(\text{watts}) \left(\frac{1}{MF^k} \right) 10^{-24} F_j^k}{V_j \lambda^{Xe} + \frac{1}{N_j^k} C_j^k \bar{v}^k f_w P(\text{watts}) \left(\frac{1}{MF^k} \right) 10^{-24}}$$

RCP01 sets the value of $f_w = 3.1(10^{10})$ fissions/sec-watt. A quantity P is defined given by

$$P = P(\text{watts}) f_w (10^{-24}) = P(\text{watts}) 3.1(10^{-14})$$

We may now write

$$N_j^{k+1} = \frac{yF_j^k P}{\frac{V_j \lambda^{Xe} MF^k}{\bar{v}^k} + \frac{C_j^k P}{N_j^k}}$$

From Section 11.1, we observe that

$$\frac{MF^k}{\bar{v}^k} = \sum_j F_j^k$$

that is $\frac{MF^k}{\bar{v}^k}$ is the total fission rate per neutron born in fission through iteration k . We now have the expression actually used by RCP01 to obtain the estimate of the ^{135}Xe atom density for the $(k+1)^{\text{st}}$ iteration upon completion of the k^{th} iteration, i.e.,

$$N_j^{k+1} = \frac{yF_j^k P}{V_j \lambda^{Xe} \sum_j F_j^k + \frac{C_j^k P}{N_j^k}}$$

In RCP01, if $N_j^k = 0$ for any iteration k , then $\frac{C_j^k}{N_j^k}$ is set to zero.

The user input required to perform an equilibrium xenon calculation consists of the following:

1. The RCPL1 job library identification number for ^{135}Xe (or for whatever fission product poison is being considered); this identification number is used in RCP01 to define a counter for the fission product absorption rate through iteration k in composition j , i.e., C_j^k .
2. Initial guess values of the ^{135}Xe atom density for iteration zero are input by composition, i.e., N_j^0 ; because of rapid convergence it is acceptable to set these values to zero.
3. The total yield, y , i.e., the sum of the direct plus precursor yields for ^{135}Xe .
4. The decay constant for ^{135}Xe , i.e., λ^{Xe} .
5. The reactor power level in watts, i.e., $P(\text{watts})$.

Finally the user must verify that the volumes per fission composition obtained by RCP01, i.e., v_j , are those desired. Recall that RCP01 computes volumes per basic region correctly, but not for problems with composite final assemblies. Hence for some such problems, the actual fission composition volumes may not be those edited by RCP01.

N. RCP01 TRAPPING SURFACE CAPABILITY

This appendix describes the trapping surface capability for modular geometry RCP. In general, the use of a trapping surface involves a base calculation during which the parameters of either the inward or outward directed neutrons (or photons) cutting a specified closed surface are recorded on a file. One or more linked calculations may then be performed using this file to obtain starting parameters. Such procedures have utility, for example, in attempting to optimize the design of a neutron detector. In this case one would use a trapping surface sufficiently removed from the detector that detector design changes would not appreciably affect the neutron parameters on the trapping surface file. As the design is altered in a sequence of linked calculations, one obtains a higher degree of correlation and smaller standard deviations per unit machine time for detector reaction rates than one would obtain if entire problems were rerun for the sequence of design changes. It is obvious that the above detector could also be one for photons, but rather than refer to this repeatedly, we will here speak only of neutron calculations.

The trapping surface capability for RCP uses one of the module zero cylinders or spheres as the trapping surface (i.e., the capability is not available in non-modular geometry). Optionally, either outward or inward directed neutrons cutting the cylinder or sphere are recorded. Also, final modules cannot intersect the trapping surface. There are no automatic input checks which insure that a final module (recall that final modules override module zero geometry) does not intersect the module zero surface chosen as the trapping surface. Should a final module intersect this module zero surface, then the trapping surface file would not include trapping surface crossings interior to that final module. The requestor can best insure no intersection of the trapping surface with a final module by carefully examining slice plots.

To enhance the use of the trapping surface capability, reverse splitting may be used. This is obtained by setting the input splitting factor, k , to be negative (See Chapter 5). In this option, the splitting occurs as the neutron moves outward through the nested set of ellipsoids and Russian Roulette occurs as the neutron moves inward (the standard RCP splitting option is just the reverse process). This splitting option, if used with the trapping surface option, could produce a good trapping surface file to use in linked calculations involving two or more detectors outside the trapping surface (see Figure N-2).

N.1 Base Calculations

The module zero cylinders or spheres are numbered in module zero input. The only additional input required in the base RCP calculation is JRAD, the number of the cylinder or sphere to be used as the trapping surface. The sign of JRAD determines whether outward or inward-directed particles are to be recorded during particle tracking for the base problem. The parameters W_i , E , x , y , z , μ , γ , η are recorded each time a particle crosses the trapping surface moving in the selected direction (a particle may scatter outside the trapping surface, free-flight to another scattering event inside the surface and subsequently cross the surface again; each such crossing is recorded). Here W_i is the particle's weight, E is its energy, x , y , z are the spatial coordinates in the absolute coordinate system for modular geometry, and μ , γ , η are direction cosines relative to the absolute x , y , z coordinate axes, respectively. To increase the density of crossings over the trapping surface, RCP splitting may be used in the base calculation (see Figure N-1 and Figure N-2).

N.2 Linked Calculation

The geometry, composition definitions, etc. of the linked calculation may be different from that of the base calculation, except that the module zero surface used to select the trapping surface in the base calculation must have the same cylinder number and the same radius in the linked calculation.

An input card is required in the linked RCP calculation to define which sites on the trapping surface file are to be used as the distribution function in the sampling of starts. One option, of course, is to use all sites on the trapping surface file as the distribution function. Alternatively, a subset of sites may be obtained and used as the distribution function by selecting only sites in an angular sector of the surface, that is from $\alpha - \Delta\alpha$ to $\alpha + \Delta\alpha$ where α is measured counterclockwise about the z -axis (the x -axis is $\alpha = 0^\circ$). The value of α and $\Delta\alpha$ in degrees, where $0 \leq \alpha < 360^\circ$ and $0 < \Delta\alpha < 180^\circ$, are input in such a case. Selection may be further restricted to only those sites lying between $Z_{\min}$ and $Z_{\max}$ as measured in the absolute coordinate system. Values of $Z_{\min}$ and $Z_{\max}$ are input in that case. Additionally, sites may be limited to those within a specified energy range. Before starts are selected in the linked calculation, an internal file is written containing only the sites meeting the above input conditions. Also, a counter is used which gives the sum of particle weights over the sites retained. This counter divided by the total number of histories in the base calculation is the weight for each starting particle in the linked calculation. The history by history accumulation of a given reaction rate in the linked calculation is divided by the total number of histories in the linked calculation to provide the reaction rate per particle born in the base calculation.

Figure N-1 Use of Trapping Surfaces With Split Factor $k > 0$ in Base Calculation

Figure N-2 Use of Trapping Surfaces With Split Factor $k < 0$ in Base Calculation

Starts in the linked calculation are obtained by sampling the above file in a manner analogous to a fission site file with one composition. This process is described in detail in Chapter 6. Here the particle weight, w_i , for a site retained plays the role of the neutron production per collision, and the sum of weights over all sites retained plays the role of the total neutron production.

During the particle tracking in the base calculation, an account was made for collisions outside and inside the trapping surface. Therefore, in a linked calculation using outward-directed (inward-directed) particles as the source, the interior (exterior) of the trapping surface is treated as black, i.e., the history is terminated if it cuts the trapping surface on or after the first free flight. This is done automatically in the RCP linked calculation, thus, e.g., one may use the identical geometry and composition input in both the base and linked calculations.

The standard deviations obtained by RCP for the linked calculation will be those for a fixed-source calculation where the fixed source is precisely defined by the sites on the trapping surface file. The only accurate way in RCP to obtain standard deviations for reaction rates in the linked calculation per particle born in the base calculation is to repeat the entire (base plus linked) procedure multiple times with random number skipping and compute standard deviations in the usual way (a minimum of five times is recommended).

O. CYLINDRICAL RCP01 SPLICE FROM A DISCRETE ORDINATE SOLUTION

A reactor shield design tool for either neutrons or photons requires transport calculations because of the importance of proper treatment of anisotropy of the neutron, or photon, vector flux. Such transport calculations can be provided by deterministic analytic programs, or by analog Monte Carlo programs. However, each type of calculation has some serious shortcomings. To be practical as a design tool, deterministic analytic transport calculations are usually restricted to two dimensions. On the other hand, analog Monte Carlo methods readily permit complex three-dimensional geometry representations, but when used alone to treat the large attenuations that occur in practical shield design problems the statistical uncertainties may become unacceptably large.

To overcome the above difficulties, a procedure was developed to splice a few group discrete ordinate solution (DOS) of the neutron transport equation in two-dimensional cylindrical r - z geometry (References 12, 13, and 24) to a detailed 3-dimensional Monte Carlo solution of the neutron transport equation, as provided by the RCP program.

In normal use, the splice would be used in a calculation where the bulk of the neutron attenuation for neutrons born in a reactor and migrating to a remote neutron detector is treated by the cylindrical DOS starting at the center of the reactor and extending to a splicing cylinder outside the reactor. The remaining attenuation from the splicing cylinder to the detector would normally be small. Beyond the splicing cylinder, one may then efficiently use the three-dimensional capability of RCP to treat complicated geometries such as neutron shield penetrations in the detector vicinity.

Because the splice procedure uses only the outward directed DOS few group vector flux at the splice cylinder, the DOS solution domain must extend a reasonable distance beyond this cylinder through use of some r - z representation of materials. Thus scattered neutrons beyond the splice cylinder which return to the interior of the cylinder and again exit as the result of multiple scattering events are accounted for in the DOS outward directed vector flux. When using such a vector flux to construct a Monte Carlo source at the splice cylinder, any neutron

path in the Monte Carlo solution which cuts the splice cylinder results in that neutron history being terminated since such neutrons are already accounted for in the DOS vector flux.

This splice procedure is similar to the slab P-3 to RCP01 splice described in Chapter 2 and the trapping surface described in Appendix N.

O.1 Form of Few Group Vector Flux in the DOS

The DOS few group vector flux at a cylinder of radius r is denoted by (following the nomenclature of Reference 12), $N_{qgs}^m(r)$, where m and q denote two angles required to specify a 3-dimensional direction of the vector flux, g is the few group (i.e., E^{g+1} to E^g in terms of energy mesh) over which the vector flux has been energy integrated, and s is the z -zone mesh interval extending from z_s to z_{s+1} over which the vector flux $N_{qgs}^m(r)$ is an average value.

The two angles, θ and ϕ , required to specify the direction, Ω , of the vector flux on a cylinder of radius r are measured in a local r - z coordinate system as shown in Figure O-1.

Figure O-1

The angle θ is discretized thereby defining a sequence of symmetrically placed cones $\theta_m, m = 1, \dots, 2M$, as shown in Figure O-2.

Figure O-2

The azimuthal angle ϕ may be viewed as discretized at midpoints of $\Delta\phi_q$ intervals, $q = 0, \dots, 2Q+1$, which in turn are defined by breakpoints ϕ^q , where ϕ^{2Q+1} always equals $\frac{\pi}{2}$, as shown in Figure O-3.

Using the above discretized values of θ and ϕ , then, for example, the DOS scalar flux energy integrated over a few group g and averaged over a z -zone s , say $N_{gs}(r)$, is given by

$$N_{gs}(r) = \sum_{m=1}^{2M} \sum_{q=0}^{2Q+1} w_q^m N_{qgs}^m(r)$$

where $w_q^m = 2w^m\Delta\phi_q$, and where w^m are quadrature weights chosen to integrate over the θ cones. The θ cone integration in DOS may be single or double Legendre-Gauss quadrature, or may be controlled by input. Commonly used in shielding applications are input θ cones which are equal intervals in $\cos\theta$ thereby resulting in $w^m = \frac{1}{M}$ for all values of m .

Figure O-3

O.2 Form of the DOS Splice Cylinder File

The splice cylinder file constructed by DOS is in the form of the usual trapping surface file constructed by RCP. This latter file contains, in the absolute coordinate system of module zero, the parameters

$$W_t, E, x, y, z, \mu, \gamma, \eta.$$

The DOS file contains the parameters

$$C_t, g, r, z_{s+1}, z_s, \mu_q^m, \gamma_q^m, \eta_q^m.$$

The parameter C_t is an outward directed neutron current contribution on the splicing cylinder r (t is an ordering index which ranges over all ordinates m, q , over all few groups g , and over all z -zones s). The parameters $\mu_q^m, \gamma_q^m, \eta_q^m$, are the direction cosines of the ordinate specified by m, q relative to the r, y , and z axes respectively as shown in Figure O-1. That is:

$$\mu_q^m = \sin \theta_m \cos \left(\varphi^{q+1} - \frac{\Delta \varphi^q}{2} \right),$$

$$\gamma_q^m = \sin \theta_m \sin \left(\varphi^{q+1} - \frac{\Delta \varphi^q}{2} \right),$$

$$\eta_q^m = \cos \theta_m.$$

RCP uses the splice cylinder file as an external source, but this source must reproduce the DOS vector flux at the splice cylinder. The relationship between a local source on the surface of a cylinder, say s , and the vector flux immediately outside the cylinder, $N_{qgs}^m(r)$, is given by

$$N_{qgs}^m(r) = \frac{S}{\mu_q^m}.$$

That is, the source s must be the outward directed current contribution of the vector flux $N_{qgs}^m(r)$. Since we will absolutely normalize the RCP calculation to the discrete ordinate solution, then the RCP source, the outward directed total current contribution in z -zone s , is

$$C_s = 2\pi r(z_{s+1} - z_s) W_q^m \mu_q^m N_{qgs}^m(r).$$

In addition to the above parameters on the splice cylinder file, this file contains other needed information: The total number of few groups G , the number of the few group g which is the top thermal group, say g_t , and the energy cut points for each few group g , i.e., E^g and E^{g+1} (where $E^{G+1} = 0$). Finally, there is a temperature T which is used to define a thermal Maxwellian neutron source spectrum in RCP.

0.3 RCP Source Generation Using Splice Cylinder File

The RCP splice cylinder must be a module zero cylinder not intersected by a final module (the user can best insure this from RCP plots.) The RCP splice cylinder number is determined in RCP by checking radii of module zero cylinders until one is found whose ratio to the value of r on the splice cylinder file lies in the range $1 - 10^{-4}$ to $1 + 10^{-4}$. (If such a value cannot be found, RCP will abort.)

The source sampling domain of the splice cylinder may first be restricted to a z -zone which in general is somewhat larger than the z -zone defined by the RCP input values z_{min} and z_{max} . This is done in RCP by rewriting a splice cylinder source file which does not include parameters for which either $z_{s+1} < z_{min}$ OR $z_s > z_{max}$.

The RCP normalization factor, i.e., the RCP neutron starting weight, is the resulting total outward neutron current over the sampling domain. This total current is given by

$$J(r) = \sum_i C_i.$$

RCP will sample starters from the splice cylinder file in the same manner as fission sites are chosen using the RCP fission file with one composition (see Chapter 6). Here $J(r)$ plays

the role of total neutron production rate, and C_i plays the role of neutron production per site. Thus for each starting neutron we know the parameters

$$g, r, z_{s+1}, z_s, \mu_q^m, \gamma_q^m, \eta_q^m.$$

The RCP neutron starting parameters in module zero are then obtained as follows:

1. E - the neutron starting energy is obtained from a flat energy distribution in few group g ; this procedure is also used in the thermal range if there are multiple thermal groups. That is

$$E = E^{g+1} + \rho(E^g - E^{g+1}), \text{ if } g < g_t \text{ or if } g_t < G.$$

The parameter ρ is a random number. If there is only one thermal group, i.e., $g_t = G$, then in this one group the neutron starting energy is that associated with a truncated Maxwellian flux. (It was found that this is necessary to give a reasonable thermal scalar flux in H_2O near the splice cylinder.) In this case we set

$$E = -kT \ln(\rho_1 \rho_2)$$

where T is the temperature on the splice cylinder file, k is Boltzmann's constant, and ρ_1 and ρ_2 are two independent random numbers. The truncation is made as follows: If $E > E^{g_t}$, then redraw ρ_1 and ρ_2 until $E < E^{g_t}$.

The above expression for sampling from a Maxwellian flux is derived as follows. The Maxwellian distribution of neutron velocities, v , is given by

$$P(v)dv = 4\pi \left(\frac{m}{2\pi kT} \right)^{\frac{3}{2}} v^2 e^{-\frac{v^2 m}{2kT}} dv$$

where m is the neutron mass. That is, the number of neutrons between v and $v + dv$ is $P(v)dv$. The neutron flux between v and $v + dv$ is then $vP(v)dv$. Thus we desire to sample in RCP a neutron velocity from a distribution function proportional to $vP(v)dv$. From the Maxwellian distributions for: a cartesian component of velocity, a radial component of velocity, and the magnitude of velocity (Chapter 3), it is suggested that a Maxwellian flux distribution may result from combining four independent cartesian components of velocity in four-dimensional space or, equivalently, two radial components in four-dimensional space. To see that this is the case, consider two independent radial components of velocity with distribution functions given by

$$P(v_1) = \frac{m}{kT} v_1 e^{-\frac{v_1^2 m}{2kT}}, v_1 \geq 0$$

$$P(v_2) = \frac{m}{kT} v_2 e^{-\frac{v_2^2 m}{2kT}}, v_2 \geq 0$$

Then their joint distribution function is given by

$$P(v_1, v_2) dv_1 dv_2 = \left(\frac{m}{kT}\right)^2 v_1 v_2 e^{-\frac{m}{2kT}(v_1^2 + v_2^2)} dv_1 dv_2.$$

A transformation to polar coordinates is now made by setting

$$v_1 = v \cos \theta$$

$$v_2 = v \sin \theta, \quad 0 \leq \theta \leq \frac{\pi}{2}$$

$$v = \sqrt{v_1^2 + v_2^2}$$

where the restriction on θ is required to insure that $v_1 \geq 0, v_2 \geq 0$. This yields

$$P(v_1, v_2) dv_1 dv_2 = \left(\frac{m}{kT}\right)^2 \int_0^{\frac{\pi}{2}} d\theta v^3 e^{-\frac{m}{2kT}v^2} \cos \theta \sin \theta dv = \frac{1}{2} \left(\frac{m}{kT}\right)^2 v^3 e^{-\frac{m}{2kT}v^2}$$

But this is the desired Maxwellian flux distribution. Since a radial component of velocity is sampled by $\sqrt{-\frac{2kT}{m} \ln \rho}$ (see Chapter 3), then we have $v = \sqrt{-\frac{2kT}{m} \ln \rho_1 - \frac{2kT}{m} \ln \rho_2}$. Or in terms of energy, $E = -kT \ln(\rho_1 \rho_2)$.

2. z - the value of z is drawn flat over a z -zone, i.e.,

$$z = z_s + \rho(z_{s+1} - z_s).$$

3. x, y - the values of x and y on the surface of the splicing cylinder in the absolute module zero coordinate system may be restricted to an angular sector, $\bar{\alpha} - \Delta\bar{\alpha}$ to $\bar{\alpha} + \Delta\bar{\alpha}$, where $0 \leq \bar{\alpha} < 360^\circ, 0 \leq \Delta\bar{\alpha} < 180^\circ$, and where $\bar{\alpha}$ is measured counter clockwise from the positive x -axis in the absolute module zero coordinate system. In the manner of an angular sector definition for an RCP trapping surface, we define α_1 and α_2 in radians restricted to the range $-\pi$ to π as follows:

$$\alpha_1 = (\bar{\alpha} - \Delta\bar{\alpha}) \frac{2\pi}{360}, \text{ if } \alpha_1 > \pi \text{ set } \alpha_1 = \alpha_1 - 2\pi$$

$$\alpha_2 = (\bar{\alpha} + \Delta\bar{\alpha}) \frac{2\pi}{360}, \text{ if } \alpha_2 > \pi \text{ set } \alpha_2 = \alpha_2 - 2\pi.$$

We now define

$$\Delta\alpha = \alpha_2 - \alpha_1, \text{ if } \Delta\alpha < 0 \text{ set } \Delta\alpha = \Delta\alpha + 2\pi.$$

Finally x and y are determined using r , α_1 , $\Delta\alpha$ as follows: First set

$$\alpha = \alpha_1 + \rho\Delta\alpha$$

and set

$$\begin{aligned} x &= r \cos \alpha, \\ y &= r \sin \alpha. \end{aligned}$$

4. μ, γ, η - the values of the neutron direction cosines in the absolute module zero coordinate system are obtained as follows. From Figure O-3, it is seen that the values of ϕ cover only the half range; hence γ_q^m is always positive. Since γ_q^m must cover the full range for the RCP splice, we first set

$$\gamma_q^m = \gamma_q^m \frac{2\rho - 1}{|2\rho - 1|},$$

then set

$$\begin{aligned} \mu &= \mu_q^m \cos \alpha - \gamma_q^m \sin \alpha \\ \gamma &= \mu_q^m \sin \alpha - \gamma_q^m \cos \alpha \\ \eta &= \eta_q^m \end{aligned}$$

(the RCP starting direction cosines are for the discrete directions of the DOS; that is, they are not distributed over a solid angle).

5. w_i - the neutron starting weight is given by

$$w_i = J(r) \frac{\Delta\alpha}{2\pi}.$$

We now have all the RCP neutron starting parameters for module zero and the RCP calculation may be performed in the conventional manner with the exception that should the splice cylinder be subsequently cut by a neutron path then that history is terminated.

P. POINT ESTIMATION TECHNIQUE FOR RCP01

P.1 Introduction

Practical calculations of the flux due to a radiation source often require the determination of the result at a point. With normal mode Monte Carlo collision scoring methods, it is almost impossible to obtain a flux estimation by a straight-forward technique since no particle is expected to intersect a given point. A time-honored approach with collision scoring techniques is to obtain an average over a finite volume surrounding the point of interest. This method may be satisfactory if the volume can be chosen small enough to adequately represent the flux at that point. As the gradient of the flux increases, the volume around the point of interest must decrease in order to preserve a true estimate of the flux at a point. However, the computer time required to generate a reasonable uncertainty increases as the volume decreases.

To circumvent this difficulty, an analytic statistical estimation of the flux at a point can be made. This technique is often referred to as a flux-at-a-point estimator or simply a point detector. A point detector uses a deterministic estimate of the flux at a point in space and is made at source and collision events throughout the normal mode random walk. A point estimator is known as a next-event estimator if a tally of the flux at a point is made when the next event is a trajectory without further collision directly to the point detector.

The chief difficulties with the next-event estimator in practical situations are: (1) The estimator requires computational effort due to extra geometric tracking. (2) An infinite variance is possible when a collision occurs near the point due to the $1/R^2$ term in the analytical flux expression. In the past, numerous approaches (References 19-22) to eliminate or minimize these shortcomings have been tried. The approach of this work continues in this vein and produces a simple but accurate detector scheme which is efficient.

P.2 Background

It can be shown (Reference 19) that the general expression for the uncollided contribution to the flux at a point is given by

$$\frac{f(\Omega' \rightarrow \Omega)}{R^2} \cdot e^{-\lambda} \quad (1)$$

where

R is the distance to the detector from the collision or source point.

$f(\Omega' \rightarrow \Omega)$ is the probability of scattering into the direction Ω from Ω' or being born into the direction Ω .

$\lambda = \int_0^R \Sigma_t(s) ds$ is the total number of mean free paths integrated over the trajectory from the collision or source point to the point detector.

s is the measured distance along the direction from the collision or source point to the detector.

$\Sigma_t(s)$ is the total macroscopic cross section at s .

Except for special cases (Reference 23), $f(\Omega' \rightarrow \Omega)$ is a function of $\Omega \cdot \Omega' = \mu_0$ only, where Ω' and Ω are the directions before and after scattering, respectively, and μ_0 is the cosine of the angle between them. The expression for the flux contribution to the detector becomes

$$\phi = \frac{W_{ex}(\mu_0)}{4\pi R^2} e^{-\lambda} \quad (2)$$

where w_{ex} is the exit neutron weight in the normal mode resulting from scattering at a collision site. It should be noted that λ can only be obtained by actual tracking through the complicated geometry; consequently, this can be an expensive process.

Next-event estimation schemes often use the energy of the particle at the collision or source site in determining the flux contribution to the point detector. In reality, $\mu_0 = 1$, where μ_0 is the cosine of the angle between the direction of the particle in the normal mode and the direction to the point detector, is extremely unlikely. The flux contribution to the point detector can be corrected by multiplying by the appropriate weight as follows

$$\phi = \frac{W_{ex} W_{sc}}{4\pi R^2} e^{-\lambda} \quad (3)$$

where w_{sc} is the weight scale factor to correct for the directional change from Ω' to Ω as discussed above. w_{sc} is determined from the actual scattering patterns for elastic, inelastic, and thermal kernel scattering. This method of correcting the energy at which the flux contribution is made to the point detector is used for all RCP01 point estimator schemes.

P.3 Point Estimator Schemes

P.3.1 The Gast Estimator

This scheme uses a flux averaging method similar to that of MCNP (Reference 19) where the flux inside a sphere of radius R_{s1} is given by

$$\phi = \frac{3W}{4\pi R_{s1}^3 \Sigma_T(s)} (1 - e^{-\lambda}) \quad (4)$$

where $w = w_{ex} w_{sc}$ and R_{s1} is a constant. This equation is based on the assumption that the scattering sites inside the sphere along the line between the collision site and the point detector are evenly distributed. Unlike equation (3), equation (4) will not lead to the infinite variance problem as $R \rightarrow \infty$. With the method proposed here, not only is the variance finite, but all moments exist for the frequency distribution function. Thus, the central limit theorem applies and the standard deviation of the flux estimate will decline as $(1/N)^{1/2}$ where N is the total number of histories.

Outside the sphere, Russian Roulette is played to reduce the amount of detailed geometry tracking. As part of the input for each point detector, the number of mean free paths (MFP) over which the flux is expected to decline by a factor of two must be specified. If the particle is outside the sphere,

$$\text{let } n = \text{Integer Part } \frac{(R - R_{s1})\Sigma_T(s)}{MFP} \quad (5)$$

Select a random number, ρ . If $\rho \leq 2^{-n}$, set $w_r = 2^n$; otherwise $w_r = 0$.

If MFP is input as negative, Russian Roulette is not played outside the sphere and detailed geometry tracking is performed for every next event estimation. In this case or if $R < R_{s1}$, $w_R = 1$. The weight term, w , in the flux contribution expression is now defined as $w = w_{ex} w_{sc} w_R$ and the flux is scored as in Equation (3). With the correct choice of MFP a large kill off probability can be achieved for contributions remote from the detector, thus increasing the efficiency of the scheme for eliminating tracking of small contributors.

P.3.2 The PACER Estimator

The PACER estimator uses the flux averaging method of Gast inside the sphere of radius R_{s1} and detailed geometry tracking outside the sphere with no Russian roulette. This is the same as the Gast estimator with a negative MFP.

P.3.3 The Hybrid Estimator

The hybrid estimator uses the flux averaging method of the Gast method plus detailed tracking with an alternate roulette. A second sphere is specified with a radius R_{s2} , larger than R_{s1} . In the region that is outside of the first sphere but inside the second sphere, detailed geometry tracking is used for the point detector. For each source or scattering event outside the larger sphere, the particle is considered to be moving to the detector with weight $w/(4\pi R^2)$, where w is the product of w_{ex} and w_{sc} . A uniformly distributed random number, ρ , is drawn from which a test mean free path is computed from $D = -\ln(\rho)$. If this falls short of the detector, tracking is terminated and no tally is made (i.e., the contribution is rejected). If the number of mean free paths selected goes beyond the detector, then $w/(4\pi R^2)$ is tallied.

P.4 Gast Estimator Specifications

P.4.1 Input Specifications

The following input restrictions apply when using a point estimator in RCP01. If an input check on any of the following results in a violation, then the problem is stopped with an appropriate comment which indicates the input problem.

1. Nuclide delta-scattering cannot be used; i.e., no nuclide i whose ID is given on card image 09000s can have a mass $A^i = 0$.
2. Composition-wise delta-scattering cannot be used, i.e., if card image 002sss is present, then it must contain all zeros.
3. Fast tracking cannot be used, i.e., if card image 000990 is present, then its parameter must be zero.
4. Modular geometry must be used, i.e., card images 65FFMs must be present.
5. Special source starts are excluded (i.e., LOPT must be zero on card image 000001).

P.4.2 Required Input

Up to 999 detector points are permitted in the module zero coordinate system (i.e., the absolute coordinate system) by the following sets of quintuplets:

$$x_1^D, y_1^D, z_1^D, r_1^D, \Delta MF_1^D, \dots, x_d^D, y_d^D, z_d^D, r_d^D, \Delta MF_d^D$$

where $d = 1, \dots, D$; $D \leq 999$ and where r_d^D is the radius of a sphere centered at x_d^D, y_d^D, z_d^D over which interior scattering and source sites may be assumed to be spatially flat over sectors, and where ΔMF_d^D is the number of mean free paths beyond r_d^D over which the "distance" Russian Roulette survival probability declines by a factor of 2.

P.4.3 Expanded Input

P.4.3.1 Conversion of 4 Block Anisotropic Scattering Patterns

The four block elastic scattering patterns over the inelastic MUFT groups and the four block thermal kernel scattering patterns over the thermal groups are converted to the positive four block pattern actually used in RCP.

The 4-block ($k = 1, \dots, 4$) elastic scattering pattern for inelastic MUFT group n is given for nuclide i by;

$$F_k^{i,n} = A_0^k + A_1^k f_1^{i,n} + A_2^k f_2^{i,n} + A_3^k f_3^{i,n}$$

In a similar manner, the thermal scattering pattern for incident thermal sub-group n and exit group m is given by:

$$F_k^{i,nm} = A_0^k + A_1^k f_1^{i,nm} + A_2^k f_2^{i,nm} + A_3^k f_3^{i,nm}$$

The following algorithm transforms the patterns to remove negative probabilities. Since the conversion process is identical for both, we will use the notation F_k^i for the block frequency distribution function where now the multigroup dependency is understood.

Set $\bar{F}_1^i = \min(\max(F_1^i, 0), 1)$.

If $F_1^i < 0$, set $F_2^i = F_2^i + F_1^i$.

Set $\bar{F}_2^i = \max(F_2^i, 0)$.

If $F_2^i < 0$, set $F_3^i = F_3^i + F_2^i$.

Set $\bar{F}_3^i = \max(F_3^i, 0)$.

If $F_3^i < 0$, set $F_4^i = F_4^i + F_3^i$.

Set $\bar{F}_4^i = \max(F_4^i, 0)$.

If $F_4^i < 0$, set $F_3^i = F_3^i + F_4^i$.

Set $\bar{F}_3^i = \max(F_3^i, 0)$.

If $F_3^i < 0$, set $F_2^i = F_2^i + F_3^i$.

Set $\bar{F}_2^i = \max(F_2^i, 0)$.

Since $\sum_{k=1}^4 \bar{F}_k^i = 1$, then arrays

$$f_k^{i,n} = \frac{B_k^{i,n}}{B_0^{i,n}} (k = 1, \dots, 3)$$

of Section 3.3.4.1 may be replaced by $\bar{F}_k^{i,n} (k = 1, \dots, 3)$ and the matrices

$$f_k^{i,nm} = \frac{C_k^{i,nm}}{C_0^{i,nm}} (k = 1, \dots, 3)$$

of Section 3.6.1.1 may be replaced by $\bar{F}_k^{i,nm} (k = 1, \dots, 3)$.

P.4.3.2 Calculation of Elastic Scattering Block Cut Points in the Lab System

Set and retain $\mu_k (k = 1, \dots, 3)$ where

$$\mu_1 = 0.652146$$

$$\mu_2 = 0.0$$

$$\mu_3 = -0.652146$$

For each nuclide i calculate and retain 3 cut points, i.e., $\mu_k^i (k = 1, \dots, 3)$ where

$$\mu_k^i = \frac{\gamma^i + \mu_k}{\sqrt{(\gamma^i + \mu_k)^2 + (1 - \mu_k^2)}} \quad \text{where } \gamma^i = \frac{1}{A^i},$$

and A^i is the target mass measured in neutron mass units.

P.5 Calculational Procedure for Point Detection in RCP01

P.5.1 Alterations to Tracking Procedures in RCP01

The conventional tracking is identical to that used normally in RCP01 with the following exception: The four block converted scattering pattern for fast elastic scattering and for thermal kernel scattering are treated as follows:

If $\rho \leq \bar{F}_1^i$ set $k = 1$ (leave checks)

$\rho^* \leq \bar{F}_1^i + \bar{F}_2^i$ set $k = 2$ (leave checks)

$\rho^* \leq \bar{F}_1^i + \bar{F}_2^i + \bar{F}_3^i$ set $k = 3$ (leave checks)

Set $k = 4$, $F_4^i = 1 - (\bar{F}_1^i + \bar{F}_2^i + \bar{F}_3^i)$

(This is identical to the block selection given in Section 3.3.4.2, where the checks are also left on a successful check).

P.5.2 The Explicit Point Detection Calculation at Each Source or Scattering Site

P.5.2.1 The Distance, Direction, and Neutron Weight Starting to Detector d

If a composition-wise source start is used, for either a fixed source or eigenvalue problem, then the starting site (x, y, z) and the direction cosines (μ, γ, η) will be in the coordinate system of an initial assembly. For this case the neutron parameters are:

$$FM, FA, \delta_{Ia}, j, E, W_I, n, m, l, \mu, \gamma, \eta, x, y, z, k_s, \rho$$

where δ_{Ia} identifies a primary or secondary IA (Initial Assembly) in a composite final assembly, k_s is a splitting (or Russian Roulette) zone index, and ρ is a random number used for cor-

related sampling. Of course, the incident neutron parameters at a scattering site in an initial assembly are of the same form.

If the neutron start is from a trapping surface splice file (see Appendices N and O), then the parameters are the same except $FM = FA = \delta_{Ia} = n = m = l = 0$. The composition j is determined when neutron tracking starts. Of course (x, y, z) and (μ, γ, η) are in the absolute (module zero) coordinate system. Again, the incident neutron parameters at a scattering site in module zero are of the same form.

The composition wise fixed source will be restricted to be isotropic, that is the value of LOPT on card image 000001 must be zero.

(a) Set Detector Number: $d = 1$

(b) Scattering Site in the Module Zero ($FM = 0$) or Start from TPT Splice or Trapping Surface

$$\text{Set: } r_d = \sqrt{(X_d^D - x)^2 + (Y_d^D - y)^2 + (Z_d^D - z)^2}$$

$$\text{Set: } \mu''_d = \frac{X_d^D - x}{r_d}, \quad \gamma''_d = \frac{Y_d^D - y}{r_d}, \quad \eta''_d = \frac{Z_d^D - z}{r_d}$$

$$\mu'_d = \mu\mu''_d + \gamma\gamma''_d + \eta\eta''_d$$

(c) Scattering Site in an Initial Assembly ($FM > 0$) or Composition-Wise Start

Convert (x, y, z) to absolute coordinate system.

$$\text{Set: } r_d = \sqrt{(X_d^D - x)^2 + (Y_d^D - y)^2 + (Z_d^D - z)^2}$$

$$\mu_d = \frac{X_d^D - x}{r_d}, \quad \gamma_d = \frac{Y_d^D - y}{r_d}, \quad \eta_d = \frac{Z_d^D - z}{r_d}$$

Now convert $(\mu_d, \gamma_d, \eta_d)$ back to the initial assembly coordinate system.

$$\text{Set: } \mu'_d = \mu\mu''_d + \gamma\gamma''_d + \eta\eta''_d$$

(d) Distance Russian Roulette Weight

Let $\Sigma^T(x, y, z, E)$ be the total cross section at (x, y, z) and energy E .

$$\text{Set: } n = \text{Int Part} \left\{ \frac{(r_d - r_d^D) \Sigma^T(x, y, z, E)}{\Delta M F_d^D} \right\}$$

$$\begin{aligned} \text{If } \rho^* > 2^{-n} \quad & \text{set } W_R = 0 \\ & \leq 2^{-n} \quad \text{set } W_R = 2^n \end{aligned}$$

(e) Weight Scale Factor for Starting Site, w_s , and Detection Energy E_d

If start is composition-wise, then set: $w_s = 1$.

If start is from a trapping surface splice file, set:

$$\begin{aligned} W_s &= 1 \quad \text{if } \mu'_d \geq 0.9 \\ W_s &= 0 \quad \text{if } \mu'_d < 0.9 \end{aligned}$$

In all cases set $E_d = E$.

(starting sites in RCP01 have $j = 0$ on slowing down file).

(f) Weight Scale Factor for Scattering Site, w_{sc} , and Detection Energy E_d .

(i) Elastic Scattering with Nuclide i

For inelastic MUFT groups n

$$\text{if } \mu_d^i \geq \mu_1^i \quad \text{set } k = 1 \quad (\text{leave checks})$$

$$\mu_d^i \geq \mu_2^i \quad \text{set } k = 2 \quad (\text{leave checks})$$

$$\mu_d^i \geq \mu_3^i \quad \text{set } k = 3 \quad (\text{leave checks})$$

$$\text{Set } k = 4, \bar{F}_4^{i,n} = 1 - (\bar{F}_1^{i,n} + \bar{F}_2^{i,n} + \bar{F}_3^{i,n})$$

$$\text{Set } W_{sc} = \frac{\bar{F}_k^{i,n} \left[\gamma^i \mu_d^i + \sqrt{1 - (\gamma^i)^2 [1 - (\mu_d^i)^2]} \right]^2}{A_0^k \sqrt{1 - (\gamma^i)^2 [1 - (\mu_d^i)^2]}}$$

For other MUFT groups:

$$\text{Set } W_{sc} = \frac{\left[\gamma^i \mu_d^i + \sqrt{1 - (\gamma^i)^2 [1 - (\mu_d^i)^2]} \right]^2}{\sqrt{1 - (\gamma^i)^2 [1 - (\mu_d^i)^2]}}$$

For all MUFT groups:

$$\text{Set: } k^i = \frac{1}{1 + \left(2 - \frac{\gamma^i}{2}\right) \frac{T^{*i}}{E}}$$

$$C_d = E \left\{ 1 - \frac{2k^i \gamma^i}{(1 + \gamma^i)^2} (1 + \gamma^i [1 - (\mu'_d)^2] - \mu'_d \cdot \sqrt{1 - \gamma^i [1 - (\mu'_d)^2] - \mu'_d}) \right\}$$

If $C_d \geq E_{th}$, set $E_d = C_d$ (E_{th} is the thermal cut point)

If $C_d < E_{th}$, set

$$\alpha^i = \left(\frac{1 - \gamma^i}{1 + \gamma^i} \right)^2, \quad C^i = \left(1 - \frac{\gamma^i T^i}{2E} \right), \quad K^i = 1 - (1 - \alpha^i) k^i$$

$$E_d = E_{th} - \left[\frac{C^i (E_{th} - C_d) (E_{th} - \alpha^i E)}{(E_{th} - K^i E)} \right]$$

$$\text{As } E \rightarrow 0; \quad E_{th} \frac{\gamma T^*}{2E} \rightarrow \infty$$

(ii) Inelastic Scattering

Let E_{ex} be the exit neutron energy resulting from inelastic scattering with nuclide i during conventional tracking.

Then we have:

$$\begin{aligned} W_{Sc} &= 1 \\ E_d &= E_{ex} \end{aligned}$$

(iii) Thermal Scattering

For thermal kernel nuclides:

$$\text{if } \mu'_d \geq \mu_1^i \quad \text{set } k = 1 \quad (\text{leave checks})$$

$$\mu'_d \geq \mu_2^i \quad \text{set } k = 2 \quad (\text{leave checks})$$

$$\mu'_d \geq \mu_3^i \quad \text{set } k = 3 \quad (\text{leave checks})$$

$$\text{Set } k = 4, \quad \bar{F}_4^i = 1 - (\bar{F}_1^{i,nm} + \bar{F}_2^{i,nm} + \bar{F}_3^{i,nm})$$

$$W_{SC} = \frac{\bar{F}_k^{i, nm}}{A_0^k}$$

$E_d = E_{ex}$ (E_{ex} is the exit neutron energy used in the conventional tracking)

For thermal non-kernel nuclides:

$$W_{Sc} = (1 + 2\mu'_d \gamma^i)$$

$$E_d = E_{ex}$$

(g) Neutron Weight, A_d , Starting for Detection Point

Let w_i be the neutron starting weight regardless of type of source start (start is known by program subroutine within an RCP energy group or is known by $j = 0$ on slowing down file). Let w_{ex} be the exit neutron weight resulting from scattering at a collision site, then

$$\begin{aligned} A_d &= W_R W_S W_i && \text{for starting neutron} \\ &= W_R W_{Sc} W_{ex} && \text{for scattered neutron} \end{aligned}$$

If $A_d = 0$, set $d = d + 1$ and go to (i) below.

In addition to point detector Russian Roulette, Russian Roulette can also occur in Russian Roulette compositions or from splitting ellipsoids. In both these latter cases the Russian Roulette is played just prior to a collision, hence the calculation of A_d is not altered. The splitting with the splitting ellipsoids occurs with the exit weight from a scattering event, i.e., with w_{ex} . Hence the value of w_{ex} in A_d must be that before splitting.

(h) Determine Flux Contribution F_d at Detector d at Energy E_d

Let $\Sigma_j^T(E_d)$ be the total cross section at energy E_d and for the composition j in which the starting site, or scattering site lies (this composition is known through the conventional tracking).

1. E_d is in the current RCP group.

$$\begin{aligned} \text{If } r_d < r_d^D \text{ set } F_d &= \frac{3A_d}{4\pi(r_d^D)^2} \frac{1}{r_d^D \Sigma_j^T(E_d)} [1 - \exp(-r_d^D \Sigma_j^T(E_d))] \\ &\text{set } d = d + 1 \text{ and go to (i) below} \end{aligned}$$

If $r_d \geq r_d^D$ perform conventional tracking starting at source, or collision site, i.e., (x, y, z) with direction cosines $(\mu''_d, \gamma''_d, \eta''_d)$. Let the distance between the l^{th} and $(l+1)^{st}$ boundary crossing be d_l . Let the total cross section between the l^{th} and $(l+1)^{st}$ boundary crossing be $\Sigma_{j(l)}^T(E_d)$. Define $\bar{d}_l = \bar{d}_{l-1} + d_l$ where $\bar{d}_0 = 0$

$$\bar{F}_l = \bar{F}_{l-1} \exp(-d_l \Sigma_{j(l)}^T(E_d)) \text{ where } F_0 = 1.$$

Starting with

$$l = 1, 2, \dots, \text{form } \bar{d}_l \text{ until } \bar{d}_l > r_d \text{ for } l = L$$

$$\text{Set: } \bar{F}_L = \bar{F}_l \exp[(\bar{d}_l - r_d) \Sigma_{j(l)}^T(E_d)]$$

$$F_d = \frac{A_d}{4\pi(r_d)^2} \bar{F}_L$$

set $d = d + 1$ and go to i .

For a uniform medium

$$F_d = \frac{A_d}{4\pi(r_d)^2} \exp[-r_d \Sigma_{j(l)}^T(E_d)]$$

2. E_d is not in the current RCP group:

Write a special detector file with the parameters (maximum of D sets):

$$x, y, z, \mu'_d, \gamma'_d, \eta'_d, E_d, r_d, A_d$$

When this detector file is read at the beginning of an RCP group, if E_d is below the lower energy cut point, then copy the parameters to the next detector file. If E_d is in the RCP group then go to a) to make the flux contribution F_d at detector d .

(i) If $d = D + 1$, set $d = 1$ and continue conventional tracking.

If $d < D + 1$ return to (b) above.

P.5.2.2 Output

At every iteration, RCP01 edits fluxes by RCP and by MUFT group and thermal subgroup for each detector d .