MASTER

SPAN-2 — AN IBM-704 CODE TO CALCULATE UNCOLLIDED FLUX OUTSIDE A CIRCULAR CYLINDER

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The SPAN-2 code calculates the uncollided gamma flux at a point outside a right circular cylinder which is surrounded by cylindrical shell shields and above which are plane slab shields. The cylinder is assumed to contain a source of gamma radiation which varies in the radial and axial directions only. Field points may be located in a plane through the axis of the cylinder. The method of integration used is three-dimensional Gaussian quadrature. Typical computing and editing time for a 20 field point problem, in which there are 10 side and 10 top shields, is four minutes per energy level. A 32,768 word IBM-704 is required for the code.

SPAN-2—AN IBM 704 CODE TO CALCULATE UNCOLLIDED FLUX OUTSIDE A CIRCULAR CYLINDER

P. A. Gillis, T. J. Lawton and K. W. Brand

The code, SPAN-2, is designed to calculate the uncollided gamma flux outside a core having the shape of a right circular cylinder (see Fig. 1). The code's primary applications are expected to be in radiation heating problems and in calculating gamma dose rates. The cylindrical geometry would seem to offer the most general application.

PART ONE

I. GENERAL INFORMATION

It is desired to find the uncollided flux at a field point outside a right circular cylinder which contains a source distribution $S(r, z)$, which is surrounded by cylindrical shell shields of infinite height, and above which are plane slab shields. It is assumed that:

- 1) The source distribution is independent of the azimuthal angle. The units of the source are photons/cubic centimeter-unit time. Note that the units of distance must be centimeters.
- 2) For all field points, $\theta = 0$, (i.e., all field points are in the $r - \theta$ plane).

Place the origin of the cylindrical coordinate system at the center of the core and use the following notation:

R_c	radius of the core
R_n	outer radius of the n^{th} cylindrical shield region
H	height of the core
$h_0 = H/2$	half-height of the core (z coordinate of all points on the upper face of the core)
h_m	height (from the center of the core) of the upper face of the m^{th} slab shield region
μ_n^s	attenuation coefficient of the material in the n^{th} cylindrical (side) shield region ($n = 0, 1, 2, \dots$)

- μ_m^t attenuation coefficient of the material in the m^{th} slab (top) shield region ($m = 1, 2, 3, \dots$)
- $P(r, \theta, z)$ point in the core
- $P_f(r_f, \theta_f, z_f)$ field point
- N_s number of cylindrical shield regions passed through in moving from P to P_f
- N_t number of slab shield regions passed through in moving from P to P_f
- D distance from P to P_f
- D_n^s distance traveled through the n^{th} cylindrical shield in moving from P to P_f
- D_k^t distance traveled through the k^{th} slab shield in moving from P to P_f

Using this notation, the uncollided flux is

$$\phi = \int_V \frac{S(r, z)}{4\pi D^2} \exp \left\{ - \left[\sum_{n=1}^{n=N_s} \mu_n^s D_n^s + \sum_{m=1}^{m=N_t} \mu_m^t D_m^t \right] \right\} dV, \quad (1)$$

with V representing the whole core (see Ref 1). The units of ϕ are particles/square cm-unit time. In cylindrical coordinates the integral takes the form

$$\phi = \frac{1}{4\pi} \int_0^{2\pi} d\theta \int_0^{R_c} r dr \int_{-H/2}^{H/2} \frac{S(r, z)}{D^2} \exp \left\{ - \left[\sum_{n=1}^{n=N_s} \mu_n^s D_n^s + \sum_{m=1}^{m=N_t} \mu_m^t D_m^t \right] \right\} dz \quad (2)$$

For computational purposes the problem is divided into three cases on the basis of the location of the field point.

Fig. 1 The Core with Surrounding Shields

Case 1: $r_f > R_c$, $|z_f| < H/2$
(side of core)

Case 2: $r_f \leq R_c$, $z_f > H/2$
(top of core)

Case 3: $r_f > R_c$, $z_f > H/2$
(corner of core)

For Case 1,

$$\sum_{m=1}^{m=N_t} \mu_m^t D_m^t = 0. \quad (3)$$

For Case 2,

$$\sum_{n=1}^{n=N_s} \mu_n^s D_n^s = 0. \quad (4)$$

Because the source is independent of θ and the field points are in the x - z plane, the actual limits of integration used in the θ direction are 0 to π , and the result is multiplied by 2 by the code.

II. NUMERICAL INTEGRATION

SPAN-2 performs the previous integration numerically by applying the method of Gauss quadrature 3 times (in the r , θ , and z directions). In this method the following summation is made for φ :

$$\varphi = K \left\{ \sum_{i=1}^{N_r} r_i w_i^1 \left[\sum_{j=1}^{N_\theta} w_j^2 \left(\sum_{k=1}^{N_z} S(r_i, z_k) f(r_i, \theta_j, z_k) w_k^3 \right) \right] \right\} \quad (5)$$

where

$$f(r_i, \theta_j, z_k) = \frac{1}{D^2} \exp \left\{ - \left[\sum_{n=1}^{N_s} \mu_n^s D_n^s + \sum_{m=1}^{N_t} \mu_m^t D_m^t \right] \right\}$$

and

$$K = \frac{1}{2\pi} \cdot \frac{R_u - R_L}{2} \cdot \frac{\theta_u - \theta_L}{2} \cdot \frac{Z_u - Z_L}{2}$$

The numbers N_r , N_θ , and N_z are the number of points taken in each direction. The points (r_i, θ_j, z_k) in the core and the weights w_i^1 , w_j^2 , w_k^3 are chosen by the quadrature method and depend on the dimensions of the core. R_u and R_L , θ_u and θ_L , and z_u and z_L are the upper and lower limits of integration in the r , θ , and z directions, respectively. These are made variable in the code to enable the user to integrate over part of the core if desired.

The following is a brief explanation of the method of integration. It is not intended to be definitive, and reference should be made to any standard work on numerical analysis (see Ref 2) or the calculus of finite differences for a fuller explanation.

Gauss' quadrature formula applied to one dimension is of the form

$$\int_a^b f(x) dx = \sum_{i=1}^n f(x_i) w_i \quad (6)$$

where n is the number of points taken and w_i represents the weights. The interval (a, b) is first transformed into the interval $(-1, 1)$ by the transformation

$$x = \frac{b-a}{2} v + \frac{b+a}{2} \quad (7)$$

The formula (6) then becomes

$$\int_a^b f(x) dx = \frac{b-a}{2} \int_{-1}^1 \varphi(v) dv = \frac{b-a}{2} \sum_{i=1}^n \varphi(v_i) dv_i \quad (8)$$

so that, for any given number of points, the v_i and the w_i values remain the same, regardless of the interval (a, b) .

The n points v_i and the n weights w_i must be found. In order to do this, $2n$ constraints on the formula are required. This may be done by requiring that the formula be exact if $\varphi(v)$ is a polynomial of degree $2n-1$ or less.

Let L_m be the Legendre polynomial of degree m which is orthogonal* over the interval $(-1, 1)$ and let $P(v)$ be an arbitrary polynomial of degree $n-1$. The polynomial $P(v)$ can be represented as a linear function of the polynomials L_m :

* Orthogonality is defined by the condition $\int_{-1}^1 L_i(v) L_j(v) dv = 0$ if $i \neq j$. All the roots of the Legendre polynomials are real and distinct.

$$P(v) = a_0 L_0(v) + a_1 L_1(v) + \dots + a_{n-1} L_{n-1}(v) ;$$

then,

$$\int_{-1}^1 P(v) L_n(v) dv = \int_{-1}^1 a_0 L_0(v) L_n(v) dv + \dots + \int_{-1}^1 a_{n-1} L_{n-1}(v) L_n(v) dv ,$$

where each of the integrals on the right is zero by the orthogonality of the L_m . Then,

$$\int_{-1}^1 P(v) L_n(v) dv = 0 . \quad (10)$$

Now, since the formula is to be exact for polynomials of degree $2n-1$ or less,

$$\int_{-1}^1 P(v) L_n(v) dv = \sum_{i=0}^n w_i P(v_i) L_n(v_i) dv = 0 . \quad (11)$$

Since $P(v)$ is an arbitrary polynomial, the formula is exact only if $L_n(v_i) = 0$ for all i . Then, the v_i 's must be taken as the zeros of the Legendre polynomial $L_n(v)$.

To calculate the weights, let

$$Q_\alpha(v) = (v-v_1)(v-v_2) \dots (v-v_{\alpha-1})(v-v_{\alpha+1}) \dots (v-v_n) , \quad (12)$$

where the v_i 's are the roots of the Legendre polynomial

$$Q_\alpha(v) = 0 \text{ for } v = v_1, v_2, \dots, v_{\alpha-1}, v_{\alpha+1}, \dots, v_n .$$

By the quadrature formula,

$$\int_{-1}^1 Q_\alpha(v) dv = \sum_{i=1}^N Q_\alpha(v_i) w_i = Q_\alpha(v_\alpha) w_\alpha . \quad (13)$$

Then,

$$w_\alpha = \frac{1}{(v_\alpha - v_1) \dots (v_\alpha - v_{\alpha-1})(v_{\alpha+1}) \dots (v_\alpha - v_n)} \int_{-1}^1 (v - v_1) \dots (v - v_{\alpha-1})(v - v_{\alpha+1}) \dots (v - v_n) dv .$$

The points v_i and the weights w_i for $n = 9$ and $n = 12$ are listed in Appendix I.

A special formula could be developed for double and triple integrals, but this is not necessary since the one-dimensional formula can simply be applied two or three times:

$$\int_{z_1}^{z_2} \int_{y_1}^{y_2} \int_{x_1}^{x_2} f(x, y, z) dx dy dz = \sum_{k=1}^{n_3} \left[\sum_{j=1}^{n_2} \left(\sum_{i=1}^{n_1} f(x_i, y_j, z_k) w_i^1 \right) w_j^2 \right] w_k^3 . \quad (14)$$

In cylindrical coordinates, this formula becomes

$$\int_{r_1}^{r_u} \int_{\theta_1}^{\theta_u} \int_{z_1}^{z_u} r F(r, \theta, z) dr d\theta dz = \sum_{k=1}^{n_3} \left[\sum_{j=1}^{n_2} \left(\sum_{i=1}^{n_1} r F(r_i, \theta_j, z_k) w_i^1 \right) w_j^2 \right] w_k^3 . \quad (15)$$

III. DISTANCE FORMULAS

As part of the evaluation of the integrand at each point in the core selected by the code, the quantity

$$\exp \left\{ - \left[\sum_{k=1}^{k=N_s} \mu_k^s D_k^s + \sum_{n=1}^{n=N_t} \mu_n^t D_n^t \right] \right\} \quad (16)$$

must be found.

The usual distance formula for cylindrical coordinates is used to find the distance from $P(r, \theta, z)$ to $P_f(r_f, 0, z_f)$. Thus,

$$D = \sqrt{r_f^2 + r^2 - 2rr_f \cos \theta + (z - z_f)^2} \quad (17)$$

Case 1

The ray from P to P_f does not pass through any top shields. Then,

$$\sum_{k=1}^{k=N_t} \mu_k^t D_k^t = 0 \quad .$$

In order to reduce the number of square roots that must be calculated in evaluating the D_n^s , the following procedure is observed.

For all points with a given r and θ coordinate, the projection of the ray from P to P_f on the $z = 0$ plane is the same (see Fig. 2).

In addition, for all these points, the percentage of the total distance contained within the n^{th} side shield is the same.

Let a point $P(r, \theta, z)$ be given. To find the distance through the n^{th} side shield along the ray from P to P_f , let the distance from $(r, \theta, 0)$ to $(r_f, 0, 0)$ be D' , and let D'_n be the distance through the n^{th} side shield along the ray from $(r, \theta, 0)$ to $(r_f, 0, 0)$ (see Fig. 3).

Fig. 2 Projection of Distances on $z = 0$ Plane

All the triangles shown are similar and, therefore, D' has the same relationship to D as D'_n has to D_n^s . Then,

$$\frac{D_n^s}{D'_n} = \frac{D}{D'}$$

or

$$D_n^s = \frac{D'_n}{D'} D \quad .$$

It follows from this result that

$$\sum_{n=1}^{N_s} \mu_n^s D_n^s = \sum_{n=1}^{N_s} \mu_n^s \frac{D_n'}{D'} D = \frac{D}{D'} \sum_{n=1}^{N_s} \mu_n^s D_n' . \quad (18)$$

Now, the quantity

$$\frac{1}{D'} \sum_{n=1}^{N_s} \mu_n^s D_n'$$

is independent of z . This quantity may be thought of as an average attenuation coefficient for points with the same r and θ coordinates. Thus, it is convenient to sweep the mesh in the z direction first. To calculate the D_n' , D' is first calculated by the formula:

$$D' = \sqrt{r^2 + r_f^2 - 2rr_f \cos \theta} . \quad (19)$$

Then, the quantity $\sqrt{R_n^2 D'^2 - r^2 r_f^2 \sin^2 \theta}$ is found for each value of n .

Finally,

$$D_1' = \frac{1}{D'} \left[\sqrt{R_1^2 D'^2 - r^2 r_f^2 \sin^2 \theta} - rr_f \cos \theta + r^2 \right] \quad (20)$$

and

$$D_n' = \frac{1}{D'} \left[\sqrt{R_n^2 D'^2 - r^2 r_f^2 \sin^2 \theta} - \sqrt{R_{n-1}^2 D'^2 - r^2 r_f^2 \sin^2 \theta} \right] . \quad (21)$$

If the ray passes completely through the n^{th} shield (see Fig. 4),

Fig. 4 Ray from P to P_f Pierces Center Region

and

$$\alpha_1 = \cos^{-1} \frac{R_2}{r_f} + \cos^{-1} \frac{R_2}{r} (\alpha_1 \geq \alpha_0) .$$

If P is in the second region and $\theta > \alpha_0$, the ray from P to P_f pierces the surface of the center region twice. If $\theta \leq \alpha_0$ the ray does not pass through the center region at all.

$$D_n' = \frac{2}{D'} \sqrt{R_n^2 D'^2 - r^2 r_f^2 \sin^2 \theta} .$$

If $P(r, \theta, z)$ is in the second cylindrical region, the ray will pierce the surface of the center region twice or not at all. If P is in the third region, the ray will pierce the center and second regions twice, or the second region twice, or neither the center nor second region at all.

Let

$$\alpha_0 = \cos^{-1} \frac{R_1}{r_f} + \cos^{-1} \frac{R_1}{r}$$

If P is in the third region and $\theta > \alpha_1$, the ray from P to P_f pierces the surfaces of the center and second regions twice each. If $\alpha \geq \theta > \alpha_0$, the ray pierces the surface of the second region twice and the surface of the center region not at all. If $\theta < \alpha_0$, the ray does not pass through the center or second regions at all (see Fig. 5).

Fig. 5 Diagram for Determination of Core Regions Passed through

Case 2

The ray from P to P_f does not pass through any side shields (see Fig. 6). Then,

$$\sum_{n=4}^{n=N} \mu_n^S D_n^S = 0.$$

Fig. 6 Ray from P_f to P Pierces Top of Core

The distances through the top shields are found by the use of the relationship

$$\frac{z_f - z}{D} = \frac{h_0 - z}{D_1^t} = \frac{h_1 - h_0}{D_2^t} = \dots = \frac{z_f - h_{N_s-1}}{D_n^t} \quad (22)$$

Then,

$$\left. \begin{aligned} D_1^t &= \frac{h_0 - z}{z_f - z} D, \\ D_n^t &= \frac{h_n - h_{n-1}}{z_f - z} D, \\ D_{N_s}^t &= \frac{z_f - h_{N_s-1}}{z_f - z} D. \end{aligned} \right\} \quad (23)$$

and

It follows from this result that:

$$\begin{aligned} \sum_{n=1}^{N_t} \mu_n D_n^t &= \sum_{n=1}^{N_t-1} \frac{h_n - h_{n-1}}{z_f - z} D \mu_n^t + \frac{z_f - h_{N_t-1}}{z_f - z} D \mu_{N_t}^t \\ &= \frac{D}{z_f - z} \left[\sum_{n=1}^{N_t-1} (h_n - h_{n-1}) \mu_n^t + (z_f - h_{N_t-1}) \mu_{N_t}^t \right] \end{aligned} \quad (24)$$

In case 2, the distance D_1^t is the portion of the ray from P to P_z which is in the core. This may pass through one or more of the cylindrical regions inside the core. It is necessary to calculate which regions the ray passes through and the distances. This is done in a manner similar to that for case 1.

For example, suppose $R_2 < r_f \leq R_3$ and $r \leq R_1$ (see Fig. 7). Let $\bar{P}_0(r_0, \theta_0, z_0)$ be the point at which the ray from P to P_f pierces the cylinder $r = R_1$, and $\bar{P}_1(r_1, \theta_1, z_1)$ be the point at which the ray pierces the plane $z = h/2$ (top of core).

The distance from P to $\bar{P}_0$ is given by the formula

$$\frac{D}{D'} \left[\sqrt{R_1^2 D'^2 - r^2 r_f^2 \sin^2 \theta} + r r_f \cos \theta + r^2 \right]$$

The distance from $\bar{P}_0$ to $\bar{P}_1$ is

$$\frac{z_1 - z_0}{z_f - z} D$$

The distance from $\bar{P}_1$ to P_f is

$$\left[(z_f - z_{N_t-1}) + \sum_{i=1}^{N_t-1} (h_i - h_{i-1}) \right] \frac{D}{z_f - z}$$

Fig. 7 Field Point above the Core

Case 3

In case 3, the ray from P to P_f may pass through both top shields and side shields. For various points inside the core, the following situations must be distinguished:

- 1) The ray from P to P_f pierces the side of the core and the side of the cylinder $r = R_3$ below the top of the core. For such points all calculations are the same as the case 1 (Fig. 8).

Fig. 8 Ray from P to P_f Pierces Side Regions Only

- 2) The ray from P to P_f pierces the side of the cylinder $r = R_3$ above the top of the core. Let $\bar{P}_1(\bar{r}_1, \bar{\theta}_1, \bar{z}_1)$ be the point at which the ray from P to P_f pierces the plane $z = h/2$ (top of core). Let $\bar{P}_2(\bar{r}_2, \bar{\theta}_2, \bar{z}_2)$ be the point at which the ray pierces the cylinder $r = R_3$. The distance from $\bar{P}_2$ to P_f may be handled as in case 1, and when z_2 has been calculated, the distance from P to $\bar{P}_1$ may be handled as the distance inside the core is handled in case 2 (see Fig. 9).

Fig. 9 Ray from P to P_f Passes through slabs

IV. SOURCE

As part of the input data, there must be a description of the source distribution. This description must be in the form of a two-dimensional mesh covering the core and reflectors. Figure 10 shows a 3×3 mesh. Since there is angular symmetry, this mesh may be rotated around the center line to cover the entire core, except for the center line itself and the boundaries. It is assumed that a line of symmetry exists at the center of the extreme mesh interval in each direction. This means that the source strength on the edge of the core and the center may not be given. If one of these values is needed, it is made equal to the source strength of the nearest interior point.

The reflector thicknesses which are used may not be the same as the reflector thicknesses which are part of the input. The reflector thickness will always be an integral number of mesh intervals from the outside of

the core. If the input reflector thickness is not equal to the sum of an integral number of mesh intervals, the integral number of mesh intervals which is closest is used.

After the reflector thicknesses have been found, the radius of the core is computed by summing the Δr 's and subtracting the side reflector thickness. The height of the core is computed by summing the Δz 's and subtracting the top and bottom reflector thicknesses. Even if the reflector thickness is given as zero, a number density must be given for it.

The origin is then placed at the center of the core and coordinates are assigned to each mesh point. The coordinates of the points required for the Gaussian quadrature are transformed from the interval $(-1, 1)$ to the intervals (R_L, R_u) , (z_L, z_u) , and (θ_L, θ_u) , which are part of the input. The transformation formulas are as follows:

TOP OF CORE			
Δr_1	Δr_2	Δr_3	Δr_4
Δz_1	s_1	s_2	s_3
Δz_2	s_4	s_5	s_6
Δz_3	s_7	s_8	s_9
Δz_4			
CENTER OF CORE			

Fig. 10 3×3 Mesh

$$\left. \begin{aligned} r &= \frac{R_u - R_L}{2} r_G + \frac{R_u + R_L}{2}, \\ z &= \frac{z_u - z_L}{2} z_G + \frac{z_u + z_L}{2}, \\ \theta &= \frac{\theta_u - \theta_L}{2} \theta_G + \frac{\theta_u + \theta_L}{2}, \end{aligned} \right\} \quad (25)$$

and

where r_G , z_G , and θ_G are Gaussian points (i.e., zeros of the n^{th} degree Legendre polynomials).

Since the Gauss quadrature method requires special points at which the integrand must be calculated, and since the points at which the source is known do not coincide with these points, interpolation between known points is required.

The interpolation is accomplished by first finding the four points between which the coordinates of the Gaussian point lies, and then using linear interpolation (see Fig. 11). The values of S at the points P' and P'' are found by the following formulas:

$$\left. \begin{aligned} S(r, z_2) &= S(r_1, z_2) + \left[S(r_2, z_2) - S(r_1, z_2) \right] \frac{r - r_1}{r_2 - r_1} \\ S(r, z_1) &= S(r_1, z_1) + \left[S(r_2, z_1) - S(r_1, z_1) \right] \frac{r - r_1}{r_2 - r_1} \end{aligned} \right\} \quad (26)$$

The desired value is then found from

$$S(r, z) = S(r, z_1) + \left[S(r, z_2) - S(r, z_1) \right] \frac{z - z_1}{z_2 - z_1}.$$

V. THE HOMOGENIZATION ROUTINE

The homogenization routine computes the attenuation coefficients for the core, the top and side reflectors, and the top and side shields. By specifying the number of materials for each of these regions, the types of materials that compose each of these regions, the number densities of these materials, and the energy level, the homogenization routine computes

$$\mu_j = \sum_i N_{i,j} \sigma_i \quad (28)$$

for every region j . The summation is taken only over the specified materials i in the region j . $N_{i,j}$ is the number density of material i which is specified as one of the materials of region j ; σ_i is the microscopic cross section of the specified material i at the specified energy level. The microscopic cross sections are stored internally in the computer, and the proper ones are chosen by the specified material at the specified energy. The cross sections used were obtained from Refs 3 and 4.

The region number j may never exceed 34. Regions 1, 2, and 3 are inside the core; region 4 is the side reflector; region 5 is the first side shield, etc. Top region 1 is the top reflector, top region 2 is the first top shield, etc.

The material number i may never exceed 10. That is, there are 10 distinct types of materials. However, any one region may never contain more than nine different materials. A maximum of 30 energy levels is allowed.

For example, suppose the materials 2, 6, and 15 compose side region 3, that is, the side reflector. Then, for a specified energy, the attenuation coefficient is computed as

$$\mu_3 = N_{2,3}\sigma_2 + N_{6,3}\sigma_6 + N_{15,3}\sigma_{15} \quad (29)$$

The homogenization routine will recognize that a region is a vacuum when the number of materials for that region is specified as zero. Then, the attenuation coefficient for that region is immediately set to zero. In this case, a number density should not be included for that region.

PART TWO

I. PREPARATION OF INPUT

General

The first two cards of all SPAN input decks must be title cards. The first title card is used to identify the problem and is printed on all output sheets for the problem. The second is used to identify the source. The source deck follows the title cards, and the SPAN input deck follows the source deck. If there is no source input deck, the SPAN input deck follows the title cards.

All cards with numeric data must be punched according to the following rules:

- 1) Integers are represented exactly and are called fixed point numbers.
- 2) Decimal numbers are represented in the excess 50 normalized floating point form. The exponent is placed first and a decimal point is assumed to be to the left of the first significant digit. These numbers are called floating point numbers. Lead zeros are not allowed in floating point numbers. (Examples are: 5011 = .11, 5111 = 1.1, 4911 = .011, and 5211 = 11.)
- 3) No more than 8 digits (exclusive of exponent and sign) may be used to represent a number, although less than 8 digits may be used.
- 4) No blank columns from columns 1 to 72 are allowed.
- 5) No double punches are allowed in columns 1 to 72.
- 6) Each field must be preceded by a sign (either plus or minus).
- 7) The last field is followed by a "+" character and the card must be filled with zeros to column 72. This is the only way in which a card may be terminated.
- 8) Floating point zero is represented by at least 3 zeros punched in consecutive columns.
- 9) Column 1 must have a "+" sign, and fields are read in order from left to right.

Title Cards

Problem Title Card

- 1) Any characters may be placed in columns 2 to 65 of the problem title card. Columns 66 and 67 must be blank (no punches). Columns 68, 69, 70, 71, and 72 must contain the characters "SPAN 2."

Source Title Card

- 1) For TURBO tape 7 input of the source, the title card must be the same as the TURBO title card (i. e., the title card used when the TURBO problem was run). (See Ref 5.)

- 2) For punched card input of sources, the source title card may contain any 71 digits in columns 2 to 72. An identical card should be used for all subsequent problems run with the same source.
- 3) When using the restart tape (tape 2) to obtain the source, the source title card must be the same as that in use when the restart tape was written.

Span Input Deck

Card Number 1000

<u>Word Number</u>	<u>Symbol</u>	<u>Fixed or Floating</u>	<u>Identification</u>
1	C. N.	fixed	card number (1000)
2	N_E	fixed	number of energy levels
3	N_s	fixed	number of side shields
4	N_t	fixed	number of top shields
5	T_{ref}	floating	top reflector thickness
6	B_{ref}	floating	bottom reflector thickness
7	S_{ref}	floating	side reflector thickness

Note 1: The number of side shields to be specified is exclusive of the core or side reflector.

Note 2: The number of top shields to be specified is exclusive of those inside the core or the top reflector.

Note 3: The reflector thicknesses should be equal to an integral number of mesh intervals as specified with the source. If one of them is not, the reflector thickness used will be equal to the nearest integral number of mesh intervals. (The reflector thicknesses may also be zero.)

Card Number 2000

<u>Word Number</u>	<u>Symbol</u>	<u>Fixed or Floating</u>	<u>Identification</u>
1	C. N.	fixed	card number (2000)
2	R_L	floating	lower integration limit for r
3	R_u	floating	upper integration limit for r
4	z_L	floating	lower integration limit for z
5	z_u	floating	upper integration limit for z
6	θ_L	floating	lower integration limit for θ
7	θ_u	floating	upper integration limit for θ
8	$\pm T. S. N.$	fixed	time step number (for TURBO tape)

Note 1: R_L cannot be less than zero or R_u greater than the radius of the core.

Note 2: z_L cannot be less than $-H/2$ or z_u greater than $H/2$. H is the height of the core.

Note 3: θ_L cannot be less than zero. θ_u cannot be greater than π . Because of symmetry, the integral is multiplied by 2. The integration that actually takes place is, therefore, from θ_L to θ_u and from $-\theta_u$ to $-\theta_L$.

Note 4: $R_L \leq R_u$, $z_L \leq z_u$, $\theta_L \leq \theta_u$.

Note 5: The T. S. N. need not appear if the source comes from punched cards or a restart tape.

Note 6: If any or all of the r , θ , or z limits are to be over the whole core, two zeros may be used for the limits.

Note 7: If the T. S. N. is positive, the thermal flux is read as the source. If the T. S. N. is negative, the TURBO source is read as the source.

Card Number 2001

Card number 2001 is used to specify the number of cylindrical regions inside the core and the thicknesses of these regions. There may be 1, 2, or 3 regions inside the core, and different compositions for each region are allowed. The sum of the thicknesses of these regions must be equal to the radius of the core as computed from the source ($R_c = \Sigma \Delta r - S_{ref}$).

<u>Word Number</u>	<u>Symbol</u>	<u>Fixed or Floating</u>	<u>Identification</u>
1	C. N.	fixed	card number (2001)
2	N_R	fixed	number of regions inside the core
3	R_1	floating	radius of 1st region inside the core
4	R_2	floating	radius of 2nd region (if needed)
5	R_3	floating	radius of 3rd region (if needed)

Note 1: $R_1 + R_2 + R_3$ must equal R_c , the radius of the core. If R_2 and R_3 , or R_3 do not appear, they are assumed to be zero.

Card Number 2002

Card number 2002 is used to specify the energy levels at which it is desired to calculate the flux. As many energy level numbers are included as specified on card 1000.

<u>Word Number</u>	<u>Symbol</u>	<u>Fixed or Floating</u>	<u>Identification</u>
1	C. N.	fixed	card number (2002)
2	E_1	fixed	energy level number
3	E_2	fixed	energy level number
.	.	.	.
.	.	.	.
.	.	.	.
31	E_{30}	fixed	energy level number

Note 1: Only as many energy level numbers as specified on card 1000 need appear. The card may be terminated following the last energy level.

Note 2: If it is desired to calculate the flux for all 30 possible energy levels, the card may be terminated following the card number.

Card Number 3000

Word Number	Symbol	Fixed or Floating	Identification
1	C. N.	fixed	card number (3000)
2	N_{s0}	fixed	number of materials in 1st core region
3	N_{s1}	fixed	number of materials in 2nd core region
4	N_{s2}	fixed	number of materials in 3rd core region
5	N_{s3}	fixed	number of materials in side reflector
6	N_{s4}	fixed	number of materials in 1st side shield
.	.	.	.
.	.	.	.
.	.	.	.
32	N_{s33}	fixed	number of materials in 29 th side shield

Note 1: The number of materials in the first core region and the side reflector must always be given. In addition, the number of materials for the 2nd and 3rd regions of the core (if they are nonzero) and for N_s side shields (as given on card 1000) must be given. The card may be terminated following the last shield to be specified. A vacuum may be indicated by specifying zero materials for that region.

Note 2: If all the regions to be specified (including the core and side reflector) have one material per region, this card may be omitted.

Note 3: There is a maximum of nine materials per region.

Note 4: If the side reflector has a thickness of zero, a zero should be placed so as to indicate a vacuum in the side reflector. Then, no number density need be given for the side reflector on card 6000, and no library numbers need be given for the side reflector on card 4000.

Card Number 35000

Word Number	Symbol	Fixed or Floating	Identification
1	C. N.	fixed	card number (3500)
2	n_{t1}	fixed	number of materials in top reflector
3	n_{t2}	fixed	number of materials in 1st top shield
4	n_{t3}	fixed	number of materials in 2nd top shield
.	.	.	.
.	.	.	.
.	.	.	.
31	n_{t30}	fixed	number of materials in 29 th top shield

Note 1: The number of materials in the top reflector must always be included. In addition, the materials for N_t top shields (as given on card 1000) must be specified. The card may be terminated following the last top shield to be specified. A vacuum may be indicated by specifying zero materials in that region.

Note 2: If all regions to be specified (including the top reflector) have one material per region, this card may be omitted.

Note 3: There is a maximum of nine materials per region.

Note 4: If the top reflector has a thickness of zero, a zero should be placed so as to indicate a vacuum in the top reflector. Then, no number density need be given for the top reflector on card 6500 and no library numbers need be given for the top reflector on card 4500.

Card Series 4000

The card series numbered 4000, 4001, 4002, etc. is used to specify the kinds of materials contained in each side region. On card 1000 the number of side shields is specified; the number of materials in each side region is given on card 3000. Thus, for each side region, as many materials as are indicated for that region on card 3000 must be specified. These materials are specified by punching the corresponding library numbers for these materials (as shown in Appendix II) in succession across the card.

The first region to be specified is the core. The first number, after the card number n_{s0} , on card 3000 gives the number of materials in the first region of the core; and the first n_{s0} numbers on card 4000 (after the card number) are used to obtain the homogenized attenuation coefficient of the core. The next n_{s1} numbers indicate the materials in the second core region (if needed). The next n_{s2} numbers indicate the materials in the third core region (if needed) and so on until all side regions are specified.

Since there may be nine materials in each region and there may be 31 regions (including the core), it may take 279 numbers to fully specify the side regions. Twenty fixed point numbers (not counting the card number) may be placed on each card of the 4000 series. If more than 20 library numbers are required, the next 20 are placed on card 4001. This is continued until all regions are fully specified.

If a vacuum is indicated on card 3000 for any region, no library numbers should be given for that region.

Card Series 4500

The card series 4500 bears the same relationship to card 3500 as card series 4000 bears to 3000. Card series 4500 is used to specify the kinds of materials in the top regions, starting with the top reflector. If a vacuum is indicated on card 3500 for any region, no library number should be given for that region.

Card Series 5000

The series of cards numbered 5000, 5001, 5002, etc. is used to specify the thickness of the side shields. The number of thicknesses which must be specified is the number given on card 1000 as the number of side shields. The side reflector is not given here since it is given on card 1000.

<u>Word Number</u>	<u>Symbol</u>	<u>Fixed or Floating</u>	<u>Identification</u>
1	C. N.	fixed	card number (5000, 5001, 5002, etc.)
2	T _{s1}	floating	side shield thickness
3	T _{s2}	floating	side shield thickness
4	T _{s3}	floating	side shield thickness
5	T _{s4}	floating	side shield thickness
6	T _{s5}	floating	side shield thickness
7	T _{s6}	floating	side shield thickness

Note 1: Six side shield thicknesses are given per card. As many cards are included as is necessary to specify all side shields. Card numbers are increased by one for each subsequent card.

Card Series 5500

The series of cards numbered 5500, 5501, 5502, etc. is used to specify the top shield thicknesses. The number of thicknesses which must be specified is equal to the number given on card 1000 as the number of top shields. The top reflector thickness is not given here since it is given on card 1000.

<u>Word Number</u>	<u>Symbol</u>	<u>Fixed or Floating</u>	<u>Identification</u>
1	C. N.	fixed	card number (5500, 5501, 5502, etc.)
2	T _{t1}	floating	top shield thickness
3	T _{t2}	floating	top shield thickness
4	T _{t3}	floating	top shield thickness
5	T _{t4}	floating	top shield thickness
6	T _{t5}	floating	top shield thickness
7	T _{t6}	floating	top shield thickness

Note 1: Six top shields are given on a card starting with the first top shield. As many cards are included as is necessary to specify all the top shields. Card numbers are increased by one for each card subsequent to the card numbered 5500.

Card Series 6000

The series of cards numbered 6000, 6001, etc. is used to specify the number densities of the materials in the cylindrical (side) regions. There must be a one-to-one correspondence between the number densities given here and the library numbers given on the 4000 series for the cylindrical (side) regions. Six number densities are placed on each card in floating point form, and enough cards are included to specify all number densities for all side regions.

<u>Word Number</u>	<u>Symbol</u>	<u>Fixed or Floating</u>	<u>Identification</u>
1	C. N.	fixed	card number (6000, 6001, etc.)
2	N. D.	floating	number density
3	N. D.	floating	number density
4	N. D.	floating	number density
5	N. D.	floating	number density
6	N. D.	floating	number density
7	N. D.	floating	number density

Note 1: The units of the number densities are (atoms or molecules/cubic centimeter) $\times 10^{-24}$.

Note 2: If concrete is used, the mass density must be given.

Note 3: Even if $N_s = 0$, a 6000 card must be included.

Note 4: If a vacuum is indicated on card 3000 for any region, no number density should be included for that region.

Card Series 6500

The series of cards numbered 6500, 6501, etc. are used to specify the number densities of the materials in the slab (top) regions. There must be a one-to-one correspondence between the number densities given here and the library numbers given on the 4500 series for the slab (top) regions. Six number densities are placed on each card in floating point form, and enough cards are included to specify all number densities for all top regions.

<u>Word Number</u>	<u>Symbol</u>	<u>Fixed or Floating</u>	<u>Identification</u>
1	C. N.	fixed	card number
2	N. D.	floating	number density
3	N. D.	floating	number density
4	N. D.	floating	number density
5	N. D.	floating	number density
6	N. D.	floating	number density
7	N. D.	floating	number density

Note 1: The units of the number densities are (atoms or molecules/cubic cm) $\times 10^{-24}$.

Note 2: If concrete is used, the mass density must be given.

Note 3: Even if $N_t = 0$, a 6500 card must be included.

Note 4: If a vacuum is indicated on card 3000 for any region, no number density should be included for that region.

The materials for which there are microscopic cross sections in the library and their corresponding library numbers are:

1. Hydrogen
2. Oxygen
3. Zirconium
4. Carbon

- 6. Iron
- 9. Aluminum
- 18. Uranium
- 48. Lead
- 75. Concrete
- 77. Water

Card Series 7000

The series of cards numbered 7000, 7001, 7002, etc., is used to specify the coordinates of the field points at which the uncollided flux is to be calculated. Since all field points must be in the $\theta = 0$ plane, only the r and z coordinates should be given. Six numbers or three field points may be given on each card. There is a limit of 100 field points per problem. The field points may be in any one of the three regions:

- 1) $r > R_c, |z| \leq H/2$
- 2) $r \leq R_c, z > H/2$
- 3) $r > R_c, z > H/2$

The field points may be given in any convenient sequence.

<u>Word Number</u>	<u>Symbol</u>	<u>Fixed or Floating</u>	<u>Identification</u>
1	C. N.	fixed	card number
2	r_f	floating	r coordinate of field point
3	z_f	floating	z coordinate of field point
4	r_f	floating	r coordinate of field point
5	z_f	floating	z coordinate of field point
6	r_f	floating	r coordinate of field point
7	z_f	floating	z coordinate of field point

Note 1: The last field point should be indicated by placing a field point with both the r coordinate and z coordinate zero as the next one, unless the last one finishes a card.

Input of Source

The code is designed to take the source from either a TURBO tape 7, or punched cards, or from the restart tape of a previous SPAN problem. In all cases, the dimensions of the core are obtained from the source. The radius of the core is obtained from the source (in the case of a TURBO tape or punched card input of the source) by adding all the mesh intervals in the r direction and subtracting the side reflector thickness. The core height is obtained by adding all the mesh intervals in the z direction and subtracting the top and bottom reflector thicknesses. If the source distribution is obtained from a restart tape, the dimensions of the core are those which were written on the restart tape when the previous problem was run.

It is assumed that the source varies only in the r and z directions. A two-dimensional mesh is specified by giving Δr 's and Δz 's. Values of the source are specified at interior mesh points (Fig. 10). The code will interpolate linearly for the values of the source at points corresponding to zeros of the Legendre polynomials required for Gauss quadrature method of solution (Part One, Section II). The values of these interpolated sources are printed off-line in table form and are also written on the restart tape for restart purposes. There may be no more than 77 points in the r direction or 113 points in the z direction. The total number of points may not exceed 6500.

Input of Source from TURBO Tape 7

If no punched card source deck is included with the first input deck (and if sense switch 1 is not depressed for restart), the code will search for the source on tape 7 during the problem. The TURBO tape 7 from an r-z TURBO problem on tape 7 should be mounted. The code will search tape 7 for the time step number specified on card 2000 of the input deck and read the mesh intervals and fluxes as the source. The thermal flux is read from the TURBO tape if the time step number which is placed on card 2000 is prefaced by a "+" sign. If the time step number is prefaced by a "-" sign, the file following the thermal flux (in TURBO, this file is called the "source") is read as the source. The thermal fluxes may be proportional to the values of the source at the same points. The code compares the source title card of the first problem to the title card which was written on tape 7 when the TURBO problem was run. If they are not the same, the computer will stop (see program steps in operating instructions). The code divides the first Δr by 2, since the TURBO problems has twice the real value. (It is not necessary to double this number for punched card input of sources.)

Punched Card Input of Source

If it is desired to use a punched card input for the source, the source deck must follow the two title cards. This same source will be used for all succeeding problems until a new source is introduced with another input deck. The information which must be included in the source deck is:

- 1) The number of source values in the r direction and the number of source values in the z direction (the total number of values is then the product of these two numbers).
- 2) The mesh intervals in the r direction.
- 3) The mesh intervals in the z direction.
- 4) The source values at all interior mesh points. If the mesh intervals in either the r or z direction are equal, only the one distance need be given. If the source is in the form $S(r, z) = S(r)S(z)$, only the values $S(r)$ and $S(z)$ need be given. If the source is a unit source, this may be indicated by including a single card (numbered 600) following the mesh intervals.

It should be remembered that the code performs the integration by using Gaussian quadrature of orders $9 \times 12 \times 9$ in the r, z, and θ directions, respectively. Thus, the contributions of each of the 972 points to the field point are calculated and multiplied by the source strength for each point. The same number of points is used regardless of the dimensions of the core.

Care should be taken to insure that the source distribution, as represented by the points chosen by the code, represents an accurate description of the source. The points which are used by the code may be computed by using the formulas from Section One, Part IV where the values r_G , z_G , and θ_G are listed for $n = 12$ and $n = 9$ in Appendix I, and R_l , R_u , z_l , z_u and θ_l , θ_u are the limits of integration.

The format of the source deck is as follows:

Card Number 100:

<u>Word Number</u>	<u>Symbol</u>	<u>Fixed or Floating</u>	<u>Identification</u>
1	C. N.	fixed	card number (100)
2	ss-1	fixed	number of interior mesh points in r direction
3	tt-1	fixed	number of interior mesh points in z direction

Note 1: The numbers ss-1 and tt-1 are the number of points to be given in the r and z directions, respectively; ss and tt are the number of mesh intervals to be given in the r and z directions, respectively.

Mesh Intervals in the r Direction: If the mesh intervals in the r direction are all equal, a single card numbered 250 may be used. The only number on this card is the common mesh interval in floating point.

If the mesh intervals are not all equal, a series of cards numbered 200, 201, 202, etc., is used to specify them. Six floating point numbers are placed on a card and enough cards are included to specify the ss mesh intervals. The mesh intervals are given, starting from the center of the core and moving out.

Word Number	Symbol	Fixed or Floating	Identification
1	C. N.	fixed	card number (200, 201, 202, etc.)
2	Δr	floating	r mesh interval
3	Δr	floating	r mesh interval
4	Δr	floating	r mesh interval
5	Δr	floating	r mesh interval
6	Δr	floating	r mesh interval
7	Δr	floating	r mesh interval

Note 1: Either (but not both) card series 200 or card number 250 must appear in the deck.

Mesh Intervals in the z Direction: If the mesh intervals in the z direction are all equal, a single card numbered 350 may be used. The only number on this card is the common mesh distance in floating point.

If the mesh intervals in the z direction are not all equal, a series of cards numbered 300, 301, 302, etc., is used to specify them. Six floating point numbers are placed on a card and enough cards are included to specify tt mesh intervals. The mesh intervals are given, starting from the top and moving down.

Word Number	Symbol	Fixed or Floating	Identification
1	C. N.	fixed	card number (300, 301, 302, etc.)
2	Δz	floating	z mesh interval
3	Δz	floating	z mesh interval
4	Δz	floating	z mesh interval
5	Δz	floating	z mesh interval
6	Δz	floating	z mesh interval
7	Δz	floating	z mesh interval

Note 1: Either (but not both) card series 300 or card number 350 must appear in the deck.

Source Values: If the source strength is to be specified at each mesh point, the series of cards numbered 450, 451, 452, etc., is used. The values are given, starting at the top of the core and moving from the center of the core to the edge of the core and then down. Six floating point numbers are placed on each card and enough cards are included to specify all (ss-1) (tt-1) interior mesh points. It is possible that more than 50 cards will be needed in the 450 series. Therefore, there is no possibility of confusing the 450 series with the 500 series, since the 500 series will not appear in this case.

Word Number	Symbol	Fixed or Floating	Identification
1	C. N.	fixed	card number (450, 451, 452, etc.)
2	$S(r, z)$	floating	source
3	$S(r, z)$	floating	source
4	$S(r, z)$	floating	source
5	$S(r, z)$	floating	source
6	$S(r, z)$	floating	source
7	$S(r, z)$	floating	source

If the source is in the form $S(r, z) = S(r)S(z)$, two series of cards may be used instead of the 450 series. The 400 series is used for $S(r)$ and the 500 series is used for $S(z)$. Six floating point numbers are placed on a card and the 400 series should include (ss-1) numbers and the 500 series should include (tt-1) numbers.

Word Number	Symbol	Fixed or Floating	Identification
1	C. N.	fixed	card number (400, 401, 402, etc.)
2	$S(r)$	floating	r component of source
3	$S(r)$	floating	r component of source
4	$S(r)$	floating	r component of source
5	$S(r)$	floating	r component of source
6	$S(r)$	floating	r component of source
7	$S(r)$	floating	r component of source

Word Number	Symbol	Fixed or Floating	Identification
1	C. N.	fixed	card number (500, 501, 502, etc.)
2	$S(z)$	floating	z component of source
3	$S(z)$	floating	z component of source
4	$S(z)$	floating	z component of source
5	$S(z)$	floating	z component of source
6	$S(z)$	floating	z component of source
7	$S(z)$	floating	z component of source

If the source is a unit source (1 everywhere), this may be indicated by including a single card numbered 600 following the mesh intervals. All that is required on this card is the card number, followed by a "+" and zeros to column 72.

11. OPERATING INSTRUCTIONS FOR SPAN-2

The GLOUT printer board is used for on-line printing.

Mount a blank tape on logical tape 5; this is the off-line output tape and must always be mounted.

If the problem requests a TURBO tape source, mount the requested TURBO tape on logical tape

7. Whenever a TURBO tape source is mounted, a blank tape must be mounted on logical tape 2.

If the problem has a source in the form of decimal card input, (card series 100, 200, 300, ..., etc.), mount a blank on logical tape 2.

If the problem requests the source from a previously written restart tape, mount the requested restart tape on logical tape 2.

In each of the last two instances, mount nothing on logical tape 7.

Logical tape 2 is saved for future restarts if the requester indicates his desire to do so. Otherwise, logical tape 2 may be released.

If a TURBO tape source has been requested, it is always saved after use.

The sense switch settings are as follows: Sense switch 1 is down whenever there is a requested restart tape source mounted on logical tape 2. Sense switches 1 and 2 are down whenever there is a requested restart tape source mounted on logical tape 2 and the problem is to be continued from some field point on. This situation occurs whenever, for any reason, the operator previously stopped the computer and is now going to continue from the point at which the computer was stopped. The operator must have previously noted the problem deck at which the computer was stopped and he must start this form of the restart procedure from that deck on. Whenever the operator stops the computer for any reason, logical tape 5, (the output tape), is to be printed off-line. When this form of the restart procedure, i. e., sense switches 1 and 2 are down, a blank must be mounted on logical tape 5 again.

Sense switch 3 may be depressed at any time during the running of the problem; the flux at the current field point will be printed on-line. When sense switch 3 is raised, there will be no on-line print of flux until sense switch 3 is depressed again.

Sense switches 4, 5, and 6 are not used.

Clear core and press the load-card button on the console. Place the program deck labeled "SPAN-2" followed by all appropriate problem decks in the card hopper, and read in the decks. Every problem deck is separated from the next problem deck by a blank card, and there are four blank cards after the last problem deck.

There are 2 computer stops. These include the WH001 error stops.

77770_g: Read the instructions printed on-line. This is a press-start type of computer stop.

77777_g: This is the normal stop...end of problem. Read instructions on-line.

Timing

The time necessary to complete a problem may be estimated by the use of the following:

- 1) Read-in program deck (1 minute).
- 2) Read-in input deck and interpolate (15 seconds).
- 3) Search TURBO tape [the time necessary to search the TURBO tape, for the desired time step, varies with the distance (on tape) that must be skipped].
- 4) The integration time depends on the location of the field point:

$$r_f > R_c, |z_f| \leq H/2 \text{ (9 seconds per field point),}$$

$$r_f < R_c, |z_f| \geq H/2 \text{ (10 seconds per field point),}$$

$$r_f > R_c, |z_f| > H/2 \text{ (13 seconds per field point).}$$

The time in each case will increase slightly as the number of shields increases.

III. THE RESTART PROCEDURE

During the running of a problem, the source distribution within the appropriate limits of integration are written on logical tape 2. This tape is the restart tape. At the problem originator's request, the restart tape may be used at any subsequent running of a set of problems, provided the source distribution within the limits of integration that had previously been written on the requested tape is desired as the source for the new set of problems. This eliminates the punching of the source distribution on decimal data cards again, (card series 100, 200, 300, ..., etc.), or the reading of the source distribution from a TURBO tape. Thus, the restart tape, remounted on logical tape 2, may be used and saved repeatedly when the problem originator requests the use of its source distribution. The requester must specify which restart tape is desired by the tape number supplied by the operator. See the operating instructions for this restart procedure's sense switch setting.

If the computer is stopped during the running of a problem, the same problem may be continued from the appropriate problem deck at a subsequent time. The restart tape contains, in addition to the source distribution within the appropriate limits of integration, the number of the field point at which the computer was stopped. Thus, at a subsequent running of the problem, the restart procedure will start at the field point at which the computer was stopped, and will continue from there to compute the flux for the remaining field points of that problem deck. See the operating instructions for the sense switch settings of this type of restart procedure.

IV. THE OUTPUT ROUTINE

The output routine describes the distribution of the source at the points of integration in the core. A description of the geometry of the core and top and side shields, including reflectors, is also given. Finally, the flux at each field point is printed out. The problem title is printed on every page of the output.

On the first page of the output, the two appropriate titles for the problem appear. The first title describes the problem in general, and the second title describes the source. Following this, the core height and radius are printed.

The distribution of the source in the core is also printed on the first page of the output. This is in the form of a table of the source in the r and z directions at the points of integration within the core. The coordinates of the points of integration in the r and z direction are printed in the horizontal and vertical directions, respectively, under and to the right of which the sources at these points are printed. This table is sufficient to completely describe the source distribution, since there is angular symmetry of source.

On the second page of output, the material compositions of the core, the reflectors, and the top and side shields will be printed in material number form.

On the third page of output, the flux is printed for each of the indicated field points, and a statement to the effect that the fluxes for all field points of the card input deck have been computed and printed appears last. The pages are numbered, and the problem number of each deck is printed.

V. CODE LIMITS

- 1) Column 1 on both title cards should be blank.
- 2) Columns 66 and 67 of the first title card must be blank, and columns 68, 69, 70, 71, and 72 must contain the characters SPAN-2.
- 3) The number of mesh intervals may not exceed 78 in the r direction or 114 in the z direction. The total number of mesh intervals may not exceed 6500.
- 4) The number of energy levels cannot exceed 30.

- 5) The number of side shields cannot exceed 30.
- 6) The number of top shields cannot exceed 30.
- 7) There may be 1, 2, or 3 regions inside the core. The sum of the thicknesses of these regions must be equal to the core radius.
- 8) The number of materials in any region cannot exceed 9. Zero indicates a vacuum.
- 9) The library numbers for each material should be taken from Appendix II. If a library number is used, for which no cross section appears in the library, a microscopic cross section of zero is used for this material and the problem is executed.
- 10) The r coordinate of any field point cannot be negative. The z coordinate of any field point cannot be less than $-h/2$.

APPENDIX I: GAUSS QUADRATURE COEFFICIENTS

n=9

<u>Roots</u>	<u>Weights</u>
-0.9681602395	0.0812743884
-0.8360311073	0.1806481607
-0.6133714327	0.2606106964
-0.3242534234	0.3123470770
0	0.3302393550
0.34242534234	0.3123470770
0.6133714327	0.2606106964
0.8360311073	0.1806481607
0.9681602395	0.0812743884

n=12

<u>Roots</u>	<u>Weights</u>
-0.9815606342	0.0471753364
-0.9041172564	0.1069393260
-0.7699026742	0.1600783285
-0.5873179543	0.2031674267
-0.3678314989	0.2334925365
-0.1253334085	0.2491470458
0.1253334085	0.2491470458
0.3678314989	0.2334925365
0.5873179543	0.2031674267
0.7699026742	0.1600783285
0.9041172564	0.1069393260
0.9815606342	0.0471753364

APPENDIX II: THE LIBRARY

The library contains the microscopic cross sections of the 10 materials listed for 30 energy levels. As part of the input, at least one of the energy levels must be selected by placing its corresponding number on card 2001. The attenuation coefficient for each region is then calculated (see Part One, Section V) by the use of material numbers (from card series 4000 and 4500) and the number densities (from cards series 6000 and card series 6500). The units of the microscopic cross sections are barns. Thus, the units of the number densities must be $(\text{particles}/\text{cm}^3) \times 10^{-24}$. The resultant units of the attenuation coefficients are $1/\text{cm}$. In the case of concrete, the units of the numbers in the library are cm^2/g . Thus, the input densities for concrete must be mass density (i.e., g/cm^3).

The following is a table of the energy levels (in Mev) and associated energy level numbers:

Number	Mev	Number	Mev	Number	Mev
1	0.5	11	2.2	21	6.3
2	0.6	12	2.5	22	6.5
3	0.7	13	2.75	23	7.0
4	0.8	14	3.0	24	7.5
5	0.9	15	3.5	25	7.65
6	1.0	16	4.0	26	8.0
7	1.25	17	4.5	27	8.5
8	1.50	18	5.0	28	9.0
9	1.75	19	5.5	29	9.5
10	2.0	20	6.0	30	10.0

The materials with their associated library numbers, for which the microscopic cross sections are included at each energy level, are as follows:

1. Hydrogen
2. Oxygen
3. Zirconium
4. Carbon
6. Iron
9. Aluminum
18. Uranium
48. Lead
75. Concrete
77. Water

There may be additions to this list in the future.

The table of microscopic cross sections as contained in the library follows:

TABLE OF MICROSCOPIC CROSS SECTIONS AS CONTAINED IN THE LIBRARY

Energy Level Number	Energy (in Mev)	Microscopic Cross Sections (in Barns)									
		$\sigma_T(\text{Fe})$	$\sigma_T(\text{Pb})$	$\sigma_T(\text{H}_2\text{O})$	$\sigma_T(\text{Zr})$	$\sigma_T(\text{U})$	$\sigma_T(\text{Al})$	Concrete	$\sigma_T(\text{C})$	$\sigma_T(\text{H})$	$\sigma_T(\text{O})$
1	0.5	7.58	49.8	2.89	12.66	69.7	3.76	0.0870	1.735	0.289	2.31
2	0.6	7.06	39.2	2.68	11.41	53.8	3.48	0.0804	1.605	0.268	2.14
3	0.7	6.55	32.8	2.508	10.539	43.9	3.25	0.0753	1.505	0.2495	1.995
4	0.8	6.16	28.77	2.35	9.8	37.6	3.06	0.0706	1.410	0.235	1.88
5	0.9	5.30	25.55	2.225	9.15	33.12	2.89	0.0668	1.334	0.2215	1.773
6	1.0	5.52	23.52	2.11	8.65	29.93	2.75	0.0635	1.267	0.211	1.690
7	1.25	4.96	19.73	1.886	7.73	24.65	2.462	0.0567	1.133	0.189	1.520
8	1.50	4.492	17.62	1.7189	7.054	21.66	2.2376	0.0517	1.0316	0.1716	1.3758
9	1.75	4.175	16.435	1.590	6.58	20.10	2.06	0.0476	0.9520	0.1575	1.27
10	2.0	3.93	15.72	1.475	6.25	19.12	1.933	0.0445	0.8843	0.1466	1.182
11	2.2	3.775	15.36	1.398	6.055	18.60	1.848	0.0425	0.8365	0.1390	1.122
12	2.5	3.600	14.56	1.307	5.813	18.06	1.738	0.0397	0.7830	0.1294	1.049
13	2.75	3.470	14.695	1.244	5.64	17.78	1.659	0.0378	0.7430	0.1219	0.9998
14	3.0	3.3403	14.471	1.1841	5.5	17.581	1.5822	0.0363	0.7091	0.1156	0.9531
15	3.5	3.18	14.37	1.082	5.33	17.395	1.475	0.0337	0.6535	0.1050	0.8830
16	4.0	3.061	14.434	1.0154	5.23	17.394	1.3876	0.0317	0.6063	0.09687	0.8214
17	4.5	2.98	14.55	0.950	5.18	17.5	1.318	0.0299	0.5695	0.0900	0.7745
18	5.0	2.903	14.649	0.901	5.14	17.63	1.264	0.0287	0.5377	0.0840	0.7339
19	5.5	2.85	14.773	0.862	5.115	17.77	1.218	0.0276	0.5120	0.07895	0.7000
20	6.0	2.818	14.98	0.823	5.1	17.97	1.181	0.0268	0.488	0.0747	0.674
21	6.3	2.800	15.13	0.798	5.105	18.13	1.158	0.0265	0.476	0.0725	0.655
22	6.5	2.800	15.225	0.782	5.11	18.23	1.140	0.0261	0.468	0.0710	0.645

23	7.0	2.775	15.44	0.755	5.128	18.44	1.115	0.0254	0.456	0.0679	0.625
24	7.5	2.75	15.62	0.732	5.155	18.68	1.093	0.0248	0.435	0.0649	0.608
25	7.65	2.745	15.66	0.728	5.16	18.75	1.085	0.0246	0.432	0.0640	0.601
26	8.0	2.738	15.79	0.718	5.19	18.94	1.078	0.0243	0.424	0.0621	0.594
27	8.5	2.736	16.00	0.695	5.22	19.13	1.055	0.0238	0.412	0.0596	0.575
28	9.0	2.734	16.24	0.680	5.258	19.45	1.040	0.0234	0.402	0.0570	0.560
29	9.5	2.733	16.51	0.667	5.28	19.80	1.028	0.0230	0.394	0.0550	0.550
30	10.0	2.732	16.81	0.654	5.305	20.21	1.024	0.0229	0.386	0.0537	0.547

2-14-59

12345-123-6 T2802

[illegible]

[illegible]

SAMPLE PROBLEM-CARD INPUT FOR SOURCE - 13 SIDE AND 6 TOP SHIELDS SPAN2
 PUNCHED CARD SOURCE - NORMALIZED TO ONE

3 PAGE 10

CORE RADII'S CORE HEIGHT

47.8600 66.4000

LIMITS OF INTEGRATION.	R1	R2	Z1	Z2	THETA1	THETA2.
	.0000	39.3000	-34.2000	34.2000	.0000	3.1416

TABLE OF INTERPOLATED SOURCE.

	R									
	6257	1 3222	1 7597	2 1328	2 1965	2 2602	2 3170	2 3608	2 3367	
Z										
2 3357	1 4709	1 4029	1 3202	1 1346	1 1177	9556	7626	8931	1 1323	
2 3092	1 5172	1 1946	1 1733	1 1409	1 1240	1 1018	8254	9558	1 1571	
2 2633	1 2959	1 1594	1 1562	1 1478	1 1309	1 1088	8949	1 1016	1 1510	
2 2009	1 1681	1 1666	1 1579	1 1408	1 1381	1 1159	9524	1 1062	1 1549	
2 1258	1 1756	1 1741	1 1619	1 1395	1 1450	1 1229	1 1007	1 1102	1 1590	
1 4286	1 1829	1 1807	1 1769	1 1656	1 1513	1 1291	1 1096	1 1169	1 1739	
1-4286	1 1896	1 1866	1 1817	1 1631	1 1555	1 1333	1 1276	1 1330	1 1834	
2-1258	1 2054	1 1927	1 1859	1 1744	1 1617	1 1391	1 1331	1 1393	1 1972	
2-2009	1 2344	1 2031	1 1915	1 1807	1 1678	1 1435	1 1393	1 1530	2 1426	
2-2633	1 2424	1 2026	1 1934	1 1812	1 1583	1 1354	1 1286	1 1439	2 1984	
2-3092	1 2253	1 1829	1 1747	1 1503	1 1290	1 1175	1 1109	1 1235	2 1756	
2-3357	1 1978	1 1440	1 1279	9531	9020	9685	9788	1 1096	2 1024	

SAMPLE PROBLEM-CARD INPUT FOR SOURCE - 13 SIDE AND 6 TOP SHIELDS SPAN2

3 PAGE 11

SIDE REGIONS

REGION	THICKNESS	OUTER RADIUS	ATTENUATION FACTOR	MATERIAL	NUMBER DENSITY
	39.3000	39.3000	.1079	77	.0100
1	8.5600	47.8600	.0080	4	.0573
2	.0000	47.8600	.0000	77	.0100
3	.6350	48.4950	.1599	6	.0571
4	.6350	49.1300	.0080	77	.0100
5	1.2700	50.4000	.1599	6	.0571
6	17.7800	68.1800	.0080	77	.0100
7	1.2700	69.4500	.1599	6	.0571
8	1.9050	71.3550	.0080	77	.0100
9	2.2200	73.5750	.1599	6	.0571
10	1.9050	75.4800	.0080	77	.0100
11	3.8100	79.2900	.1599	6	.0571
12	1.9050	81.1950	.0080	77	.0100
13	7.9400	89.1350	.1599	6	.0571
14	2.2200	91.3550	.0080	77	.0100
15	15.8700	107.2250	.1599	6	.0571

TOP REGIONS

REGION	THICKNESS	UPPER HEIGHT	ATTENUATION FACTOR	MATERIAL	NUMBER DENSITY
1	1.0000	35.2000	.0080	77	.0100
2	4.2400	39.4400	.1599	6	.0571
3	.6350	40.0750	.0080	77	.0100
4	17.7800	57.3550	.1599	6	.0571
5	1.2700	59.1250	.0080	77	.0100
6	7.9400	67.0650	.1599	6	.0571
7	2.2200	69.2850	.1599	6	.0571

SAMPLE PROBLEM-CARD INPUT FOR SOURCE - 13 SIDE AND 6 TOP SHIELDS SPAN2

3 PAGE 12

ENERGY LEVEL NUMER = 21

..FLUX AT FIELD POINT..

	R	Z
1 1749	60.0600	.0000
1 1099	68.9400	.0000
2413	80.0500	.0000
-1 4791	89.8950	.0000
-2 2299	107.9850	.0000
-2 2702	.0000	103.4850
-2 2313	20.0000	103.4850
-2 1473	39.4000	103.4850
-2 4403	60.0600	103.4850
-2 9420	68.9400	103.4850
-2 1461	80.0500	103.4850
-3 2455	89.8950	103.4850

SIDE REGIONS

REGION	THICKNESS	OUTER RADIUS	ATTENUATION FACTOR	MATERIAL	NUMBER DENSITY
	39.3000	39.3000	.1058	77	.0100
1	8.5600	47.8600	.0078	4	.0573
2	.0000	47.8600	.0000	77	.0100
3	.6350	48.4950	.1599	5	.0571
4	.6350	49.1300	.0078	77	.0100
5	1.2700	50.4000	.1599	6	.0571
6	17.7800	68.1800	.0078	77	.0100
7	1.2700	69.4500	.1599	6	.0571
8	1.9050	71.3550	.0078	77	.0100
9	2.2200	73.5750	.1599	6	.0571
10	1.9050	75.4800	.0078	77	.0100
11	3.8100	79.2900	.1599	6	.0571
12	1.9050	81.1950	.0078	77	.0100
13	7.9400	89.1350	.1599	6	.0571
14	2.2200	91.3550	.0078	77	.0100
15	15.8700	107.2250	.1599	6	.0571

TOP REGIONS

REGION	THICKNESS	UPPER HEIGHT	ATTENUATION FACTOR	MATERIAL	NUMBER DENSITY
1	1.0000	35.2000	.0078	77	.0100
2	4.2400	39.4400	.1599	6	.0571
3	.6350	40.0750	.0078	77	.0100
4	17.7800	57.8550	.1599	6	.0571
5	1.2700	59.1250	.0078	77	.0100
6	7.9400	67.0650	.1599	6	.0571
7	2.2200	69.2850	.1599	6	.0571

SAMPLE PROBLEM-CARD INPUT FOR SOURCE - 13 SIDE AND 6 TOP SHIELDS SPAN2

3 PAGE 14

ENERGY LEVEL NUMBER = 22

..FLUX AT FIELD POINT..

	R	Z.
1 1779	60.0600	.0000
1 1119	68.9400	.0000
2 2463	80.0500	.0000
-1 4881	89.8950	.0000
-3 2342	107.9850	.0000
-2 2752	.0000	103.4850
-2 2356	20.0000	103.4850
-2 1502	39.4000	103.4850
-2 4528	60.0600	103.4850
-2 9695	68.9400	103.4850
-2 1504	80.0500	103.4850
-3 2524	89.8950	103.4850

..ALL FIELD POINTS DONE, PROBLEM COMPLETED..

END OF RUN, PROBLEM COMPLETED. PRINT OUTPUT TAPE 5 AND IF REQUESTOR DESIRES, SAVE RESTART TAPE 2, SAVE TAPE 7, IF ANY..

+100+11+12+000000000G00
+200+505+5121+5137+515+5156+5159+000
+201+5156+515+5137+5121+501+51856+000
+300+511+5138+5164+5185+5199+52102+000
+301+5199+5185+5164+5138+511+521+000
+302+000
+450+51460+51457+51430+51137+51126+51105+000
+451+50860+50690+50950+51170+000000+51550+000
+452+51154+51152+51146+51135+51114+50950+000
+453+50780+51104+51176+000000+51164+51163+000
+454+51161+51155+51144+51123+51104+50870+000
+455+51111+51180+000000+51173+51172+51170+00
+456+51116+51152+51132+51112+50910+51115+000
+457+51185+000000+51182+51180+51179+51168+00
+458+51160+51140+51120+51100+51120+51190+000
+459+000000+51190+51187+51186+51170+51165+00
+460+51145+51125+51130+51135+51200+000000+000
+461+51210+51195+51190+51178+51172+51153+000
+462+51129+51137+51142+51220+000000+51250+000
+463+51210+51197+51185+51180+51159+51136+000
+464+51145+51165+52270+000000+51240+51199+000
+465+51194+51190+51160+51135+51119+51115+000
+466+51135+52250+000000+51210+51160+51160+00

SAMPLE PROBLEM-TURBO TAPE 7 FOR SOURCE- 3 SIDE AND 5 TOP SHIELDS00SPANZ
2-14-59 12345-123-6 TRB02

2 PAGE 5

CORE RADIUS CORE HEIGHT

11.0010 20.0000

LIMITS OF INTEGRATION.	R1	R2	Z1	Z2	THETA1	THETA2.
	.0000	10.0010	-10.0000	10.0000	.0000	3.1416

TABLE OF INTERPOLATED SOURCE.

	R								
	1592	8197	1 1933	1 3379	1 5000	1 6622	1 8068	1 9181	1 9842
Z									
1 9816	3 4964	3 4960	3 4942	3 4895	3 4816	3 4764	3 4596	3 4499	3 4439
1 9041	3 4817	3 4812	3 4792	3 4742	3 4656	3 4542	3 4415	3 4307	3 4241
1 7699	3 4594	3 4589	3 4567	3 4509	3 4413	3 4279	3 4135	3 4009	3 3930
1 5873	3 4345	3 4339	3 4314	3 4249	3 4138	3 3983	3 3815	3 3665	3 3570
1 3678	3 4138	3 4130	3 4102	3 4029	3 3905	3 3729	3 3537	3 3363	3 3251
1 1253	3 4018	3 4009	3 3980	3 3902	3 3770	3 3581	3 3373	3 3183	3 3059
1-1253	3 4018	3 4009	3 3980	3 3902	3 3770	3 3581	3 3373	3 3183	3 3059
1-3678	3 4138	3 4130	3 4102	3 4029	3 3905	3 3729	3 3537	3 3363	3 3251
1-5873	3 4345	3 4339	3 4314	3 4249	3 4138	3 3983	3 3815	3 3665	3 3570
1-7699	3 4594	3 4589	3 4567	3 4509	3 4413	3 4279	3 4135	3 4009	3 3930
1-9041	3 4817	3 4812	3 4792	3 4742	3 4656	3 4539	3 4415	3 4307	3 4241
1-9816	3 4964	3 4960	3 4942	3 4895	3 4816	3 4709	3 4596	3 4499	3 4439

SAMPLE PROBLEM-TURBO TAPE 7 FOR SOURCE- 3 SIDE AND 5 TOP SHIELDS00SPAN2

2 PAGE 6

SIDE REGIONS

REGION	THICKNESS 10.0010	OUTER RADIUS 10.0010	ATTENUATION FACTOR .1249	MATERIAL 18	NUMBER DENSITY .0012
				6	.0029
				77	.0144
1	1.0000	11.0010	.0063	77	.0024
2	.0000	11.0010	.0000		
3	17.7800	28.7810	.3969	48	.0101
4	12.4000	41.1810	.0643	1	.1925
				4	.0079
5	.6000	41.7810	.0870	9	.0250

TOP REGIONS

REGION	THICKNESS	UPPER HEIGHT	ATTENUATION FACTOR	MATERIAL	NUMBER DENSITY
1	1.0000	11.0000	.0063	77	.0024
2	19.1000	30.1000	.0162	3	.0011
				1	.0136
3	6.2000	36.3000	.3969	48	.0101
4	.4700	36.7700	.0870	9	.0250
5	10.5000	47.2700	.3969	48	.0101
6	4.4000	51.6700	.0432	1	.0130
				4	.0008
				6	.0054

SAMPLE PROBLEM-TURBO TAPE 7 FOR SOURCE- 3 SIDE AND 5 TOP SHIELDS00SPAN2

2 PAGE 7

ENERGY LEVEL NUMBER = 2

..FLUX AT FIELD POINT..

	R	Z.
-1 5520	28.7800	.0000
-1 1298	41.1800	.0000
-1 1198	41.7800	.0000
-1 3613	28.7800	10.0000
-2 9815	41.1800	10.0000
-2 9109	41.7800	10.0000
2 7412	.0000	30.2000
-2 2498	28.7800	30.2000
-2 1715	41.1800	30.2000

SAMPLE PROBLEM-TURBO TAPE 7 FOR SOURCE- 3 SIDE AND 5 TOP SHIELDS00SPAN2

2 PAGE 8

SIDE REGIONS

REGION	THICKNESS	OUTER RADIUS	ATTENUATION FACTOR	MATERIAL	NUMBER DENSITY
	10.0010	10.0010	.1089	18	.0012
				6	.0029
				77	.0144
1	1.0000	11.0010	.0059	77	.0024
2	.0000	11.0010	.0000		
3	17.7800	28.7810	.3321	48	.0101
4	12.4000	41.1810	.0599	1	.1925
				4	.0079
5	.6000	41.7810	.0812	9	.0250

TOP REGIONS

REGION	THICKNESS	UPPER HEIGHT	ATTENUATION FACTOR	MATERIAL	NUMBER DENSITY
1	1.0000	11.0000	.0059	77	.0024
2	19.1000	30.1000	.0150	3	.0011
				1	.0136
3	6.2000	36.3000	.3321	48	.0101
4	.4700	36.7700	.0812	9	.0250
5	10.5000	47.2700	.3321	48	.0101
6	4.4000	51.6700	.0401	1	.0130
				4	.0008
				6	.0054

SAMPLE PROBLEM-TUREO TAPE 7 FOR SOURCE- 3 SIDE AND 5 TOP SHIELDSJOSPAH2

2 PAGE 9

ENERGY LEVEL NUMBER = 3

..FLUX AT FIELD POINT..

	R	Z.
2037	28.7800	.0000
-1 5033	41.1800	.0000
-1 4662	41.7800	.0000
1391	28.7800	10.0000
-1 3916	41.1800	10.0000
-1 3645	41.7800	10.0000
2 8246	.0000	30.2000
-1 1233	28.7800	30.2000
-2 8113	41.1800	30.2000

..ALL FIELD POINTS DONE, PROBLEM COMPLETED..

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