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The Fang Angular Folding Code for Channel Theory Analysis

M. L. Williams
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OAK RIDGE NATIONAL LABORATORY

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Neutron Physics Division

THE FANG ANGULAR FOLDING CODE FOR CHANNEL THEORY ANALYSIS

M. L. Williams and F. B. Sadler*

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*Computer Sciences Division

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Abstract

The development of the FANG code for performing channel analysis is documented. An input description is provided for users, as well as a brief description of the basic channel theory concepts. A sample streaming problem is described, for which FANG input and output are given.

Code Abstract

1. Name: FANG (Fold with Angle)
2. Coding Language: Written in FORTRAN IV for use on an IBM 360 computer
3. Nature of Problem Solved: FANG calculates the "contributon flux" and "contributon leakage" necessary for performing "channel theory" analysis, by using information available on a DOT¹ (2-D discrete ordinates transport code) scalar flux tape. It also provides three-dimensional plots of streaming channels, performs space-energy dependent folding, and computes 2-D angular fluxes by expanding DOT flux moments.
4. Typical Running Time: Relatively complex problems run for 1-3 minutes on a 360/91 computer.
5. Storage Requirement: A large problem requires approximately 540 k-bytes.
6. Input: The code is flexibly dimensioned and reads input in fixed or free form FIDO format. Forward and adjoint fluxes are assumed available from previous DOT calculations.
7. Status: FANG has been tested on several complex problems and is in production use at ORNL.
8. How to Obtain Code: Contact M. L. Williams, Bldg. 6025, ORNL, or phone (615) 483-8611, ext. 30308.

FANG Options

1. Calculates "channel theory" analysis functions, using various folding options for direction, interval, and group. Prints several edits of results.
2. Plots a three-dimensional perspective or isometric graph² of contributon flux. Plot can be either logrithmic or linear.
3. Folds forward and adjoint scalar fluxes with an energy function, $\sigma(E)$. Option of doing calculation at every mesh interval, at a constant axial interval, or at a constant radial interval.
4. Calculates angular forward and adjoint fluxes by group, interval, and angle from expansion of Legendre moments on DOT scalar flux tape.

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Introduction

A technique known as spatial channel theory has been developed at Oak Ridge National Laboratory which has been found useful in locating streaming paths in complex shielding calculations. The theory is based on the concept of a "contributon", which is identified as a member of that subset of the particle flux that contributes to the response of interest. Associated with each contributon is the "response-flux", or "contributon flux", that represents the flow of the future response which the contributon produces; i.e., the contributon flux has units of response/cm²-sec. In shielding calculations, the observed response functional is usually a dose rate at some particular location, and the response-flux is then associated with only those particles which affect the dose at that specified position. A brief discussion of the fundamentals of channel theory appears in Appendix I, and further theoretical aspects can be found in other papers^{3,4}.

The FANG code was written to calculate the functions that are used in channel theory analysis, from the information available on a DOT scalar flux tape. The response flux is calculated with the equation:

$$CFLX(I,J) = \sum_{IGM=1}^{IGM} CON(IG) \sum_{MD=1}^{MM} FLX(MD,I,J,IG) * AFX(MD,I,J,IG) * W(MD) \quad (1)$$

where:

CON = an input energy function (usually equal to one)

IG = group index

J = axial interval index

I = radial interval index

MD = angle index

W = angle quadrature weight

IGM = number of energy groups

MM = number of directions in quadrature set, and

FLX, AFX = the angle dependent forward flux and the angle dependent adjoint flux, respectively.

These functions are reconstructed from the moments on a DOT scalar flux tape by:

$$FLX(MD, I, J, IG) = \sum_{N=1}^{NOM} P_N(MD) M_N[I, J, IG] \quad (2)$$

$$AFX(MD, I, J, IG) = \sum_{N=1}^{NOM} P_N(-MD) M_N^*[I, J, (IGM-IG+1)] \quad (3)$$

where P_N = Nth spherical harmonic

M_N, M_N^* = Nth moment for the forward and adjoint fluxes, respectively

N = moment index

NOM = number of Legendre moments.

A short discussion on the theory for spherical harmonic expansion is found in Appendix II.

FANG also calculates the contribution leakage across internal surfaces. For a surface corresponding to a constant axial interval, the following equation is used:

$$\begin{aligned} \text{FLDJ}(J) = & \sum_{IG=1}^{IGM} \text{CON}(IG) * \sum_{I=1}^{IM} \text{LOC}(I) * S(I) * \\ & \sum_{MD=1}^{MM} \text{ETA}(MD) * \text{FLX}(MD, I, J, IG) * \text{AFX}(MD, I, J, IG) * W(MD) \end{aligned} \quad (4)$$

where: LOC = input mesh-dependent function

ETA = polar cosine from quadrature set

W = weight from angular quadrature set

$S(I) = [R^2(I) - R^2(I-1)] * \pi$

An analogous equation is used to determine leakage across a radial surface.

According to channel theory, the value for the contribution leakage is equal to the response for which the adjoint flux was calculated:

$$\text{FLDJ}(J) = \text{Response} = \langle \phi, Q^* \rangle = \langle \phi^*, Q \rangle^a, \quad \begin{array}{l} Q = \text{forward source} \\ Q^* = \text{adjoint source} \end{array} \quad (5)$$

for all J lying between Q and Q*, but not intersecting either source.

A check of the consistency of FLDJ is a convenient method to ascertain the accuracy of the channel theory calculation and also of the DOT forward and adjoint calculations.

^aIndicates integration over all phase space.

FIDO Input System^{*}

The FIDO input method is especially devised to allow the entering or modifying of large data arrays with minimum effort. Special advantage is taken of patterns of repetition or symmetry wherever possible. The FIDO system was patterned after the input method used with the FLOCO coding system at Los Alamos Scientific Laboratory, and was first applied to the DTF-II code. Since that time, numerous features requested by users have been added, a free-field option has been developed, and the application of FIDO has spread to innumerable codes.

The data are entered in units called "arrays". An array comprises a group of contiguous storage locations which are to be filled with data at one time. These arrays usually correspond on a one-to-one basis with FORTRAN arrays used in the program. A group of one or more arrays read with a single call to the FIDO package forms a "block", and a special delimiter is required to signify the end of each block. Arrays within a block may be read in any order with respect to each other, but an array belonging to one block must not be shifted to another. The same array can be entered repeatedly within the same block. For example, an array could be filled with "0" using a special option, and then a few scattered locations could be changed by reading in a new set of data for that array. If no entries to the arrays in a block are required, the delimiter alone satisfies the input requirement.

Three major types of input are available: fixed-field input, free-field input, and user-field input.

^{*}Description of FIDO input system by W. A. Rhoades

The data are entered in units called "arrays". An array comprises a group of contiguous storage locations which are to be filled with data at one time. These arrays usually correspond on a one-to-one basis with FORTRAN arrays used in the program. A group of one or more arrays read with a single call to the FIDO package forms a "block", and a special delimiter is required to signify the end of each block. Arrays within a block may be read in any order with respect to each other, but an array belonging to one block must not be shifted to another. The same array can be entered repeatedly within the same block. For example, an array could be filled with "0" using a special option, and then a few scattered locations could be changed by reading in a new set of data for that array. If no entries to the arrays in a block are required, the delimiter alone satisfies the input requirement.

Three major types of input are available: fixed-field input, free-field input, and user-field input.

Fixed-field input - Each card is divided into six 12-column data fields, each of which is divided into three subfields. The following sketch illustrates a typical data field. The three subfields always comprise 2, 1, and 9 columns, respectively.

To begin the first array of a block, an array originator field is placed in any field on a card:

Subfield 1: An integer array identifier < 100 specifying the data array to be read in.

Subfield 2: An array-type indicator

"\$" if the array is integer data

"*" if the array is real data

Subfield 3: Blank

Data are then placed in successive fields until the required number of entries have been accounted for. A sample data sheet shown below illustrates this input.

In entering data, it is convenient to think of an "index" or "pointer" which is under control of the user, and which specifies the position in the array into which the next data entry is to go. The pointer is always positioned at array location #1 by entering the array originator field. The pointer subsequently moves according to the data operator chosen. Blank fields are a special case, in that they do not cause any data modification and do not move the pointer. A data field has the following form:

Subfield 1: The data numerator, an integer < 100 . We refer to this entry as N_1 in the following discussion.

Subfield 2: One of the special data operators listed below.

Subfield 3: A nine-character data entry, to be read in F9.0 format.

It will be converted to an integer if the array is a "\$" array or if a special array operator such as Q is being used. Note that an exponent is permissible but not required. Likewise, a decimal is permissible but not required. If no decimal is supplied, it is assumed to be immediately to the left of the exponent, if any; and otherwise to the right of the last column. This entry is referred to as N_3 in the following discussion.

A list of data operators and their effect on the array being input follows:

"Blank" indicates a single entry of data. The data entry in the third subfield is entered in the location indicated by the pointer, and the pointer is advanced by one. However, an entirely blank field is ignored.

"+" or "-" indicates exponentiation. The data entry in the third field is entered and multiplied by $10^{\pm N_1}$, where N_1 is the data numerator in the first subfield, given the sign indicated by the data operator itself. The pointer advances by one. In cases where an exponent is needed, this option allows the entering of more significant figures than the blank option.

"&" has the same effect as "+".

"R" indicates that the data entry is to be repeated N_1 times. The pointer advances by N_1 .

"I" indicates linear interpolation. The data numerator, N_1 , indicates the number of interpolated points to be supplied. The data entry in the third subfield is entered, followed by N_1 interpolated entries equally spaced between that value and the data entry found in the third subfield of the next non-blank field. The pointer is advanced by $N_1 + 1$. The field following an "I" field is then processed normally, according to its own data operator. The "I" entry is especially valuable for specifying a spatial mesh. In "\$" arrays interpolated values will be rounded to the nearest integer.

"L" indicates logarithmic interpolation. The effect is the same as that of "I" except that the resulting data are evenly separated in log-space. This is especially convenient for specifying an energy mesh.

"Q" is used to repeat sequences of numbers. The length of the sequence is given by the third subfield, N_3 . The sequence of N_3 entries is to be repeated N_1 times. The pointer advances by $N_1 * N_3$. If either N_1 or N_3 is 0, then a sequence of $N_1 + N_3$ is repeated one time only, and the pointer advanced by $N_1 + N_3$. This feature is especially valuable for geometry specification:

The "N" option has the same effect as "Q", except that the order of the sequence is reversed each time it is entered. This is valuable for the type of symmetry possessed by S_n quadrature coefficients.

"M" has the same effect as "N" except that the sign of each entry in the sequence is reversed each time the sequence is entered. For example, the entries:

1 2 3 2M2

would be equivalent to:

1 2 3 -3 -2 2 3.

This option is also useful in entering quadrature coefficients.

"Z" causes the position of the last array item entered to be printed. This is the position of the pointer, less 1. The pointer is not moved.

"O" causes the print trigger to be changed. The trigger is originally off. Successive "O" fields turn it on and off alternately. When the trigger is on, each card image is listed as it is read.

"S" indicates that the pointer is to skip N_1 positions leaving those array positions unchanged. If the third subfield is non-blank, that data entry is entered following the skip, and the pointer is advanced by $N_1 + 1$.

"A" moves the pointer to the position, N_3 , specified in the third subfield.

"F" fills the remainder of the array with the datum entered in the third subfield.

"E" skips over the remainder of the array. The array length criterion is always satisfied by an E, no matter how many entries have been specified. No more entries to an array may be given following an "E", except that data entry may be restarted with an "A".

The reading of data to an array is terminated when a new array original field is supplied, or when the block is terminated. If an incorrect number of positions has been filled, an error edit is given, and a flag is set which will later abort execution of the problem. FIDO then continues with the next array if an array origin was read. Otherwise, it returns control to the calling program.

A block termination consists of a field having "T" in the second subfield. All entries following "T" on a card are ignored, and control is returned from FIDO to the calling program.

Comment cards can be entered within a block by placing an apostrophe (') in column 1. Then columns 2-80 will be listed, with column 2 being used for printer carriage control. Such cards have no effect on the data array or pointer.

Free-Field Input - with free-field input, data are written without fixed restrictions as to field and subfield size and positioning on the card. The options used with fixed-field input are available, although some are slightly restricted in form. In general, fewer data cards are required for a problem, the interpreting print is easier to read, a card

listing is more intelligible, the cards are easier to keypunch, and certain common keypunch errors are tolerated without affecting the problem. Data arrays using fixed- and free-field input can be intermingled at will within a given block.

The concept of three subfields per field is still applicable to free-field input, but if no entry for a field is required, no space for it need be left. Only columns 1-72 may be used, as with fixed-field input.

The array originator field can begin in any position. The array identifiers and type indicators are used as in fixed-field input. The type indicator is entered twice, to designate free-field input (i.e., "\$\$" or "***"). The blank third subfield required in fixed-field input is not required. For example: 31** indicates that array 31, a rea-data array, will follow in free-field format.

Data fields may follow the array origin field immediately. The data field entries are identical to the fixed-field entries with the following restrictions:

- (1) Any number of blanks may separate fields, but at least one blank must follow a third subfield entry if one is used.
- (2) If both first- and second subfield entries are used, no blanks may separate them, i.e., 24S, but not 24 S.
- (3) Numbers written with exponents must not have imbedded blanks, i.e., 1.0E+4, 1.0E4, 1.0+4, or even 1+4, but not 1.0 E4.
- (4) In third-subfield data entries, only 9 digits, including decimal but not including the exponent field, can be used, 123456.89E07, but not 123456.789E07.
- (5) The Z entry must be of the form: 738Z, not Z738 or 738 Z.

- (6) The + or - data operators are not needed and are not available.
- (7) The Q, N, and M entries are restricted: 3Q4, 1N4, or M4, 4Q, 4N, or 4M.

User-Field Input - if the user follows the array identifier in the originator field with the character "U" or "V", the input format is to be specified by the user. If "U" is specified, the FORTRAN FORMAT to be used must be supplied in columns 1-72 of the next card. The format must be enclosed by the usual parentheses. Then the data for the entire array follow on successive cards. The rules of ordinary FORTRAN input as to exponents, blanks, etc. apply. If the array data do not fill the last, the remainder must be left blank.

"V" has the same effect as "U" except that the format read in the preceding "U" array is used.

Logical Unit Numbers

FANG requires the use of the following logical units:

- 1 = DOT forward scalar flux tape
- 2 = DOT adjoint scalar flux tape
- 3 = Scratch direct access, to hold all of the adjoint,
($IM*JM*(NOM+1)$)*IGM words
- 9 = Only required if IWAY = ± 3 . Angular flux output
($IM*JM*MM*IGM$)
- 8 = Output of fold - contribution flux ($IM*JM$)
- 5 = Card input
- 6 = Printed output
- 49 = DISK PLOT

Storage Requirement

NSTOR = 76

- + $3*(MM + IM + JM + NVUW)$
- + IGM
- + NIT + NJT
- + $NOM*(MM + 2)$
- + $IM*JM*(2*NOM + 3)$
- + $IM*IGM$ (IGPF $\neq 0$)
- + IGM (ISP1 $\neq 0$)
- + IGM (ISP2 $\neq 0$)
- + MM (IWAY 2 and IDIR $\neq 0$)
- + $MM*IM*JM$ (IWAY= ± 3)
- + $3*(IM*JM + 24*(IM + JM))$ (IPL0T $\neq 1$)

Input Description

Title Card: 72 characters

1\$ Integer Parameters 28 entries

1. ICR - Type of coordinates
 - = 1, XY coordinates
 - = 2, RZ coordinates
2. IBM - Number of energy groups
3. IM - Number of radial intervals
4. JM - Number of axial intervals
5. MM - Number of directions in quadrature set for reconstructing angular flux (data note 1)
6. ISCT - Order of Legendre expansion associated with moments on flux tape
7. IWAY - Method for calculating contribution leakage (data note 2)
 - = 0, fold forward and adjoint with eta
 - = 1, fold forward and adjoint with mu
 - = 2, fold forward and adjoint, using no angle
 - = 3, no fold - calculate angular flux
 - = -3, no fold - calculate adjoint angular flux
8. IDIR - Direction for angular flux reconstruction
 - = 0, reconstruct for all directions
 - = 1, reconstruct for positive directions (up, right)
 - = -1, reconstruct for negative directions (down, left)
9. IGP - Edit contribution flux by group
 - = 0, no effect
 - = N, print contribution flux by radius and group at J=N

10. ISP1 - Edit contributon leakage by group and Z
 - = 0, no effect
 - = N, print contributon leakage by group, (integrated over R) at J=N
11. ISP2 - Edit contributon leakage by group and R
 - = 0, no effect
 - = N, print contributon leakage by group, (integrated over Z) at I=N
12. ISP3 - Interior radial boundary calculation
 - = 0, no effect
 - = N, perform channel theory calculation only along I=N
13. ISP4 - Interior axial boundary calculation
 - = 0, no effect
 - = N, perform channel theory calculation only along J=N
14. ISP5 - Interior neutron current calculation
 - = 0, no effect
 - = 1, find neutron current component indicated by IWAY and IDIR (no channel theory calculation)
15. IPLOT - Type of 3-D plot (data note 3)
 - = -1, isometric plot of contributon flux
 - = 0, perspective plot of contributon flux
 - = 1, no plot
16. NIT - Number of radial tic marks on plot (data note 4)
17. NJT - Number of axial tic marks on plot
18. NVUM - Number of 3-D plot views
- 19-28. IEX1-IEX10, Spare - fill with 0

8* Real parameters 13 entries

1. HSP - Horizontal plot size
2. VSP - Vertical plot size
3. ZEXAG - Z-axis exaggeration factor (data note 5)
4. XEXAG - X-axis exaggeration (data note 5)

5-13. EX1-EX9, Spare - fill with 0.0

T - End of Data Block 1

2* - Quadrature directions. Mu's precede eta's; negative etas precede positive etas (2*MM entries)

3* - Quadrature weights (MM entries)

4* - Radial mesh (IM + 1 entries)

5* - Axial mesh (JM + 1 entries)

6* - Group conversion factors (IGM entries, normally fill with 1.0)

7* - Interval conversion factor (IM entries, if IWAY = 0 or JM entries, if IWAY = 1; normally fill with 1.0)

9* - Viewing positions: Xo, Yo, Zo (3* NVUM entries)

10\$ - Intervals for radial tic marks (NIT entries)

11\$ - Intervals (data note 4) axial tic marks (NJT entries)

T - End of Data Block 2

Title of Plot

Data Notes

Data Note #1. It is important to realize that FANG does not use the angular quadrature set in exactly the same manner as do discrete ordinates calculations. In channel theory calculations, the quadrature is used entirely for integrating spherical harmonic functions, and as such is not directly related to neutron streaming. The order of SN constants used in FANG is independent of the SN constants used in DOT for generating the flux-moments; they are closely related to the number of flux-moments available for reconstructing the angular flux (a parameter which is calculated with ISCT in the DOT run).

Good results in determining proper quadrature order have been obtained using the formula:

$$\begin{aligned} (SN)_{FANG} &= (ISCT)_{DOT} + 3 \\ MM &= \frac{SN(SN + 4)}{2} \end{aligned} \tag{6}$$

If an excessively high order of quadrature is used in FANG, the calculation can require long CPU time with no increase in accuracy. It is therefore worthwhile to properly match the parameters "ISCT" and "MM".

Data Note #2. The "IWAY" parameter serves several purposes. First, for channel theory calculations it tells FANG which surface to find the contribution leakage across: Eta→axial surface; Mu→radial surface. If IWAY = 2, no angle is folded in the leakage calculation, and the response is merely $\phi\phi^*$ integrated over surface. For IWAY = 3, no channel theory analysis is performed; instead, the angular flux (or adjoint) is recon-

structed and placed on logical unit 9. In neutron leakage calculations (ISP5 = 1) IWAY serves the same purpose as in channel theory calculations; i.e., it tells how to calculate leakage.

Data Note #3. If IPLOT is given the value of 0 or -1, a 3 dimensional plot will be drawn of the radial and axial interval midpoints on the X and Y axes and the contribution flux in the Z direction. A perspective plot is drawn such that parallel lines would eventually meet as in the picture of looking down a railroad track. In an isometric plot, however, parallel lines will be drawn parallel. Normally, isometric plots are chosen.

Data Note #4. The 3-D plots may have tic marks with values drawn out on the plots if NIT and NJT are specified greater than zero, and arrays 10\$ and 11\$ are included. The values given in the 10\$ and 11\$ arrays are the I's and J's for the intervals where the tic marks are to occur.

Data Note #5. ZEXAG is an exaggeration factor for the Z direction on the plot. Normally a zero is given for this value, in which case a value for ZEXAG will be calculated and printed out. If a plot turns out to be tall and thin or short and flat, ZEXAG may be increased to make the plot taller or decreased to make it smaller.

ZEXAG is used when the range of radial points and axial points are of different magnitudes which would cause a long and thin plot. This can be alleviated by setting ZEXAG to the following:

$$ZEXAG = \frac{Y_{MAX} - Y_{MIN}}{X_{MAX} - X_{MIN}} \quad (7)$$

where Y_{MAX} and Y_{MIN} are maximum and minimum axial intervals, and X_{MAX} and X_{MIN} are radial intervals.

Subroutines PERSPX, PERROR, ZSCAL, ROTATE, and PRJECT belong to the "CATCH" three-dimensional plot package written by T. C. Tucker and described in ORNL-TM-3790. Subroutines TICM and ANGLE were added (by F. B. Sadler) to produce tic marks for the X and Y axes of the plot. Subroutines PLOTS, PLOT, NUMBER, and SYMBOL are calcomp drum plot routines.

Figure 1. FANG Calling Sequence

FANG Subroutines

<u>Name</u>	<u>Function</u>	<u>Called From</u>
MAIN	Allocates common storage	--
CONTROL	Establishes arrays and reads input data	MAIN
GRUNT	Reconstructs angular flux from Legendre moments; folds forward and adjoint to find contribution flux and leakage	CONTROL
FIDO, FFREAD	Data input system	CONTROL
PCON	Evaluates spherical harmonic functions	GRUNT
DEFILE	Sets up direct access parameters for adjoint flux	GRUNT
WOT8	Prints tables up to 8 columns wide	CONTROL
WOT	Prints large 2-D tables	CONTROL, GRUNT
PLTIN	Sets up arguments for call to plot package	CONTROL
PERSPX ISOSPX	Creates 3-D map plots on calcomp drum plotter. ISOSPX is an entry point	PLOTIN
ZSCAL	Sets up scale factor for Z-axis	PERSPX
PERROR	Error routine for PERSPX	PERSPX
ROTATE	Calculates coordinate transformation matrix	PERSPX
PROJECT	Calculates X and Y values for plotting	PERSPX, TICM, ANGLE
TICM	Draws tic marks and titles on plot	PERSPX
ANGLE	Calculates angle of the title	TICM
PLOTS	Sets up plot output buffer	PLOTIN
PLOT	Outputs lines to plotter	PERSPX, TICM
NUMBER	Outputs numeric values to plotter	TICM
SYMBOL	Outputs character strings to plotter	PLOTIN, TICM

Sample Problem

An example problem is illustrated by Fig. 2, which shows the perspective plot from FANG of the response-flux $C(X,Z)$ for the geometry shown at the bottom of the page. The bottom row of intervals contains a uniform, forward source of 10.0, and the top row contains an adjoint source identical to the forward source. The shaded areas in the geometry are highly absorbing regions, and the remainder is a predominantly scattering medium. Forward and adjoint fluxes were found by DOT, using a S8 quadrature and P3 scattering expansion.

The plot of the response-flux clearly shows the origin of the name "channel theory". The favored trajectories appear as ridges, whose altitudes represent the contribution of the streaming channel to the response.

Fig. 3 shows the card input for this problem, and following this is the printer output from FANG.

Figure 2. Perspective Plot of Contribution Flux in Example Calculation

```

FANG SAMPLE PROBLEM R-2.  P3-S6.  12/19/75
1$$$ 1 1 10 60 30 3 0 1 60 60 42 -1 3R5  F0  8** 15.0 10.0 0.0 6.0 F0  T
2*
0 -36515- 5 0 -25820- 5 0 625820- 5 0 -73030- 5 0 -68313- 5 0 -25820- 5
0 625820- 5 0 668313- 5 0 -96609- 5 0 -93095- 5 0 -68313- 5 0 -25820- 5
0 625820- 5 0 668313- 5 0 693095- 5 0 -36515- 5 0 -25820- 5 0 625820- 5
-73030- 5 0 -68313- 5 0 -25820- 5 0 625820- 5 0 668313- 5 0 -96609- 5
0 -93095- 5 0 -68313- 5 0 -25820- 5 0 625820- 5 0 668313- 5 0 693095- 5
3R-93095- 5 5R-68313- 5 7R-25820- 5 3R693095- 5 5R668313- 5 7R625820- 5
3*
0 6 06 0 2R641667- 6 0 6 06 0 0 641667- 6 2R641667- 6 0 641667- 6
0 6 06 0 0 641667- 6 0 641667- 6 2R641667- 6 0 641667- 6 0 641667- 6
6 06 0 2R641667- 6 0 6 06 0 0 641667- 6 2R641667- 6 0 641667- 6
6 0 0 641667- 6 0 641667- 6 2R641667- 6 0 641667- 6 0 641667- 6
4** 910.0 10.0
5** 5910.0 60.0
6** F1.0 7** F1.0
9** 2000 2000 6000
-1000 1000 1000
1000 -1000 1000
-1000 -1000 1000
1000 -1000 2000
10$$$ 1 3 5 7 9 11 11$$$ 1 13 25 37 49 61 T
FANG SAMPLE CALCULATION
//

```

Figure 3. FANG Input to the Example Problem

FANG Output for Sample Problem

FANG SAMPLE PROBLEM B-2. P3-S6.

12/19/75

1\$ ARRAY 28 ENTRIES READ

8\$ ARRAY 13 ENTRIES READ

OT

16811 WORDS OF STORAGE REQUIRED FOR INPUT VS AVAILABLE 18000

2\$ ARRAY 60 ENTRIES READ

3\$ ARRAY 30 ENTRIES READ

4\$ ARRAY 11 ENTRIES READ

5\$ ARRAY 61 ENTRIES READ

6\$ ARRAY 1 ENTRIES READ

7\$ ARRAY 10 ENTRIES READ

9\$ ARRAY 15 ENTRIES READ

10\$ ARRAY 5 ENTRIES READ

11\$ ARRAY 5 ENTRIES READ

OT

FANG SAMPLE PROBLEM B-2. P3-S6.

12/19/75

ICR =	1	TYPE OF COORDINATES: 1/2 = XY/RZ
IGM =	1	NUMBER OF ENERGY GROUPS
IM =	10	NUMBER OF RADIAL INTERVALS
JM =	60	NUMBER OF AXIAL INTERVALS
MM =	30	NUMBER OF COSINES IN QUADRATURE SET FOR INTEGRATING FLUX-MOMENTS
ISCT =	3	ORDER OF LEGENDRE EXPANSION
IWAY =	0	ANGULAR FOLDING METHOD: 0/1/2/3 = FOLD WITH ETA/FOLD WITH MU/FOLD WITH NO ANGLE/NO FOLD; CALC ANG FLX
IDIR =	1	DIRECTION OF ANGULAR FOLDING: +/-0 = UP(RT)/DOWN(LFT)/ALL DIRECTIONS
GPF =	50	FOLD AS FUNCTION OF GROUP: 0/N = NO EFFECT/PRINT CONTRIBUTION FLUX BY GROUP AND RADIUS AT J=N
ISP1 =	50	GROUP RESPONSE OF Z1: 0/N = NO EFFECT/PRINT CONTRIBUTION LEAKAGE BY GROUP, INTEGRATED OVER R AT J=N
ISP2 =	0	GROUP RESPONSE OF R1: 0/N = NO EFFECT/PRINT CONTRIBUTION LEAKAGE BY GROUP, INTEGRATED OVER Z AT I=N
ISP3 =	0	INTERIOR RADIAL BOUNDARY CALC: 0/N = NO EFFECT/PERFORM CALC ONLY ALONG I=N
ISP4 =	0	INTERIOR AXIAL BOUNDARY CALC: 0/N = NO EFFECT/PERFORM CALC ONLY ALONG J=N
ISP5 =	0	INTERIOR BOUNDARY LEAKAGE CALC: 0/1 = NO EFFECT/CALC NEUTRON LEAKAGE COMPONENT
IPLT =	-1	TYPE OF 3-D PLOT: -1/0/1 = ISOMETRIC/PERSPECTIVE/NO PLOT
NIT =	5	NUMBER OF RADIAL TIC MARKS ON PLOT
NJT =	5	NUMBER OF AXIAL TIC MARKS ON PLOT
NVUW =	5	NUMBER OF 3-D PLOT VIEWS
IEX1 =	0	EXTRA
IEX2 =	0	EXTRA
IEX3 =	0	EXTRA
IEX4 =	0	EXTRA
IEX5 =	0	EXTRA
IEX6 =	0	EXTRA
IEX7 =	0	EXTRA
IEX8 =	0	EXTRA
IEX9 =	0	EXTRA
IEX10 =	0	EXTRA
HSP =	15.000	HORIZONTAL PLOT SIZE
VSP =	10.000	VERTICAL PLOT SIZE
ZEXAG =	0.0	Z-AXIS EXAGGERATION FACTOR
XNORM =	6.000	X-AXIS NORMALIZATION FACTOR
EX1 =	0.0	EXTRA
EX2 =	0.0	EXTRA
EX3 =	0.0	EXTRA
EX4 =	0.0	EXTRA
EX5 =	0.0	EXTRA
EX6 =	0.0	EXTRA
EX7 =	0.0	EXTRA
EX8 =	0.0	EXTRA
EX9 =	0.0	EXTRA

cont'd

cont'd

FANG SAMPLE PROBLEM B-2, P3-56.

12/19/75

	R	R MID	Z	Z MID	GRP MODIFIER	INT MODIFIER
1	0	5.00000E-01	0	5.00000E-01	1.00000E 00	1.00000E 00
2	1.00000E 00	1.50000E 00	9.99999E-01	1.50000E 00		1.00000E 00
3	2.00000E 00	2.50000E 00	2.00000E 00	2.50000E 00		1.00000E 00
4	3.00000E 00	3.50000E 00	3.00000E 00	3.50000E 00		1.00000E 00
5	4.00000E 00	4.50000E 00	4.00000E 00	4.50000E 00		1.00000E 00
6	5.00000E 00	5.50000E 00	5.00000E 00	5.50000E 00		1.00000E 00
7	6.00000E 00	6.50000E 00	6.00000E 00	6.50000E 00		1.00000E 00
8	7.00000E 00	7.50000E 00	7.00000E 00	7.50000E 00		1.00000E 00
9	8.00000E 00	8.49999E 00	8.00000E 00	8.49999E 00		1.00000E 00
10	9.00000E 00	9.49999E 00	8.99999E 00	9.49999E 00		1.00000E 00
11	1.00000E 01		9.99999E 00	1.05000E 01		
12			1.10000E 01	1.15000E 01		
13			1.20000E 01	1.25000E 01		
14			1.30000E 01	1.35000E 01		
15			1.40000E 01	1.45000E 01		
16			1.50000E 01	1.55000E 01		
17			1.60000E 01	1.65000E 01		
18			1.70000E 01	1.75000E 01		
19			1.80000E 01	1.85000E 01		
20			1.90000E 01	1.95000E 01		
21			2.00000E 01	2.05000E 01		
22			2.10000E 01	2.15000E 01		
23			2.20000E 01	2.25000E 01		
24			2.30000E 01	2.35000E 01		
25			2.40000E 01	2.45000E 01		
26			2.50000E 01	2.55000E 01		
27			2.60000E 01	2.65000E 01		
28			2.70000E 01	2.75000E 01		
29			2.80000E 01	2.85000E 01		
30			2.90000E 01	2.95000E 01		
31			3.00000E 01	3.05000E 01		
32			3.10000E 01	3.15000E 01		
33			3.20000E 01	3.25000E 01		
34			3.30000E 01	3.35000E 01		
35			3.40000E 01	3.45000E 01		
36			3.50000E 01	3.55000E 01		
37			3.60000E 01	3.65000E 01		
38			3.70000E 01	3.75000E 01		
39			3.80000E 01	3.85000E 01		
40			3.90000E 01	3.95000E 01		
41			4.00000E 01	4.05000E 01		
42			4.10000E 01	4.15000E 01		
43			4.20000E 01	4.25000E 01		
44			4.30000E 01	4.35000E 01		
45			4.40000E 01	4.45000E 01		
46			4.50000E 01	4.55000E 01		
47			4.60000E 01	4.65000E 01		
48			4.70000E 01	4.75000E 01		
49			4.80000E 01	4.85000E 01		
50			4.90000E 01	4.95000E 01		
51			5.00000E 01	5.05000E 01		
52			5.10000E 01	5.15000E 01		
53			5.20000E 01	5.25000E 01		
54			5.30000E 01	5.35000E 01		
55			5.40000E 01	5.45000E 01		
56			5.50000E 01	5.55000E 01		
57			5.60000E 01	5.65000E 01		
58			5.70000E 01	5.75000E 01		
59			5.80000E 01	5.85000E 01		
60			5.90000E 01	5.95000E 01		
61			6.00000E 01			

	ETA	MU	WEIGHT
1	-9.30950E-01	-3.65150E-01	0
2	-9.30950E-01	-2.58200E-01	4.16670E-02
3	-9.30950E-01	2.58200E-01	4.16670E-02
4	-6.83130E-01	-7.30300E-01	0
5	-6.83130E-01	-6.83130E-01	4.16670E-02
6	-6.83130E-01	-2.58200E-01	4.16670E-02
7	-6.83130E-01	2.58200E-01	4.16670E-02
8	-6.83130E-01	6.83130E-01	4.16670E-02
9	-2.58200E-01	-9.66090E-01	0
10	-2.58200E-01	-9.30950E-01	4.16670E-02
11	-2.58200E-01	-6.83130E-01	4.16670E-02
12	-2.58200E-01	-2.58200E-01	4.16670E-02
13	-2.58200E-01	2.58200E-01	4.16670E-02
14	-2.58200E-01	6.83130E-01	4.16670E-02
15	-2.58200E-01	9.30950E-01	4.16670E-02
16	9.30950E-01	-3.65150E-01	0
17	9.30950E-01	-2.58200E-01	4.16670E-02
18	9.30950E-01	2.58200E-01	4.16670E-02
19	6.83130E-01	-7.30300E-01	0
20	6.83130E-01	-6.83130E-01	4.16670E-02
21	6.83130E-01	-2.58200E-01	4.16670E-02
22	6.83130E-01	2.58200E-01	4.16670E-02
23	6.83130E-01	6.83130E-01	4.16670E-02
24	2.58200E-01	-9.66090E-01	0
25	2.58200E-01	-9.30950E-01	4.16670E-02
26	2.58200E-01	-6.83130E-01	4.16670E-02
27	2.58200E-01	-2.58200E-01	4.16670E-02
28	2.58200E-01	2.58200E-01	4.16670E-02
29	2.58200E-01	6.83130E-01	4.16670E-02
30	2.58200E-01	9.30950E-01	4.16670E-02

cont'd

LEGENDRE EXPANSION COEFFICIENTS

ANGL	PLMC 1	PLMC 2	PLMC 3	PLMC 4	PLMC 5	PLMC 6	PLMC 7	PLMC 8
1	-3.65150E-01	-9.30949E-01	-2.99999E-01	5.88786E-01	7.50554E-01	4.26007E-01	1.90026E-01	-6.12827E-01
2	-2.58200E-01	-9.30950E-01	-3.99999E-01	4.16335E-01	6.92822E-01	3.44266E-01	3.80057E-01	-4.00002E-01
3	-2.58200E-01	-9.30950E-01	-3.99999E-01	-4.16335E-01	6.92822E-01	-3.44266E-01	3.80057E-01	4.00002E-01
4	-7.30300E-01	-6.83127E-01	3.00007E-01	8.64097E-01	4.04141E-01	1.21709E-01	-6.97222E-01	-6.59961E-01
5	-6.83130E-01	-6.83130E-01	1.99999E-01	8.08289E-01	3.46409E-01	2.27711E-01	-5.57772E-01	-5.29148E-01
6	-2.58200E-01	-6.83129E-01	-3.99999E-01	3.05506E-01	0.0	3.44266E-01	2.78885E-01	0.0
7	-2.58200E-01	-6.83129E-01	-3.99999E-01	-3.05506E-01	0.0	-3.44266E-01	2.78885E-01	0.0
8	6.83130E-01	-6.83130E-01	1.99999E-01	-8.08289E-01	3.46409E-01	-2.27711E-01	-5.57772E-01	5.29148E-01
9	-9.30950E-01	-2.58206E-01	8.99999E-01	4.32065E-01	5.77287E-02	-8.05063E-01	-5.79774E-01	-1.24721E-01
10	-9.30950E-01	-2.58200E-01	8.00000E-01	4.16338E-01	0.0	-6.20632E-01	-5.27053E-01	0.0
11	-6.83130E-01	-2.58200E-01	1.99999E-01	3.05506E-01	-3.46409E-01	2.27711E-01	-2.10819E-01	5.29148E-01
12	-2.58200E-01	-2.58200E-01	-3.99999E-01	1.15471E-01	-6.92818E-01	3.44266E-01	1.05409E-01	4.00000E-01
13	-2.58200E-01	-2.58200E-01	-3.99999E-01	-1.15471E-01	-6.92818E-01	-3.44266E-01	1.05409E-01	-4.00000E-01
14	6.83130E-01	-2.58200E-01	1.99999E-01	-3.05506E-01	-3.46409E-01	-2.27711E-01	-2.10819E-01	-5.29148E-01
15	-9.30950E-01	-2.58200E-01	8.00000E-01	-4.16338E-01	0.0	6.20632E-01	-5.27053E-01	0.0
16	-3.65150E-01	9.30949E-01	-2.99999E-01	-5.88786E-01	7.50554E-01	4.26007E-01	-1.90026E-01	-6.12827E-01
17	-2.58200E-01	9.30950E-01	-3.99999E-01	-4.16335E-01	6.92822E-01	3.44266E-01	-3.80057E-01	-4.00002E-01
18	-2.58200E-01	9.30950E-01	-3.99999E-01	4.16335E-01	6.92822E-01	-3.44266E-01	-3.80057E-01	4.00002E-01
19	-7.30300E-01	6.83127E-01	3.00007E-01	8.64097E-01	4.04141E-01	1.21709E-01	6.97222E-01	-6.59961E-01
20	-6.83130E-01	6.83130E-01	1.99999E-01	8.08289E-01	3.46410E-01	2.27711E-01	5.57773E-01	-5.29149E-01
21	-2.58200E-01	6.83130E-01	-3.99999E-01	3.05506E-01	0.0	3.44266E-01	-2.78885E-01	0.0
22	-2.58200E-01	6.83130E-01	-3.99999E-01	3.05506E-01	0.0	-3.44266E-01	-2.78885E-01	0.0
23	6.83130E-01	6.83130E-01	1.99999E-01	8.08289E-01	3.46410E-01	-2.27711E-01	5.57773E-01	5.29149E-01
24	-9.30950E-01	2.58206E-01	8.99999E-01	-4.32065E-01	5.77287E-02	-8.05063E-01	5.79774E-01	-1.24721E-01
25	-9.30950E-01	2.58200E-01	8.00000E-01	-4.16339E-01	0.0	-6.20632E-01	5.27054E-01	0.0
26	-6.83130E-01	2.58200E-01	1.99999E-01	-3.05506E-01	-3.46409E-01	2.27711E-01	-2.10820E-01	5.29147E-01
27	-2.58200E-01	2.58201E-01	-3.99999E-01	-1.15471E-01	-6.92818E-01	3.44266E-01	-1.05409E-01	4.00000E-01
28	-2.58200E-01	2.58201E-01	-3.99999E-01	1.15471E-01	-6.92818E-01	-3.44266E-01	-1.05409E-01	-4.00000E-01
29	6.83130E-01	2.58200E-01	1.99999E-01	3.05506E-01	-3.46409E-01	-2.27711E-01	2.10820E-01	-5.29147E-01
30	9.30950E-01	2.58200E-01	8.00000E-01	4.16339E-01	0.0	6.20632E-01	5.27054E-01	0.0

ANGL	PLMC 9
1	-6.37848E-01
2	-4.90656E-01
3	-4.90656E-01
4	-2.52026E-01
5	-1.44015E-01
6	5.04058E-01
7	5.04058E-01
8	-1.44015E-01
9	-1.35881E-02
10	2.72033E-02
11	2.72167E-01
12	5.17116E-01
13	5.17116E-01
14	2.72167E-01
15	2.72033E-02
16	6.37848E-01
17	4.90657E-01
18	4.90657E-01
19	2.52026E-01
20	1.44016E-01
21	-5.04056E-01
22	-5.04056E-01
23	1.44016E-01
24	1.35881E-02
25	-2.72032E-02
26	-2.72167E-01
27	-5.17117E-01
28	-5.17117E-01
29	-2.72167E-01
30	-2.72032E-02

cont'd

	R	RADIAL INTRVL AREA	Z	AXIAL INTRVL AREA	INTRVL MULTIPLIER	CONTRIBUTON LEAKAGE(=RESPONSE)
1	0	1.00000E 00	0	9.99999E-01	1.00000E 00	4.88556E-23
2	1.00000E 00	9.99999E-01	9.99999E-01	9.99999E-01	1.00000E 00	1.51907E-22
3	2.00000E 00	9.99999E-01	2.00000E 00	1.00000E 00	1.00000E 00	1.58417E-22
4	3.00000E 00	1.00000E 00	3.00000E 00	9.99999E-01	1.00000E 00	1.58306E-22
5	4.00000E 00	9.99999E-01	4.00000E 00	1.00000E 00	1.00000E 00	1.57577E-22
6	5.00000E 00	1.00000E 00	5.00000E 00	9.99999E-01	1.00000E 00	1.56760E-22
7	6.00000E 00	9.99999E-01	6.00000E 00	1.00000E 00	1.00000E 00	1.56201E-22
8	7.00000E 00	1.00000E 00	7.00000E 00	9.99999E-01	1.00000E 00	1.55489E-22
9	8.00000E 00	1.00000E 00	8.00000E 00	9.99999E-01	1.00000E 00	1.54469E-22
10	9.00000E 00	1.00000E 00	9.99999E 00	1.00000E 00	1.00000E 00	1.53106E-22
11	1.00000E 01		9.99999E 00	9.99999E-01		1.51305E-22
12			1.10000E 01	1.00000E 00		1.50025E-22
13			1.20000E 01	9.99999E-01		1.92648E-22
14			1.30000E 01	1.00000E 00		2.29348E-22
15			1.40000E 01	9.99999E-01		2.28173E-22
16			1.50000E 01	1.00000E 00		1.81820E-22
17			1.60000E 01	9.99999E-01		1.33969E-22
18			1.70000E 01	1.00000E 00		1.26987E-22
19			1.80000E 01	1.00000E 00		1.22028E-22
20			1.90000E 01	1.00000E 00		1.17680E-22
21			2.00000E 01	1.00000E 00		1.16259E-22
22			2.10000E 01	1.00000E 00		1.18093E-22
23			2.20000E 01	1.00000E 00		1.22544E-22
24			2.30000E 01	1.00000E 00		1.28792E-22
25			2.40000E 01	1.00000E 00		1.52479E-22
26			2.50000E 01	1.00000E 00		1.80185E-22
27			2.60000E 01	1.00000E 00		1.95893E-22
28			2.70000E 01	1.00000E 00		2.01689E-22
29			2.80000E 01	9.99999E-01		2.04590E-22
30			2.90000E 01	1.00000E 00		2.07709E-22
31			3.00000E 01	1.00000E 00		2.07709E-22
32			3.10000E 01	1.00000E 00		2.04590E-22
33			3.20000E 01	1.00000E 00		2.01689E-22
34			3.30000E 01	1.00000E 00		1.95893E-22
35			3.40000E 01	1.00000E 00		1.80185E-22
36			3.50000E 01	1.00000E 00		1.52479E-22
37			3.60000E 01	1.00000E 00		1.28792E-22
38			3.70000E 01	1.00000E 00		1.22544E-22
39			3.80000E 01	1.00000E 00		1.18093E-22
40			3.90000E 01	1.00000E 00		1.16259E-22
41			4.00000E 01	1.00000E 00		1.17680E-22
42			4.10000E 01	1.00000E 00		1.22028E-22
43			4.20000E 01	1.00000E 00		1.26987E-22
44			4.30000E 01	1.00000E 00		1.33969E-22
45			4.40000E 01	1.00000E 00		1.81820E-22
46			4.50000E 01	1.00000E 00		2.28173E-22
47			4.60000E 01	1.00000E 00		2.29348E-22
48			4.70000E 01	1.00000E 00		1.92648E-22
49			4.80000E 01	1.00000E 00		1.50025E-22
50			4.90000E 01	1.00000E 00		1.51305E-22
51			5.00000E 01	1.00000E 00		1.53106E-22
52			5.10000E 01	1.00000E 00		1.54469E-22
53			5.20000E 01	1.00000E 00		1.55489E-22
54			5.30000E 01	1.00000E 00		1.56201E-22
55			5.40000E 01	1.00000E 00		1.56760E-22
56			5.50000E 01	1.00000E 00		1.57577E-22
57			5.60000E 01	9.99999E-01		1.58306E-22
58			5.70000E 01	1.00000E 00		1.58417E-22
59			5.80000E 01	1.00000E 00		1.51907E-22
60			5.90000E 01	1.00000E 00		4.88556E-23
61			6.00000E 01			

FOLD BY GROUP, INTEGRATED OVER R AT J= 60

1 4.88556E-23

FANG SAMPLE PROBLEM B-2. P3-S6.

12/19/75

CONTRIBUTON FLX BY GROUP AND RADIAL INTERVAL, ALONG J= 60

RAD.	GRP.	1
1	8.99119E-24	
2	8.78377E-24	
3	9.18792E-24	
4	8.91271E-24	
5	8.80470E-24	
6	8.80317E-24	
7	8.91443E-24	
8	9.18754E-24	
9	8.78307E-24	
10	8.99008E-24	

cont'd

FANG SAMPLE PROBLEM B-2, P3-S6.

12/19/75

FORWARD*ADJOINT FOLDED BY INTERVAL (CONTRIBUTOR FLX, RESPONSE-UNITS/CM**3)

RX	ZY 1	ZY 2	ZY 3	ZY 4	ZY 5	ZY 6	ZY 7	ZY 8
1	8.99119E-24	2.47085E-23	2.32735E-23	2.21843E-23	2.04715E-23	1.80046E-23	1.54006E-23	1.16527E-23
2	8.78377E-24	2.42751E-23	2.37832E-23	2.22274E-23	2.16812E-23	2.08399E-23	1.85147E-23	1.57530E-23
3	9.18792E-24	2.42451E-23	2.30104E-23	2.31538E-23	2.29527E-23	2.33005E-23	2.37091E-23	2.33023E-23
4	8.91271E-24	2.48330E-23	2.32084E-23	2.29528E-23	2.40972E-23	2.41367E-23	2.59460E-23	2.94844E-23
5	8.80470E-24	2.44221E-23	2.42017E-23	2.34323E-23	2.30662E-23	2.44747E-23	2.64590E-23	2.88814E-23
6	8.80317E-24	2.44246E-23	2.41993E-23	2.34356E-23	2.30592E-23	2.44807E-23	2.64607E-23	2.88753E-23
7	8.91442E-24	2.48307E-23	2.32094E-23	2.29484E-23	2.41015E-23	2.41301E-23	2.59431E-23	2.94815E-23
8	9.18754E-24	2.42476E-23	2.30068E-23	2.31536E-23	2.29490E-23	2.33020E-23	2.37016E-23	2.32933E-23
9	8.78307E-24	2.42731E-23	2.37840E-23	2.22243E-23	2.16789E-23	2.08396E-23	1.85077E-23	1.57474E-23
10	8.99008E-24	2.47070E-23	2.32720E-23	2.21833E-23	2.04717E-23	1.80003E-23	1.53990E-23	1.16494E-23
RX	ZY 9	ZY 10	ZY 11	ZY 12	ZY 13	ZY 14	ZY 15	ZY 16
1	6.63125E-24	2.78370E-24	8.67220E-25	1.34113E-25	1.36251E-29	1.05840E-29	1.09542E-29	1.51308E-29
2	1.26320E-23	7.18593E-24	2.51340E-24	2.95805E-25	1.05387E-28	1.20205E-29	1.18500E-29	9.81108E-29
3	2.30194E-23	1.99501E-23	1.03953E-23	2.11542E-24	5.22699E-27	1.82029E-28	1.62918E-28	4.57859E-27
4	3.22160E-23	3.60624E-23	3.62900E-23	1.59219E-23	6.11523E-25	2.73312E-25	2.84864E-25	5.57884E-25
5	3.34589E-23	4.01288E-23	5.27938E-23	7.93545E-23	1.19234E-22	1.41553E-22	1.42149E-22	1.12707E-22
6	3.34614E-23	4.01140E-23	5.27894E-23	7.93081E-23	1.19189E-22	1.41429E-22	1.42095E-22	1.12676E-22
7	3.22021E-23	3.60532E-23	3.62641E-23	1.59067E-23	6.11601E-25	2.72934E-25	2.85086E-25	5.58526E-25
8	3.30107E-23	1.99360E-23	1.03845E-23	2.11633E-24	5.22097E-27	1.82199E-28	1.62967E-28	4.58097E-27
9	1.26275E-23	7.17728E-24	2.51497E-24	2.96796E-25	1.05501E-28	1.20523E-29	1.18882E-29	9.84900E-29
10	6.62574E-24	2.78468E-24	8.66100E-25	1.33366E-25	1.36548E-29	1.06251E-29	1.10087E-29	1.52048E-29
RX	ZY 17	ZY 18	ZY 19	ZY 20	ZY 21	ZY 22	ZY 23	ZY 24
1	1.33782E-25	8.41674E-25	2.84411E-24	7.50434E-24	1.79368E-23	2.27334E-23	3.21282E-23	4.48480E-23
2	2.95276E-25	2.43758E-24	6.72796E-24	1.25681E-23	1.71802E-23	2.30338E-23	2.80319E-23	3.39041E-23
3	1.92310E-23	9.50842E-24	1.77619E-23	1.96173E-23	2.01528E-23	1.97213E-23	1.79716E-23	7.18444E-24
4	1.44649E-23	3.10790E-23	2.84495E-23	2.27621E-23	1.71019E-23	1.18811E-23	5.61948E-24	1.08092E-24
5	7.11073E-23	4.34175E-23	2.99224E-23	2.08461E-23	1.30942E-23	6.13235E-24	1.77250E-24	2.20157E-25
6	7.08311E-23	4.35739E-23	2.99161E-23	2.09263E-23	1.31072E-23	6.11924E-24	1.78554E-24	2.20379E-25
7	1.44052E-23	3.10987E-23	2.86256E-23	2.28622E-23	1.72435E-23	1.19241E-23	5.64073E-24	1.09823E-24
8	1.93097E-23	9.50832E-24	1.78186E-23	1.97939E-23	2.02831E-23	1.98608E-23	1.81191E-23	7.20489E-24
9	2.93302E-25	2.44422E-24	6.75885E-24	1.26253E-24	1.73451E-23	2.31981E-23	2.82034E-23	3.41823E-23
10	1.34825E-25	8.44842E-25	2.85996E-24	7.55835E-24	1.50247E-23	2.28790E-23	3.24682E-23	4.51629E-23
RX	ZY 25	ZY 26	ZY 27	ZY 28	ZY 29	ZY 30	ZY 31	ZY 32
1	6.08810E-23	7.75505E-23	8.28422E-23	8.20408E-23	8.28434E-23	8.21362E-23	8.21362E-23	8.28434E-23
2	3.93568E-23	4.03193E-23	4.46852E-23	4.84649E-23	4.89358E-23	5.18988E-23	5.18988E-23	4.89358E-23
3	1.99805E-25	8.03408E-26	8.74992E-26	1.12750E-25	9.04664E-26	1.02699E-25	1.02699E-25	9.04664E-26
4	1.33787E-27	3.09410E-27	1.13801E-27	1.35558E-29	1.52537E-29	1.29702E-29	1.29702E-29	1.52537E-29
5	2.38108E-29	3.07016E-31	6.95480E-33	2.17428E-33	2.71606E-33	2.62886E-33	2.62886E-33	2.71606E-33
6	2.38219E-29	3.08656E-31	6.99036E-33	2.18128E-33	2.72837E-33	2.64007E-33	2.64007E-33	2.72837E-33
7	1.34658E-27	3.10966E-29	1.14409E-29	1.36327E-29	1.53245E-29	1.30241E-29	1.30241E-29	1.53245E-29
8	2.01626E-25	8.08328E-26	8.79319E-26	1.13568E-26	9.08596E-26	1.03171E-25	1.03171E-25	9.08596E-26
9	3.95578E-23	4.06236E-23	4.49478E-23	4.86665E-23	4.93049E-23	5.20573E-23	5.20573E-23	4.93049E-23
10	6.14085E-23	7.81218E-23	8.31569E-23	8.24255E-23	8.34706E-23	8.24891E-23	8.24891E-23	8.34706E-23
RX	ZY 33	ZY 34	ZY 35	ZY 36	ZY 37	ZY 38	ZY 39	ZY 40
1	8.20408E-23	8.28422E-23	7.75505E-23	8.08810E-23	4.48480E-23	3.21282E-23	2.27334E-23	1.49368E-23
2	4.84649E-23	4.46852E-23	4.03193E-23	3.93568E-23	3.39041E-23	2.80319E-23	2.30338E-23	1.71802E-23
3	1.12750E-25	8.74992E-26	8.03408E-26	1.99805E-25	7.18444E-24	1.79716E-23	1.97213E-23	2.01528E-23
4	1.35558E-29	1.13801E-27	3.09410E-27	1.33787E-27	1.08092E-24	5.61948E-24	1.18811E-23	1.71019E-23
5	2.17428E-33	6.95480E-33	3.07016E-31	2.38108E-29	2.20157E-25	1.77250E-24	1.77250E-24	1.30942E-23
6	2.18128E-33	6.99036E-33	3.08656E-31	2.38219E-29	2.20379E-25	1.78554E-24	1.78554E-24	1.31072E-23
7	1.36327E-29	1.14409E-29	1.36327E-29	1.34658E-27	1.09823E-24	5.64073E-24	1.19241E-23	1.72435E-23
8	1.13568E-26	8.08328E-26	8.79319E-26	2.01626E-25	7.20489E-24	1.81191E-23	1.98608E-23	2.02831E-23
9	4.86665E-23	4.49478E-23	4.06236E-23	3.95578E-23	3.41823E-23	3.41823E-23	3.19981E-23	1.73451E-23
10	8.24255E-23	8.31569E-23	7.81218E-23	6.14085E-23	5.16299E-23	3.24682E-23	2.28790E-23	1.50247E-23
RX	ZY 41	ZY 42	ZY 43	ZY 44	ZY 45	ZY 46	ZY 47	ZY 48
1	7.50434E-24	2.84411E-24	8.41674E-25	1.33782E-25	1.51308E-29	1.09542E-29	1.05840E-29	1.36251E-29
2	1.25681E-23	6.72796E-24	2.43758E-24	2.95276E-25	9.81108E-29	1.18500E-29	1.20205E-29	1.05387E-28
3	1.96173E-23	1.77619E-23	9.50842E-24	1.92310E-23	4.57859E-27	1.82029E-28	1.82029E-28	5.22699E-27
4	2.27621E-23	2.84495E-23	3.10790E-23	1.44649E-23	2.94844E-23	2.84864E-25	2.73312E-25	6.11523E-25
5	2.08461E-23	2.99224E-23	4.34175E-23	7.11073E-23	1.12707E-22	1.42149E-22	1.41553E-22	1.19234E-22
6	2.09263E-23	2.99161E-23	4.35739E-23	7.08311E-23	1.12676E-22	1.42095E-22	1.41429E-22	1.19189E-22
7	2.28622E-23	2.86256E-23	3.10987E-23	1.44052E-23	5.58526E-25	2.85086E-25	2.72934E-25	6.11601E-25
8	1.97939E-23	1.78186E-23	9.50832E-24	1.93097E-23	4.58097E-27	1.62967E-28	1.62967E-28	5.22097E-27
9	1.26253E-23	6.75885E-24	2.44422E-24	2.93302E-25	9.84900E-29	1.18882E-29	1.20523E-29	1.05501E-28
10	7.55835E-24	8.44842E-24	2.85996E-24	1.34825E-25	1.52048E-29	1.10087E-29	1.06251E-29	1.36548E-29
RX	ZY 49	ZY 50	ZY 51	ZY 52	ZY 53	ZY 54	ZY 55	ZY 56
1	1.34113E-25	8.67220E-25	2.78370E-24	6.63125E-24	1.16527E-23	1.54006E-23	1.80046E-23	2.04715E-23
2	2.95805E-25	2.51340E-24	7.18593E-24	1.26320E-23	1.57530E-23	1.85147E-23	2.08399E-23	2.16812E-23
3	2.11542E-24	1.03953E-23	1.99501E-23	2.30194E-23	2.33023E-23	2.37091E-23	2.33005E-23	2.29527E-23
4	1.59219E-23	3.62900E-23	3.60624E-23	3.22160E-23	2.94844E-23	2.59460E-23	2.41367E-23	2.40972E-23
5	7.93545E-23	5.27938E-23	4.01288E-23	3.34589E-23	2.88814E-23	2.64590E-23	2.44747E-23	2.30662E-23
6	7.93081E-23	5.27894E-23	4.01140E-23	3.34614E-23	2.88753E-23	2.64607E-23	2.44807E-23	2.30592E-23
7	1.59067E-23	3.62641E-23	3.60532E-23	3.22021E-23	2.94815E-23	2.59431E-23	2.41301E-23	2.41015E-23
8	2.11633E-24	1.03845E-23	1.99360E-23	2.30107E-23	2.32933E-23	2.37016E-23	2.33020E-23	2.29490E-23
9	2.96796E-25	2.51497E-24	7.17728E-24	1.26275E-23	1.57474E-23	1.85087E-23	2.08396E-23	2.16789E-23
10	1.33366E-25	8.66100E-25	2.78468E-24	6.62574E-24	1.16494E-23	1.53990E-23	1.80003E-23	2.04717E-23
RX	ZY 57	ZY 58	ZY 59	ZY 60				
1	2.21843E-23	2.32735E-23	2.47085E-23	8.99119E-24				
2	2.22274E-23	2.37832E-23	2.42751E-23	8.78377E-24				
3	2.31538E-23	2.30104E-23	2.42451E-23	9.18792E-24				
4	2.29528E-23	2.32084E-23	2.48330E-23	8.91271E-24				
5	2.34323E-23	2.42017E-23	2.44221E-23	8.80470E-24				
6	2.34356E-23	2.41993E-23	2.44246E-23	8.80317E-24				
7	2.29484E-23	2.32094E-23	2.48307E-23	8.91442E-24				
8	2.31536E-23	2.30068E-23	2.42476E-23	9.18754E-24				
9	2.22243E-23	2.37840E-23	2.42731E-23	8.78307E-24				
10	2.21833E-23	2.32720E-23	2.47070E-23	8.99008E-24				

APPENDIX I. CHANNEL THEORY

Spatial channel theory is based on two basic observations. First, for any given response, only a portion of the neutrons present in a reactor will end their history at the response-detector location, and these particles are the only ones of interest for that particular response. The others are extraneous, and only tend to mask the behavior of these "contributing neutrons," which may be a small fraction of the total neutron population. Second, even among the contributing neutrons, certain ones will produce a greater physical effect on the detector than others. Therefore, it is desirable to associate a "future response" to the contributing neutrons.

To further identify the future response, it is first necessary to introduce the term "importance," as used by Lewins:⁵

"The importance is defined as the expected or probable contribution of one particle at $\vec{r}$ to the meter reading."

We now specify the response due to all the neutrons contained in a volume dV about $\vec{r}$ as:

$$dV \int_E \int_{\Omega} n(\vec{r}, E, \hat{\Omega}) \phi^*(\vec{r}, E, \Omega) d\Omega dE \quad (8)$$

where n is the angular neutron density, and ϕ^* is the angular neutron importance.

This quantity has units of "response," and it is physically the total observable effect that will be registered on the detector by the neutrons within dV .

Equation (1) can be written as:

$$dV \int_E \int_{\Omega} B(\vec{r}, E, \hat{\Omega}) d\Omega dE \quad (9)$$

where $B(\vec{r}, E, \hat{\Omega}) = n(\vec{r}, E, \hat{\Omega}) \phi^*(\vec{r}, E, \hat{\Omega})$.

The quantity $B(\vec{r}, E, \hat{\Omega})$ is called the angular "contributon density function," and has units of response/cm³ per unit energy, per steradian. Just as the neutron density function is a continuum interpretation of a limiting process applied to discrete particles,^a so too can we define a pseudo-particle known as a "contributon," whose continuum density function is the contributon density. But first we will digress to consider the discrete particle analog to the continuum neutron density function:

If $N(V)$ is equal to the number of discrete particles contained in some volume V , about point $\vec{r}$, then,

$$n(\vec{r}) = \lim_{V \rightarrow 0} \frac{N(V)}{V}, \quad \vec{r} \in V \quad (10)$$

Note that $N(V)$ is associated with a discrete set, while $n(\vec{r})$ is continuous.

Within the $N(V)$ neutrons located in V , some may possibly be among those neutrons that strike the detector and register a response. We will denote these special neutrons as "contributing neutrons," and will designate $N_c(V)$ to be the number of contributing neutrons contained in V ; obviously, $N_c(V) \leq N(V)$. The definition for the "contributing neutron density" follows naturally:

^aIt has been tacitly assumed that neutrons can be represented as "discrete" particles, ignoring their wave characteristics at low energies.

$$N_c(\vec{r}) = \lim_{V \rightarrow 0} \frac{N_c(V)}{V}, \quad \vec{r} \in V \quad (11)$$

We are now in a position to identify the contribution particle, by associating with each contributing neutron the magnitude of its future contribution:

$$\begin{aligned} P_i &= \text{effect of } i\text{th contribution contained in } V \\ &= \text{detector response arising from } i\text{th contributing} \\ &\quad \text{neutron} = \phi_i^* \end{aligned} \quad (12)$$

The continuum contribution response density function is:

$$p(\vec{r}) = \lim_{V \rightarrow 0} \sum_{i=1}^{N_c(V)} \frac{P_i}{V}, \quad \vec{r} \in V \quad (13)$$

and the angular contribution density is equal to

$$B(\hat{r}, E, \Omega) = \lim_{V \rightarrow 0} \sum_{j=1}^{N_c(V, E, \Omega)} \frac{P_j}{V}, \quad \vec{r} \in V \quad (14)$$

where $N_c(V, E, \Omega)$ is the number of contributing neutrons contained in the volume V , which have an energy E and direction Ω . At this point, there has been a subtle switch from discrete to continuous neutron coordinates, since

$$N_c(V) = \int_E \int_{\Omega} N_c(V, E, \hat{\Omega}) \, d\Omega dE \quad (15)$$

If $N(V, E, \Omega)$ is the total number of neutrons contained in V , with energy E and direction Ω , Eq. (14) can be written as:

$$B(\vec{r}, E, \Omega) = \lim_{V \rightarrow 0} \sum_{j=1}^{N_c(V, E, \Omega)} \left(\frac{N(V, E, \Omega)}{V} \right) * \left(\frac{P_j}{N(V, E, \Omega)} \right) \quad (16)$$

We now note that in the limit

$$\frac{N(V, E, \Omega)}{V} = n(r, E, \Omega) \quad (17)$$

and

$$\sum_{j=1}^{N_c(V, E, \Omega)} \frac{P_j}{N(V, E, \Omega)} = \begin{array}{l} \text{expected contribution from a} \\ \text{neutron with coordinates} \\ (r, E, \Omega) = \phi^*(r, E, \Omega) \end{array} \quad (18)$$

Once again the expression for $B(\vec{r}, E, \hat{\Omega})$ is obtained:

$$B(\vec{r}, E, \hat{\Omega}) = n(\vec{r}, E, \hat{\Omega}) \phi^*(r, E, \Omega) \quad , \quad (19)$$

and it is easily shown that

$$p(\vec{r}) = \int_E \int_{\Omega} B(\vec{r}, E, \hat{\Omega}) dE d\Omega \quad (20)$$

Equation (20) is related to Equation (8) in that $p(\vec{r})dV$ = collective response contained in dV . Since response transport has been attributed to

contributing neutrons, we can speak of such quantities as contributon flux ($= \int \phi \phi^* d\Omega dE$) and contributon current ($= \int \hat{\Omega} \phi \phi^* d\Omega dE$) with the same connotation as in familiar particle transport theory.

It is the purpose of channel theory to apply the various contributon variables to the analysis of shielding problems. The contributon flux and contributon density are indicative of the response concentration at each point in the system, and therefore positions where these quantities have large values represent the most effective location for shielding. The contributon current is a vector in the direction of net response flow. Its dot product with any unit vector gives the response leakage through the differential surface perpendicular to the unit vector.

An interesting consequence of channel theory is that contributon response is conserved as it flows from the forward source to the detector sink, since by definition contributon must contribute to the detector response. As might be expected, the contributon response density obeys an equation (in non-source, non-sink regions) which is similar to the conservation of mass equation in fluid mechanics:

$$\nabla \cdot \hat{v}_c^>(r) B(r)^> = 0 \quad (21)$$

where $\hat{v}_c^>(r)$ = average contributon velocity at r .

This fact implies that the response leakage per unit time through any closed surface surrounding the forward or adjoint sources must equal the detector reading:

$$\int dS \hat{n} \cdot \int \hat{\Omega} \phi \phi^* d\Omega dE = \langle Q^*, \phi \rangle = \langle Q, \phi^* \rangle = R$$

FANG computes this value for axial or radial surfaces, and most test problems have given values for the leakage that agree fairly well with the calculated detector response. In complex problems, however, the leakage may differ somewhat from the response due to numerical approximations (e.g., inadequate mesh size in the transport calculation, or insufficient number of flux moments input to FANG).

APPENDIX II. SPHERICAL HARMONIC EXPANSION

Any continuous function, $F(r, \phi, \theta)$, which is defined in a domain D , with:

$$\begin{aligned} D(\theta) &= [-1, 1] \quad , \\ D(\phi) &= [0, 2\pi] \end{aligned} \quad (25)$$

can be expanded in an infinite series of functions known as "Spherical Harmonics:"

$$F(\vec{r}, \phi, \theta) = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} A_{\ell m}(\vec{r}) Y_{\ell m}(\phi, \theta) \quad (26)$$

where $\vec{r}$ = vector representing all independent variables, excluding ϕ and θ ,

$A_{\ell m}(r)$ = expansion coefficients, and

$Y_{\ell m}(\phi, \theta)$ = eigenfunctions for Laplace's equation in spherical coordinates.

The functions $Y_{\ell m}$ are called the spherical harmonics, and they are given explicitly by:

$$\begin{aligned} Y_{\ell m}(\phi, \theta) &= P_{\ell}^m(\theta) e^{-im\phi} \\ &= P_{\ell}^m(\theta) [\cos m\phi - i \sin m\phi] \end{aligned} \quad (27)$$

where P_ℓ^m are the "associated Legendre functions" defined by⁷

$$P_\ell^m(\theta) = \frac{(-1)^m}{(2^\ell)(\ell!)} (1-\theta^2)^{m/2} \frac{d^{\ell+m}}{d\theta^{\ell+m}} (\theta^2-1)^\ell \quad (28)$$

The spherical harmonics form a complete set and are orthonormal such that

$$\int_0^{2\pi} \int_{-1}^1 Y_{\ell m}(\theta, \phi) Y_{\ell' m'}^*(\theta, \phi) d\phi d\theta = \delta_{\ell\ell'} \delta_{mm'} \quad (29)$$

with $Y_{\ell m}^* =$ complex conjugate of $Y_{\ell m}$ and $\delta_{qr} =$ Kronecker delta.

Thus applying Equation (29) to Equation (26), the expansion coefficients are found to be

$$A_{\ell m}(\vec{r}) = \int_0^{2\pi} \int_{-1}^1 F(\vec{r}, \theta, \phi) Y_{\ell m}^*(\theta, \phi) d\theta d\phi \quad (30)$$

Equation (27) can be expressed by

$$F(\vec{r}, \phi, \theta) = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} A_{\ell m}(\vec{r}) P_\ell^m(\theta) \cos m\phi + B_{\ell, m} P_\ell^m(\theta) \sin m\phi \quad (31)$$

Where $A_{\ell m}$ and $B_{\ell, m}$ are found using Equation (30), and $P_\ell^m(\theta)$ is independent of the angle ϕ . Written in the form of Equation (31), the expansion coefficients are real numbers if F is a real function.

In neutron physics, the angular variables of the directional flux have exactly the domains given in Equation (25), and, therefore, a

spherical harmonic expansion is a convenient method for expressing the angular flux:

$$\begin{aligned}\Phi(\vec{r}, \phi, \eta) &= \sum_{\ell} \sum_m A_{\ell m}(\vec{r}) Y_{\ell, m}(\phi, \eta) \\ &= \sum_{\ell} \sum_m M_{\text{even}}^{\ell, m}(\vec{r}) P_{\ell}^m(\eta) \cos m\phi + M_{\text{odd}}^{\ell, m}(\vec{r}) P_{\ell}^m(\eta) \sin m\phi\end{aligned}\quad (32)$$

where M_{even} is the expansion coefficient associated with the even ϕ -eigenfunction ($\cos m\phi$), and M_{odd} is the one associated with the odd ϕ -eigenfunction ($\sin m\phi$). The relation between the angles (ϕ, η) and the neutron direction cosines of propagation is shown below:⁸

Figure 4

For the particular case of a two-dimensional r - z geometry, multi-energy group phase space domain, as encountered in the DOT discrete ordinates code;

$$\Phi = \Phi(r, z, E_g, \mu, \eta) \quad (33)$$

where, shown in Fig. 4, $\mu = \sqrt{1-\eta^2} \cos \phi$

Also, because of the two-dimensional approximation, the flux must be independent of the third angular coordinate, and hence must be an even function of ϕ , which, because P_ℓ^m is independent of ϕ , causes the odd expansion coefficients to vanish. Furthermore, the sum from $-\ell$ to ℓ , can be replaced by twice the sum from 0 to ℓ , and thus, Equation (31) becomes:

$$\Phi(r, z, E_g, \mu, \eta) = 2 \sum_{\ell=0}^{\infty} \sum_{m=0}^{\ell} M_{(r, z, E_g)}^{\ell, m} P_\ell^m(\eta) \cos m\phi \quad (34)$$

In a DOT calculation, the expansion coefficients are called the "flux moments," and they are given by:

$$M^{\ell, m}(r, z, E_g) = \int_0^{2\pi} \int_{-1}^1 \Phi(r, z, E_g, \eta, \mu) P_\ell^m(\eta) \cos m\phi d\eta d\phi \quad (35)$$

In reality, of course, the series is truncated at some finite number of terms, so that the extremely large amount of data required to describe the angular flux is reduced to a relatively small amount that is contained in the moments. Using Equation (34) the angular flux can be reconstructed from the moments to within some degree of error, which is related to the number of moments retained in describing the angular flux. In general the reconstructed flux is not as accurate as the flux used to calculate

the moments, and therefore some care must be used in dealing with angular fluxes obtained from a finite Legendre expansion. A user of FANG should be aware that reconstructed forward and adjoint angular fluxes are used in the calculation of the contribution flux; and if unreasonable answers appear (e.g., negative values), he should check the number of moments input to FANG.

REFERENCES

- (1) W. A. Rhoades and F. R. Mynatt, "The DOT III Two-Dimensional Discrete Ordinates Transport Code," ORNL-TM-4280, September 1973.
- (2) T. C. Tucker, "CATCH: Computer Assisted Topography, Cartography, Hypsography, Part III, PERSPX: A Subroutine Package for Perspective and Isometric Drawings," ORNL-TM-3790, 1973.
- (3) M. L. Williams and W. W. Engle, Jr., "The Concept of Spatial Channel Theory Applied to Reactor Shielding Analysis," Nuclear Science and Engineering, Vol. 62, pps. 92-104, January 1977.
- (4) M. L. Williams and W. W. Engle, Jr., "Spatial Channel Theory - A Technique for Determining the Directional Flow of Radiation Through Reactor Systems," To be published in the Proceedings of the Fifth International Conference on Reactor Shielding, April 18-22, 1977.
- (5) J. Lewins, "IMPORTANCE: The Adjoint Function," Pergamon Press, 1965.
- (6) R. Courant and D. Hilbert, Methods of Mathematical Physics, Volume 1, Interscience Publishers, Inc., New York, June 1953.
- (7) George I. Bell and Samuel Glasstone, "Nuclear Reactor Theory," Van Nostrand Reinhold Company, 1970.
- (8) F. R. Mynatt, F. J. Muckenthaler, and P. N. Stevens, "Development of Two-Dimensional Discrete Ordinates Transport Theory for Radiation Shielding," CTC-INF-952, August 1969.

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