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IN THE P_1 OR B_1 APPROXIMATION

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HRG3: A CODE FOR CALCULATING THE SLOWING-DOWN SPECTRUM
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COMPUTER CODE ABSTRACT

1. Name: HRG3
2. Computer: The HRG3 Code is designed to operate on the UNIVAC 1108 computer system.
3. Problem solved: The code computes the slowing-down spectrum over the energy range 10 MeV-0.414 eV in either the B_1 or P_1 approximation, using 68 groups of neutrons with a constant group width of $\Delta u = 0.25$. The calculated flux and current spectra are used to reduce the original 68-group cross-section data to average values over as many as 33 broad groups.
4. Method of Solution: The 68 fine group fluxes and currents are calculated by one sweep through the group structure, starting from a specified source distribution. The source may be selected from among the 8 available on the data tape or may be read in. The multigroup model uses a full down-scattering matrix, with inelastic, n_2n , and P_0 and P_1 components of elastic scattering explicitly included. Macroscopic fine group parameters are constructed from input nuclide concentrations and microscopic parameters, available on the data tape for more than 200 individual nuclides. There is no restriction, other than availability, on the number of nuclides usable in a case. A special calculation is made in the resonance range for certain nuclides, using an adaptation of the Adler, Hinman, and Nordheim method to an intermediate resonance approximation for both the absorber nuclide and an admixed moderator. The resonance contribution is

additional data a table of single level resonance parameters for a specified resolved resonance range and average resonance parameters for a specified unresolved range. The code uses these data and additional input data to calculate the resonance contribution to the fine group cross sections. The resonance calculation is based on that of Adler, Hinman, and Nordheim⁽³⁾ and is described more fully in Appendix B.

The second part of the code is concerned with calculating ϕ_n and J_n and with performing various edits using these quantities. First the remaining parameters in the fine group equations are determined: the L_n are read from input for a P_1 calculation, or k is read and the α_n calculated for a B_1 calculation. The applicable pair of fine group equations is then solved for the ϕ_n and J_n in one sweep through the fine groups. The ϕ_n and J_n are then used to calculate broad group averages of various parameters. Macroscopic averages are formed over the broad group structure and are also given for a single group covering the entire fast and epithermal range. Microscopic broad group averages may also be found for each nuclide present. Specific definitions of these broad group parameters are given below.

Several options other than the one described are available. Among the most frequently used of these is the so-called "age" calculation, a plane moments calculation of the slowing down length to each fine group. The equations for this calculation are also derived in Appendix A. The calculation uses the same fine group macroscopic cross sections as the ϕ_n and J_n calculation and is done immediately following it. The fine group results are printed but are not otherwise used. Another common option is the punching of the broad group parameters for input to other codes; this option is described more fully in the input instructions. It is also possible to read in the flux, the

current, and the source by fine group under conditions described in the input instructions and to punch the fine group fluxes and currents for later read-in.

THE BROAD GROUP PARAMETERS

The broad group parameters are calculated from the fine group parameters using, for the most part, quite obvious definitions. Let g be the index of a broad group. Then the following sums over the fine groups in g

$$\phi_g = \sum_n \phi_n$$

$$J_g = \sum_n J_n$$

$$\chi_g = \sum_n \chi_n$$

$$L_g \phi_g = \sum_n L_n \phi_n$$

give the broad group flux, current, source spectrum and leakage, respectively. These are the only broad group parameters which are direct sums; all the other parameters require weighted averages.

To find the weighted averages, let P_n be a fine group parameter and W_n be a fine group weighting function. Then the broad group counterpart of P_n is

$$P_g = \sum_n P_n W_n / W_g$$

where

$$W_g = \sum_n W_n$$

and $W_n = \phi_n$ for flux weighting or $W_n = J_n$ for current weighting. For those scattering parameters involving transfers within or

for the single group as useful gross measures of the calculation; these are D/Σ_{rem} , $v\Sigma_f/\Sigma_a$, and $\Sigma_{\text{out}}/\Sigma_{\text{rem}}$ which are approximations to the age, the nonthermal multiplication factor, and the resonance escape probability, respectively.

PROGRAMMING INFORMATION

The logical units used by HRG3 and their functions are described in the following tabulation.

Logical Unit	Function	Words of Drum Storage Allocated
2	Normal input	--
3	Normal output	--
4	Temporary storage of fine group cross sections for each nuclide in present case.	100,000
7	Auxiliary temporary storage of card images of punch output used in certain punch options.	100,000
8	Temporary storage of card images of punch output.	100,000
9	Location of the HRG3 Library Data Tape as read by MNHRG1.	260,000
17	Location of the HRG3 Library Data Tape as read by TPFILF.	--

Information given later in this section shows how some of these units may be eliminated if necessary.

The HRG3 code is written in FORTRAN-IV with two exceptions. One of these is the use of the INCLUDE statement, a UNIVAC system statement, which is retained in the package for the convenience of avoiding the duplication of the Common, Dimension, and Equivalence statements in each of the subroutines requiring them. The other is the use of a statement return feature, of the form \$NNN, in the call list of some of the service routines. Although this feature is not standard FORTRAN-IV, it is acceptable to the FORTRAN-IV compilers in common use. In lieu of a flow chart, a short verbal

description is given of each of the subroutines distinctive to HRG3. Several special subroutines of the UNIVAC 1108 systems under which the code has been developed are also used. The functions of these subroutines are also described verbally.

A glossary of the variables in Common is given to aid in describing their meaning. The meaning of the local variables of a subroutine can be determined straightforwardly.

A recent overhaul of the editing procedure resulted in the use of the same arrays for both macroscopic and microscopic quantities and in the introduction of a more descriptive notation in that part of the code. In this notation, the first character of a variable name is either B, F, or S to designate a broad group, fine group, or single group quantity. The remaining characters are descriptive of the type of the quantity. For example, BDIFF is the broad group diffusion coefficient and BTPTCD is the broad group transport cross section in the consistent definition. For quantities in the transfer arrays, IJ indicates transfers from I to J and a preceding or following S indicates a sum over J including I. For example, BINII is the broad group inelastic in-group transfer and BP1JIS is the sum over J of the broad group P_1 transfer from J to I. The suffix CW indicates current-weighting of a quantity which is usually flux weighted. Principally for reasons of compatibility with earlier versions of HRG, this notation has not been put in Common. The effect is instead achieved by equivalencing in the subroutines involved. Some of these equivalences are functional, in that they represent the old and new names of a quantity. The other equivalences are to share available memory. A table of the functional equivalences is given on page 22.

The printed output is designed for paper at least 120 columns wide with a maximum of 51 lines per page. The

output can be readily adapted to a different number of lines per page by changing the value of MLC in subroutine MNHRG1.

DISTINCTIVE HRG3 ROUTINES

<u>Routine</u>	<u>Function</u>	<u>Principal Subroutines Called</u>
BEGIN	Sets input, output units; exerts over-all supervisory control	MNHRG1 MNHRG2
MNHRG1	Controls setup of problem, reading of input data, resonance calculation, and accumulation of cross sections into macroscopic arrays	TPFILE INTERP RIC ACCUM
TPFILE	Transfers library data from tape to drum, permitting random access to library data on subsequent cases in a run	
INTERP	Provides values of J, L, or L' functions for resonance calculations by interpolation, extrapolation, or evaluation from tables	
RIC	Calculates effective cross sections in resonance region from resonance parameter tables	INTERP SIMPS
SIMPS	Performs Simpson's Rule integration	GINT
GINT	Intermediate function in Simpson's Rule calculation	FUN1
FUN1	Evaluates integrand in unresolved resonance integration over Porter-Thomas distribution	INTERP
ACCUM	Transfers nuclide data from library input array into fine group arrays according to cross section type	

<u>Routine</u>	<u>Function</u>	<u>Principal Subroutines Called</u>
MNHRG2	Controls calculation of spectrum and averaging of macroscopic and microscopic parameters over broad groups; punches fluxes and currents	PONE BONE AGE CSAV
PONE	Calculates fine group fluxes and currents in P_1 approximation	
BONE	Calculates fine group fluxes and currents in B_1 or Fourier transform P_1 approximation	
AGE	Calculates fine group zeroth through second plane moments of spatial distribution and square of slowing down length	
CSAV	Supervises averaging of both macroscopic and microscopic parameters over broad groups and punching of broad group parameters	CLAPSE WRITE ACCUM PNCH DTRANS
CLAPSE	Provides one-group averages of macroscopic parameters and broad group averages of both macroscopic and microscopic parameters	
WRITE	Writes one group macroscopic and broad group macroscopic and microscopic parameters	
PNCH	Combines and arranges broad group parameters and provides formats for input to selected multigroup codes	PNCHCD

<u>Routine</u>	<u>Function</u>	<u>Principal Subroutines Called</u>
PNCHCD	Punches broad group parameters according to specified formats	
DTRANS	Transfers card images of punched cards to end of regular printed output for case	
NUPG	Prints title card, page number, and time of day as heading on each new page of regular output; called by several subroutines.	

Two of the HRG3 subroutines, TPFIL and DTRANS, are convenience subroutines which may be removed without impairing the operation of the remainder of the code. If the two TPFIL calls are removed from MNHRG1, the library data will be read from tape on Logical Unit 9 instead of from temporary drum storage and the random access capabilities for subsequent cases in the run will be lost. If the DTRANS call is removed from CSAV, the card images of the punched output will not appear at the end of printed output for the case. This card image output will be lost unless Logical Unit 8 is printed; this can be done, for example, by equivalencing 8 to the normal output unit, in which case the card image will appear along with the normal output of macroscopic and individual nuclide data.

SPECIAL SYSTEM ROUTINES USED BY HRG3

<u>Routine</u>	<u>Function in HRG3</u>
SETIO	Changes logical unit assignments in System Unit Table to use 2 as input, 3 as output.
SETDR	Assigns specified portions of magnetic drum storage to function as Logical Units 4, 7, 8, and 9.

<u>Routine</u>	<u>Function in HRG3</u>
SAVEOF	Allow HRG3 to control exit procedure when an end-of-file is encountered in reading from a logical unit. Used by DTRANS to terminate transfer of punch card images to normal output tape at end of run and by MNHRG1 to terminate run.
SETEOF	
RESEOF	
TOD	Returns time of day. Used by NUPG in writing heading on each page of output.

GLOSSARY OF VARIABLES IN COMMON

The letters preceding some of the variable names indicate the following:

- I - Normal input quantity
- L - Obtained from library tape
- O - Optional input quantity

<u>Name</u>	<u>Type</u>	<u>Description</u>
Real, Nondimensioned		
ADELL		Lethargy width of a fine group, set internally to 0.25
ADENA		Absolute value of nuclide density
AMOD	I	Mass of admixed moderator in neutron masses, used in resonance integral calculation
AST		Asterisk, a data item in alphanumeric form
AU		Parameter used in unresolved resonance calculation
BLANK		Blank, a data item in alphanumeric form

<u>Name</u>	<u>Type</u>	<u>Description</u>
Real, Nondimensioned		
DLEV	L	Average level spacing, used in unresolved resonance calculation
EC	L	Energy boundary separating resolved and unresolved resonance ranges
ET	L	Upper energy of unresolved resonance range
GAMFS	L	Average fission width in unresolved resonance range
GAMGA	L	Average capture width in unresolved resonance range
GAMNO	L	Average reduced neutron width in unresolved resonance range
GUNR	L	Statistical weight factor for unresolved resonance range
RAI		Sum of absorption resonance contributions calculated for a nuclide
RBAR	I	Mean chord length in resonance calculations
RFI		Sum of fission resonance contributions calculated for a nuclide
SMAS	L	Mass of resonance absorber, used in resonance integral calculation
STPFAC	I	Signal to punch fine groups fluxes and currents if non-zero
TKN	I	Fourier transform parameter in B_1 approximation

<u>Name</u>	<u>Type</u>	<u>Description</u>
Real, Nondimensioned		
WAG	I	Control parameter choosing between B_1 and P_1 Fourier transform methods
WCTP	I	Control parameter for punched card output
WOIN	I	Control parameter for punched card output
XTRAP	I	L-table extrapolation specification
Real, Dimensioned		
ACS(4,2346)		Fine group transfer matrix
ADUM(5100)	L	Storage array for fine group parameters of a nuclide
AFSS(69)	OL	Fine group source spectrum
AJ(69)	O	Fine group current
AL1(69)	I	Fine group leakage. May also be input in broad group form.
AMAR(69)		Fine group absorption cross section
ANSQ(68)		Fine group ν -fission cross section
APHI(69)	O	Fine group flux
AR(1)	I	Lumped nuclide density, used in resonance range calculations
AT(108)		Resolved resonance absorption integral
B(108)		Broad group fission cross section
BETA(1,100)		Parameter in resonance integral calculation

Name	Type	Description
Real, Dimensioned		
BST(69)		Fine group removal cross section
BWD(68)	I	Alphanumeric output array, usually blank, with asterisks inserted for signalling
BXCX(12)	I	Alphanumeric array for case title card
CEG(33)		Broad group lower energy boundary
CGM(33)		Broad group flux
CNSQ(33)		Broad group ν -fission cross section
COEF1(1,100)		Parameter in resonance integral calculation
CRAM(33)		Broad group leakage
CSAR(33)		Broad group absorption cross section
CTL(33)		Broad group current
CX(33)		Broad group source spectrum
CY(33)		Broad group current weighted removal cross section
D(108)		Fine group fission cross section
DB0(528)		Broad group P_0 downscattering matrix
DB1(528)		Broad group P_1 downscattering matrix
DBIN(528)		Broad group inelastic downscattering matrix
DBJ(528)		Broad group current weighted downscattering matrix
DBN(528)		Broad group n_2n downscattering matrix

<u>Name</u>	<u>Type</u>	<u>Description</u>
Real, Dimensioned		
E(69)		Fine group energy mesh
EN(108)		Resolved resonance energies for a nuclide
F(9,33,14)	L	L-tables and L'-table for resonance integral calculation
FAC1(100)		Parameter in resonance integral calculation
FAC3(100)		Parameter alpha in B_1 calculation
FACT(1)		Parameter in resonance integral calculation
FF(4158)		One-dimensional equivalent of F array, for ease in equivalencing
FIRM(69)		Fine group (0,0) flux component in age calculation
FSN(13)		Alphanumeric title of source spectrum from library tape
FT(108)		Resolved resonance fission integral
FTM(528)		Broad group total transfer matrix to lower energy groups
G(100)	L	Statistical weight factor for resolved resonance
GAMFI(100)	L	Fission width for resolved resonance
GAMGAM(100)	L	Capture width for resolved resonance
GAMN(100)	L	Neutron width for resolved resonance

<u>Name</u>	<u>Type</u>	<u>Description</u>
Real, Dimensioned		
GAMT(100)		Total width for resolved resonance
GDJ(2,70)		Fine group within-group cross sections for elastic and n2n scattering
GK(1,100)		Parameter in resonance integral calculation
P(3)		Parameter in unresolved resonance calculation
PLCK(2,68)		Fine group within-group cross sections for P_0 and P_1 components of elastic scattering
PSFS(70)	0	Fine group self-shielding factor for a nuclide. Set to 1.0 internally if not read in
Q(3)		Parameter in unresolved resonance calculation
RB0(33)		Broad group within-group P_0 scattering cross section
RB1(33)		Broad group within-group P_1 scattering cross section
RBIN(33)		Broad group within-group inelastic scattering cross section
RBN(33)		Broad group within-group n2n scattering cross section
SAR(1,68)		Fine group effective absorption cross-section contribution from resonance calculation

<u>Name</u>	<u>Type</u>	<u>Description</u>
Real, Dimensioned		
SECM(69)		Fine group (1,1) flux component in age calculation
SFR(1,68)		Fine group effective fission cross-section contribution from resonance calculation
SIG(2,1)	I	Scattering cross sections per absorber atom, used in resolved resonance calculations
SIGU(1)	I	Scattering cross section per absorber atom, used in unresolved resonance calculations
SIGZ(100)		Peak of resolved resonance cross section
T(1)	I	Temperature in resonance integral calculation
TAU(69)		Fine group ratio of (2,0)/(0,0) flux components in age calculation
TERM(9)		Temporary storage in interpolation in resonance integral calculation
THRM(69)		Fine group (2,0) flux component in age calculation
TPB(33)		Broad group transport cross section, consistent definition
TTR(33)		Broad group within-group total transfer cross section
Z(2)		Parameter in resonance integral calculation

<u>Name</u>	<u>Type</u>	<u>Description</u>
Real, Dimensioned		
ZI(1,100)		Parameter in resonance integral calculation
ZONE(9)		Parameter in resonance integral calculation
Integer, Nondimensioned		
IBCD		Not used
IWA	L	Control parameter for nuclide data from library tape, positive if absorption cross sections present
IWF	L	Control parameter for nuclide data from library tape, positive if fission cross sections present
IWR	L	Control parameter for nuclide data from library tape, positive if resonance parameter tables present
IYOS	I	Control parameter, non-zero if source spectrum to be read in
JGM	I	Control parameter indicating geometry for resonance integral calculations
K		Integer
KF		Index of top energy group with effective cross-section contribution from resonance calculation
KS		Index of bottom energy group with effective cross-section contribution from resonance calculation
LCNT		Line counter, used to control pagination

<u>Name</u>	<u>Type</u>	<u>Description</u>
Integer, Nondimensioned		
LIBLOC		Not used.
MAGE	I	Control parameter, non-zero if age calculation to be done
MANU	I	Input identification number of a nuclide
MICR	I	Control parameter, non-zero for broad group averaging of microscopic data for individual nuclides
MLC		Maximum line count, used in pagination control
MTP	I	Control parameter indicating type of problem to be solved
NAUSF		Counter used in tracking nuclide cross sections in ADUM array
NIDC		Count of number of nuclides read from library tape
NITL	L	Total number of nuclides in library tape
NOAG	I	Number of broad groups
NOI	I	Number of nuclides this case
NOID	I	Identification number of library data tape
NPAG		Output page number
NRGYS	L	Number of resolved resonance for this nuclide
NT0		Not used

<u>Name</u>	<u>Type</u>	<u>Description</u>
Integer, Dimensioned		
LA(4)	L	Number of fine groups from which down-scattering occurs
LD(4)	L	Maximum number of fine groups to which downscattering occurs
LGBN(35)		Index of fine group forming low energy boundary of broad group
LOL(4)	L	Total number of cross sections in this scattering array
LR(100)	L	Index indicating whether resolved resonance is broad or narrow

FUNCTIONAL EQUIVALENCES

<u>Broad Group</u>		<u>Fine Group</u>	
<u>New Name</u>	<u>Old Name</u>	<u>New Name</u>	<u>Old Name</u>
BABS	CSAR	FABS	AMAR
BALPHA	FAC3	FCURR	AJ
BCAP	GAMN	FFISS	D
BCURR	CTL	FFLUX	APHI
BDIFF	CD	FLEAK	AL1
BFISS	B	FNUFIS	ANSQ
BFLUX	CGM	FREM	BST
BINII	RBIN	FSPEC	AFSS
BINIJ	DBIN		
BLEAK	CRAM		
BNU	EN		
BNUFIS	CNSQ		
BN2NII	RBN		
BN2NIJ	DBN		
BOUT	GAMT		
BP0II	RB0		
BP0IJ	DB0		

<u>Broad Group</u>	
<u>New Name</u>	<u>Old Name</u>
BP1II	RB1
BP1IJ	DB1
BREMCW	CY
BSIJCW	DBJ
BSPEC	CX
BTPTCD	TPB
BTTII	TTR
BTTIJ	FTM

INPUT INSTRUCTIONS

General instructions for preparing HRG3 input are given directly below. The additional information needed for the identification of the nuclides, the broad group energies, and the punch options, follows the general instructions. Fuller explanations of some of the other entries, for example those related to the resonance calculations, are given elsewhere in the document.

GENERAL INSTRUCTIONS

An HRG3 run consists of one or more cases. A case is one computational pass through the code. Multiple cases are processed sequentially. Since cases are logically independent, sufficient input data must be supplied for each case to specify it completely. Data for each case must appear in the order specified. Except for the library tape identification number and the alphanumeric case title card, all input is in floating point, in 12-column fields. Some of the input variables are given with alternate integer names in parentheses. The integer names for these variables are the one used internally.

<u>Columns</u>	<u>Variable</u>	<u>Description</u>
<u>CARD TYPE 0 - Library Specification</u>		
1-6	NOID	HRG Library tape identification number (I6) (Needed only at start of run)

Note: Repeat from here for each case in this run.

CARD TYPE 1 - Case Title

1-72	BXCX(I)	Any alphanumeric information (12A6) This information is printed as heading on each page of output and is punched at the beginning of any card output for this case.
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Note: All remaining cards use 6E12.6 format.

CARD TYPE 2 - Control Parameters

1-12	WTP (MTP)	Type of problem: 1.0 - P_1 calculation 2.0 - B_1 calculation 3.0 - Fine group fluxes to be read in; fine group currents zeroed internally. 4.0 - Fine group fluxes and currents and P_1 leakage terms to be read in. 5.0 - Fine group fluxes and currents and B_1 transform parameter to be read in.
13-24	WSTU (MSTU)	Source: -1.0 - Spectrum to be read in from cards 0.0 - Unit source in one fine group 1.0 - ^{235}U fission spectrum

<u>Columns</u>	<u>Variable</u>	<u>Description</u>
13-24 (contd)	WSTU (MSTU) (contd)	2.0 - ^{235}U fission spectrum 3.0 - ^{239}Pu fission spectrum 4.0 - ^{241}Pu fission spectrum 5.0 - ^{252}Cf fission spectrum 6.0 - Po-Be (Whitmore-Baker) 7.0 - Po-Be (Cochrane-Henry) 8.0 - Ra-Be (Hill)
25-36	WGHUS (MGHUS)	Unit source specification: (Needed only if 0.0 in columns 13-24) Group number of fine group having the unit source.
37-48	WCTP	Punch control, broad group parameters Cards to be punched for the following programs. See page 30 for further details. 0.0 - None 1.0 - Program S 2.0 - HFN 3.0 - DTF/2DF, no thermal group 4.0 - DTF-IV/2DB
49-60	WOIN	Punch control, additional information (Needed only for certain values of WCTP). See page 30 for further details.

<u>Columns</u>	<u>Variable</u>	<u>Description</u>
61-72	STPFAC	Signal to punch fine group fluxes and currents: 0.0 - No punch 1.0 - Punch fine group currents, 6 per card, followed by fine group fluxes, 6 per card, in format for Card Type 5 and 6 input to subsequent HRG runs.
<u>CARD TYPE 3 - Control Parameters</u>		
1-12	POI (NOI)	Number of nuclides
13-24	PNOAG (NOAG)	Number of broad groups (≤ 33)
25-36	PMAGE (MAGE)	Age calculation option: 0.0 - No 1.0 - Yes
37-48	PMICR (MICR)	Parameters for individual nuclides to be averaged over broad groups: 0.0 - No 1.0 - Yes -1.0 - Yes, and punch in addition to macroscopic values
49-60	SJGM	Geometry specification for resonance integral calculations: 0.0 - None 1.0 - Slab 2.0 - Cylinder 3.0 - Sphere

<u>Columns</u>	<u>Variable</u>	<u>Description</u>
<u>CARD TYPE 4 - Broad Group Energy Boundaries</u>		
1-72	CEG(I)	Broad group energy boundaries: Lower energy boundary, in electron volts and in decreasing magnitude, 6 values per card for as many broad groups as given by PNOAG, Columns 13-24 of Card 3. See page 41 for list of fine group energies.
<u>CARD TYPE 5 - Fine Group Currents (Optional)</u> [Needed only if WTP(Card 2, Columns 1-12) = 4.0 or 5.0]		
1-72	AJ(I)	Fine group currents: Fine group currents to be read in, 6 per card, 68 total.
<u>CARD TYPE 6 - Fine Group Fluxes (Optional)</u> [Needed only if WTP (Card 2, Columns 1-12) = 3.0, 4.0 or 5.0]		
1-72	APHI(I)	Fine group fluxes: Fine group fluxes to be read in, 6 per card, 68 total.
<u>CARD TYPE 7 - Fine Group Source Spectrum (Optional)</u> [Needed only if WSTU (Card 2, Columns 13-24) = -1.0]		
1-72	AFSS(I)	Fine group source spectrum: Fine group source spectrum to be read in, 6 per card, 68 total.
 <u>Note:</u> A set of Card Types 8-10 must be supplied in order, as needed, for each nuclide in this case; the sets must be arranged in ascending order of nuclide identification number.		
<u>CARD TYPE 8 - Nuclide Specifications</u>		
1-12	PMANU (MANU)	Nuclide identification number: See page 37 for list.

<u>Columns</u>	<u>Variable</u>	<u>Description</u>
13-24	ADEN	Nuclide density per barn-cm. A negative value indicates nuclide cross sections should be converted to macroscopic form (multiplied by ADEN) before being written and punched as output.
25-36	SSON	Self-shielding factor input specification: 0.0 - No 1.0 - Yes, by broad group 2.0 - Yes, by fine group
37-48	XTRAP	L-table extrapolation specification (see Appendix B for interpretation) 0.0 - Analytic 1.0 - Numerical
49-60	AMOD	Mass of admixed moderator in neutron mass units (Needed only if nuclide also requires Card 10 data and admixed moderator is to be treated in intermediate resonance approximation)

CARD TYPE 9 - Nuclide Self-Shielding Factors (Optional)
[Needed only if SSON (Card 8, Columns 25-36) $\neq$ 0.0].

1-72	PSFS(I)	Self-shielding factors: Self-shielding factors to be read in, 6 per card, for a total of: PNOAG values (Card 3, Columns 13-24) if SSON (Card 8, Columns 25-36) = 1.0 68 values if SSON = 2.0
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<u>Columns</u>	<u>Variable</u>	<u>Description</u>
<u>CARD TYPE 10</u>	- Additional Data for Resonance Nuclide (Needed only if resonance integral calculation is required for this nuclide. Such nuclides are indicated by an asterisk in the list of identification numbers).	
1-12	SIG(1,1)	σ_m , admixed moderator scattering cross section in barns per atom of this nuclide ($\sigma_m = 0.0$ for pure metal).
13-24	SIG(2,1)	σ_p , total off-resonance scattering cross section in barns per atom of this nuclide ($\sigma_m + \sigma_{pot, heavy}$)
25-36	SIGU(1)	$\sigma_{m,eff}$, effective total off-resonance scattering cross section in barns per atom of this nuclide, based on Wigner's rational approximation; used in unresolved resonance calculation.
37-48	AR(1)	Nuclide density of resonance absorber in single equivalent "fuel lump", per barn-cm.
49-60	RBAR	Mean chord length, $\bar{l}$, of single equivalent "fuel lump", in cm. (Set $\bar{l} = 0.0$ to signal a calculation for a homogeneous system)
61-72	T(1)	Temperature of "fuel lump" in °K.

Note: Either a set of Card Types 11 and 12 or a Card Type 13 is needed for each case, unless WTP(Card 2, Columns 1-12) = 3.0, in which case no further cards are needed.

CARD TYPE 11 - P_1 calculation
[Needed only if WTP(Card 2, Columns 1-12) = 1.0 or 4.0]

1-12	HATLT	Input control, leakage factors
		0.0 - Broad group
		1.0 - Fine group

<u>Columns</u>	<u>Variable</u>	<u>Description</u>
<u>CARD TYPE 12</u>	$- P_1$	calculation [Needed only if WTP(Card 2, Columns 1-12) = 1.0 or 4.0]
1-72	AL1(I)	Leakage factors: Leakage factors to be read in, 6 per card, for a total of: PNOAG values (Card 3, Columns 13-24) if HATLT(Card 11, Columns 1-12) = 0.0; 68 values if HATLT = 1.0
<u>CARD TYPE 13</u>	$- B_1$	calculation [Needed only if WTP(Card 2, Columns 1-12) = 2.0 or 5.0]
1-12	TKN	Fourier transform parameter, k, the square root of the buckling
13-24	WAG	Control parameter: 0.0 - B_1 method 1.0 - P_1 Fourier transform method ($\alpha_n = 1.0$)

SPECIAL PUNCH OPTION INSTRUCTIONS

The principal punched card output of HRG3 is broad group parameters in combinations and formats for input to selected multigroup codes. Descriptions of the punched output of these options are given here. The option to punch the fine group fluxes and currents is described in the regular input instructions.

The control numbers for these punch options are WCTP and WGIN on Card Type 2 and PMICR on Card Type 3. The value of WCTP indicates the code for which the parameters are to be punched, according to information already given in the input instructions, and a negative value of PMICR signals that, in addition to macroscopic parameters, microscopic parameters should also be punched for each nuclide present. The value of WGIN provides other information needed, and depends on WCTP as described below.

Some features are common to all the options and will be described first. Regarding identification, each card is punched with sufficient information in Columns 73-80 to enable its positive identification. The case title card is the first card and contains 12-punches in Columns 73-80. Cards containing data for a nuclide have the nuclide identification number, NID (=MANU), in Columns 73-75, with NID = 0 indicating macroscopic data. Serialization by group is numeric in Columns 76-77 and serialization within group is alphabetic in Column 78 unless otherwise specified. Regarding content, a single thermal group is assumed unless otherwise specified. A dummy value of $-7.7777777 \times 10^{33}$ is inserted for any missing thermal group values. For user convenience, card image output is listed at the end of the regular output for a case.

A description of the options follows. For convenience, the microscopic notation is used for both macroscopic and microscopic parameters. A total of G groups is assumed.

$$\text{WCTP} = 1.0 \text{ (Program S)}^{(4,5)}$$

Order of group parameters:

$$v\sigma_{f,g}$$

$$\sigma_{t,g}$$

$$\sigma_{o,g-i \rightarrow g} \quad i = 0, G-1$$

$$\sigma_{l,g-i \rightarrow g} \quad i = 0, G-1$$

Thermal group treatment:

$$\text{WOIN} = 0.0$$

Use dummy values for four ingroup parameters

$$= 1.0$$

Read in four ingroup parameters, in I5, 4E14 format. Contents: NID, $v\sigma_{f,G}$, $\sigma_{t,G}$, $\sigma_{o, G \rightarrow G}$, $\sigma_{l, G \rightarrow G}$.

One card, with NID = 0 for macroscopic data, always required; an additional card required for each nuclide if PMICR = - 1.0. These cards appear in ascending order of NID, directly behind the regular HRG3 input for this case.

Additional comments:

An F0 format card, with the identification P 820 in Columns 73-78, immediately follows the title card in the punched output. The parameters are punched in 1P5E14.7 format.

$$\underline{WCTP = 2.0 \text{ (HFN)}}^{(6)}$$

Order of group parameters:

$$D_g = 1/3\sigma_{tr,g}$$

$$B_{\perp,g}^2 \quad \text{left blank for later insertion}$$

$$\sigma_{rem,g}$$

$$v\sigma_{f,g}$$

$$\chi_{fiss,g} \quad \text{The source spectrum specified in input is used}$$

$$\sigma_{in,g} = 0.0 \quad \text{(needed by HFN only if no transfer matrix)}$$

$$\chi_{ext,g} = 0.0$$

After the above parameters have been punched for all groups, the transfer matrix is punched as follows:

$$\sigma_{g' \rightarrow g} \quad (g' = 1, g), g = 1, G$$

where

$$\begin{aligned}\sigma_{g' \rightarrow g} &= \sigma_{Po, g' \rightarrow g} + \sigma_{in, g' \rightarrow g} + 2\sigma_{n2n, g' \rightarrow g} \\ WGIN &= 0.0 \quad \sigma_{g \rightarrow g} = 0.0 \quad (\text{normal use}) \\ &= 1.0 \quad \sigma_{g \rightarrow g} = \sigma_{g' \rightarrow g} \quad \text{for } g' = g\end{aligned}$$

Thermal group treatment:

The arrangement of the parameters is such that, except for $\sigma_{G \rightarrow G}$, which is normally set to 0.0, all the thermal group parameters appear together on separate cards. It is assumed that the user will add these cards and no dummy values are punched.

Additional comments:

All cards are punched in 1P6E10.4 format, starting in Column 11, with the first address field left blank and with other controls compatible with sequential loading by the HFN input routine. Thermal group values must of course be inserted in a similar format. The identification supplied in Columns 73-78 of each card in addition to the HRG nuclide number is (a) the letter G for group values or T for the transfer matrix and (b) the group number for group values or a numerical sequence number for the transfer matrix. The 7 group values for each group appear on two cards, each with the same identification in Columns 73-78; these cards can be distinguished by a 1 in Column 3 of the second card.

$$\underline{WCTP = 3.0 \text{ (DTF/2DF, no thermal group)}}$$

Order of group parameters:

$$\begin{aligned}\sigma_{f, g} \\ \sigma'_{a, g} &= \sigma_{a, g} - \sigma_{n2n, g}\end{aligned}$$

$$v^{\sigma} f, g$$

$$\sigma_{tr, g}$$

$$\sigma_{o, g-i \rightarrow g} \quad i = o, G-1$$

Thermal group treatment:

No thermal group

Additional comments:

Downscatter is limited to 10 groups. Card format is determined as follows.

$$WOIN = 0.0 \quad 8F9.3$$

$$WOIN = 1.0 \quad 1P6E12.6$$

$$\underline{WCTP = 4.0 \text{ (DTF-IV/2DB)}}^{(7,8)}$$

Order of group parameters:

1-table set or 1st table of 2-table set

$$\sigma_{f, g}$$

$$\sigma'_{a, g} = \sigma_{a, g}^*$$

$$v^{\sigma} f, g$$

$$\sigma_g = \sigma_g^*$$

$$\sigma'_{o, g \rightarrow g} = \sigma_{o, g \rightarrow g} + \sigma_g^* - \sigma_{t, g}^{(0)}$$

$$\sigma_{o, g-i \rightarrow g} \quad i = 1, G-1$$

2nd table of 2-table set

$$0.0$$

$$\sigma_{tr, g} - \sigma_g^*$$

0.0

$$\sigma'_{1,g \rightarrow g} = \sigma_{1,g \rightarrow g} + \sigma_g^* - \sigma_{t,g}(1)$$

$$\sigma_{1,g-i \rightarrow g} \quad i = 1, G-1$$

Thermal group treatment:

Dummy values for ingroup parameters

Additional comments:

Choice of number of tables and entries in special positions are determined by WOIN as follows:

WOIN = 1.0 1-table set only, with

$$\sigma_{a,g}^* = \sigma_{a,g} - \sigma_{n2n,g}$$

$$\sigma_g^* = \sigma_{tr,g}$$

for both macroscopic and microscopic parameters

= 2.0 2-table set only, with

$$\sigma_{a,g}^* = \sigma_{a,g} - \sigma_{n2n,g}$$

$$\sigma_g^* = \sigma_{t,g}(0)$$

for both macroscopic and microscopic parameters

= 3.0 both 1-table and 2-table sets, with 2-table set as for WOIN = 2.0

= 4.0 2-table set only, with

$$\sigma_{a,g}^* = \sigma_{a,g} - \sigma_{n2n,g}$$

$$\sigma_g^* = \sigma_{t,g}(2) - \sigma_{2,g}(2)$$

for both macroscopic and microscopic parameters

= 5.0 both 1-table and 2-table sets, with 2-table
set as for WGIN = 4.0

= -N same as for WGIN = N for macroscopic parameters
but $\sigma_{a,g}^* = \sigma_{a,g}$ and $\sigma_{n2n,g}$ instead subtracted
from $\sigma_{o,g \rightarrow g}'$ for microscopic parameters.

In the above, $\sigma_{t,g}(i)$ indicates $\sigma_{t,g}$ is calculated by weighting
with the i th moment of the angular flux and $\sigma_{2,g}(2)$ is the
second Legendre moment of the scattering cross section also
weighted by the second moment of the angular flux. This latter
procedure is described more completely in Appendix C.

The best position for the "extra" $\sigma_{n2n,g}$ is determined by
the use of the parameters. In general, $\sigma_{n2n,g}$ should be sub-
tracted from $\sigma_{a,g}$. For burnup calculations, however, $\sigma_{a,g}$
should be correct and the $\sigma_{n2n,g}$ correction is shifted to
 $\sigma_{o,g \rightarrow g}'$ for microscopic parameters only. Use WGIN > 0.0 for
reactivity calculations, WGIN < 0.0 for burnup calculations.

Source spectrum cards follow the case title card for each
set.

A name card precedes the macroscopic parameters for each
nuclide. Each name card contains the value of WGIN in
Columns 71-72.

All parameters are punched in 1P6E12.6 format.

*** ALPHA DECAY LISTING OF NUCLIDES ON DATA TAPE HRG 60170 ***

NUMBER	NUCLIDE NAME	NUMBER	NUCLIDE NAME	NUMBER	NUCLIDE NAME
11	304SS	246	BY165	144	HG201 0102
90	G107*	6	D20	145	HG202 101
91	G109*	233	EUROPIUM-151	146	HG204 101
3	L27	234	EUROPIUM-153	1	H1 101
81	M241	235	EUROPIUM-154	2	H2 0103
82	M242	236	EUROPIUM-155	5	H20 w/UPSCAT
83	M243	237	EU156	195	IRIDIUM-115
112	U197*	49	FISSION PRODUCT	92	IN115*
211	AR108-134	48	FISSION PRODUCT	199	IODINE-127
212	AR108-136	56	FISSION PRODUCT	200	IODINE-129
213	AR108-137	47	FISSION PRODUCT	124	IRIDIUM 101
214	AR108-138	117	F19	9	IRON
13	BE9 0103	238	GD152	201	LI35
148	LI209 0103	95	GD152*	155	KRYPTON-83
19	ORON	239	GD153	156	KRYPTON-84
154	ORON-142-81	240	GD154	157	KRYPTON-85
20	LI	96	GD154*	158	KRYPTON-86
21	LI	241	GD155	215	LANTHANUM-139
35	CA2100 0102	97	GD155*	147	LEAD 0103
190	CA2100-110	242	GD156	114	LITHIUM 101
191	CA2100-111	98	GD156*	115	LI6 101
192	CA2100-112	243	GD157	116	LI7 101
193	CA2100-113	99	GD157*	102	LI175A
194	CA2100-114	244	GD158	103	LI175B
122	CALC108 101	100	GD158*	104	LI176A
216	CE108-140	245	GD160	105	LI176B
217	CE108-142	101	GD160*	23	MAGNESIUM 0103
208	CE108-135	113	HE4	140	MERCURY 0102
209	CE108-135	126	HE174	29	MS55
210	CE108-137	106	HE174*	87	MS55* (ENDF/B RES) 12/69
120	CHLORINE 0103	127	HE176	34	MO176ENDUM 0102
28	CHROMIUM	107	HE176*	176	MO176ENDUM-100
121	CL37	123	HE177	172	MO176ENDUM-95
84	CM242	108	HE177*	173	MO176ENDUM-96
85	CM243	129	HE178	174	MO176ENDUM-97
86	CM244	109	HE178*	175	MO176ENDUM-98
32	COPPER	130	HE179	7	NI23
33	CO59	110	HE179*	170	NI93
123	CU63	131	HE180	171	NI94
83	CU63*	111	HE180*	219	NEOLYM100-142
89	CU65*	141	HE196	220	NEOLYM100-143
3	LI2	142	HE199	221	NEOLYM100-144
247	LY164	143	HE200	222	NEOLYM100-145

AN ASTERISK(*) IN A NUCLIDE NAME INDICATES THAT DATA FOR THE NUCLIDE INCLUDES RESONANCE PARAMETER TABLES

*** ALPHABETIC LISTING OF NUCLIDES ON DATA TAPE HRG 60170 ***

NUMBER	NUCLIDE	NAME	NUMBER	NUCLIDE	NAME	NUMBER	NUCLIDE	NAME
223	NEODYMIUM-146	OR-G2	118	P31	0102	149	UNIT ONE/V	
224	NEODYMIUM-148	OR-G2	182	RHODIUM-103		62	U232	A 042866
225	NEODYMIUM-150	OR-G2	159	RUBIDIUM-85		64	U233(W)	CR030967
31	NICKEL	A 051666	160	RUBIDIUM-87		63	U233(W)*	CR030967
71	NP237	C 053069	178	RUTHENIUM-101		65	U234	A 092766
72	NP238 0103		179	RUTHENIUM-101		66	U235(W)	C 013169
73	NP239 101		180	RUTHENIUM-102		12	U235(W)*	C 013169
22	N14	AL081066	181	RUTHENIUM-104		67	U236	C 053069
4	O16	AL042966	227	SAMARIUM-147		68	U237	C 041367
183	PALLADIUM-104	OR-G2	228	SAMARIUM-148		69	U238	C 010968
184	PALLADIUM-105	OR-G2	94	SAMARIUM-149		13	U238*	C 010968
185	PALLADIUM-106	OR-G2	229	SAMARIUM-150		70	U239	101
186	PALLADIUM-107	OR-G2	230	SAMARIUM-151		27	V51	0102
187	PALLADIUM-108	OR-G2	231	SAMARIUM-152		136	W182	0102
188	PALLADIUM-110	OR-G2	232	SAMARIUM-154		137	W183	
58	PA231	A 030967	153	SELENIUM-82		138	W184	0102
59	PA232 101		SE77			139	W186	0102
60	PA233	C 042667	150	SE78		202	XENON-128	OR-G2
61	PA234 101		151	SE78		203	XENON-130	OR-G2
25	POTASSIUM 0103		152	SE80		204	XENON-131	OR-G2
218	PRASEODYMIUM-141	OR-G2	24	SILICON 0103		205	XENON-132	OR-G2
226	PROMETHIUM-147	OR-G2	189	SILVER-109		206	XENON-134	OR-G2
37	PSEUDO FPROD 1 235		161	STRONTIUM-88		93	XENON-135	OR-G2
41	PSEUDO FPROD 1 239		162	STRONTIUM-90		207	XENON-136	OR-G2
38	PSEUDO FPROD 2 235		119	SULFUR 0103		163	YTRIUM-89	OR-G2
42	PSEUDO FPROD 2 239		132	TA181		33	ZINC 0102	
39	PSEUDO FPROD 3 235		133	TA182		10	ZIRCONIUM	0103
43	PSEUDO FPROD 3 239		134	TA183		164	ZIRCONIUM-90	OR-G2
40	PSEUDO FPROD 4 235		177	TECHNETIUM-99		165	ZIRCONIUM-91	OR-G2
44	PSEUDO FPROD 4 239		196	TELLURIUM-126		166	ZIRCONIUM-92	OR-G2
45	PSEUDO FPRODS 1-4 235		197	TELLURIUM-128		167	ZIRCONIUM-93	OR-G2
46	PSEUDO FPRODS 1-4 239		198	TELLURIUM-130		168	ZIRCONIUM-94	OR-G2
74	PU236	CR052869	246	TERBIUM-159		169	ZIRCONIUM-96	OR-G2
75	PU238	C 053169	51	TH228				
76	PU239(W)	CR062067	52	TH230				
14	PU239(W)*	CR062067	53	TH231 101				
77	PU240	CR062068	54	TH232				
15	PU240*	CR062068	56	TH232*	101			
78	PU241(W)	CR081966	57	TH234				
16	PU241(W)*	CR081966	36	TIN				
17	PU242	C 052869	26	TITANIUM				
79	PU243	C 092366	125	TM169	0103			
80	PU244	C 110166	135	TUNGSTEN	0102			

AN ASTERISK(*) IN A NUCLIDE NAME INDICATES THAT DATA FOR THE NUCLIDE INCLUDES RESONANCE PARAMETER TABLES

*** NUMERICAL LISTING OF NUCLIDES ON DATA TAPE HRG 60170 ***

NUMBER	NUCLIDE NAME	NUMBER	NUCLIDE NAME	NUMBER	NUCLIDE NAME
1	H1 101	44	PSEUDO FPROD 4 239	87	MN55* (ENDF/B RES) 12/69
2	H2 0103	45	PSEUDO FPROD 1-4 235	88	CU63*
3	C12	46	PSEUDO FPROD 1-4 239	89	CU65*
4	C16	47	FISSION-PRODUCT OK-62	90	AG107*
5	H20 WUPSCAT	48	FISSION-PRODUCT 25 OK-62	91	AG109*
6	D20	49	FISSION-PRODUCT 23 OK-62	92	IN115*
7	A23	50	FISSION-PRODUCT 39 OK-62	93	XENON-135 OR-62
8	AL27	51	TH228	94	SAMARIUM-149
9	IRON	52	TH230	95	GD152*
10	IRONIUM 0103	53	TH231	96	GD154*
11	304SS	54	TH232*	97	GD155*
12	U235(W)*	55	TH232	98	GD156*
13	U238*	56	TH233	99	GD157*
14	PU239(W)*	57	TH234	100	GD158*
15	PU240*	58	PA231	101	GD160*
16	PU241(W)*	59	PA232	102	LU175A
17	PU242	60	PA233	103	LU175B
18	BE9 0103	61	PA234	104	LU176A
19	GORON	62	U232	105	LU176B
20	B10	63	U233(W)*	106	HF174*
21	B11	64	U233(W)	107	HF176*
22	K14	65	U234	108	HF177*
23	MAGNESIUM 0103	66	U235(W)	109	HF178*
24	SILICON 0103	67	U236	110	HF179*
25	POTASSIUM 0103	68	U237	111	HF180*
26	TITANIUM 0103	69	U238	112	AU197*
27	V51 0102	70	U239	113	HF4
28	CHROMIUM	71	NP237	114	LI7
29	MN55	72	NP238	115	LI6
30	CO59	73	NP239	116	LI7
31	NICKEL	74	PU236	117	F19
32	COPPER	75	PU238	118	P31
33	ZINC 0102	76	PU239(W)	119	SULFUR 0103
34	MOLYBDENUM 0102	77	PU240	120	CHLORINE 0103
35	CADMIUM 0102	78	PU241(W)	121	CL37
36	TIN	79	PU243	122	CALCIUM 101
37	PSEUDO FPROD 1 235	80	PU244	123	CU63
38	PSEUDO FPROD 2 235	81	AM241	124	IRIDIUM 101
39	PSEUDO FPROD 3 235	82	AM242	125	TM169
40	PSEUDO FPROD 4 235	83	AM243	126	HF174
41	PSEUDO FPROD 1 239	84	CW242	127	HF176
42	PSEUDO FPROD 2 239	85	CW243	128	HF177
43	PSEUDO FPROD 3 239	86	CW244	129	HF178

AN ASTERISK(*) IN A NUCLIDE NAME INDICATES THAT DATA FOR THE NUCLIDE INCLUDES RESONANCE PARAMETER TABLES

LISTING OF INPUT DATA FOR SAMPLE PROBLEM

' XQT HRG3

060170

U02 - 2 WPC PU02 (8 APC PU240), 0.5 RODS, 0.75 SQ LATTICE

1.0	2.0	0.0	0.0		
9.0	3.0	1.0	1.0	2.0	
1.17	+04 2.38	0.683			
4.0	1.51620 -02				
5.0	1.83630 -02				
10.0	3.86440 -03				
12.0	5.41750 -05			16.0	
1.052280+03	2.548632+03	7.006288+03	1.506530-04	1.489072	293.6
13.0	7.37600 -03			16.0	
7.728792+00	1.871921+01	5.145983+01	2.051150-02	1.489072	293.6
14.0	1.38070 -04			16.0	
4.128868+02	1.000016+03	2.749082+03	3.839530-04	1.489072	293.6
15.0	1.148 -05			16.0	
4.965611+03	1.202676+04	3.306202+04	3.192540-05	1.489072	293.6
16.0	1.04610 -06			16.0	
5.449309+04	1.319828+05	3.628258+05	2.909160-06	1.489072	293.6
17.0	4.46490 -09				
0.0					
-1.0	-10 -1.0	-10 -1.0	-10		

HRG	0
HRG	1
HRG	2
HRG	3
HRG	4
	016
	H20
	ZR
	U235*
	U235 RP
	U238*
	U238 RP
	PU239*
	PU39 RP
	PU240*
	PU40 RP
	PU241*
	PU41 RP
	PU242
HRG	11
HRG	12

BNWL-1452

U02 - 2 WPC PU02 (8 APC PU240), 0.5 RODS, 0.75 SQ LATTICE

16:09:14

*
* HRG3 OUTPUT *
*

DATA TAPE NUMBER

60170

NUMBER OF
NUCLIDES

NUMBER OF
BROAD GROUPS

AGE
CALCULATION

MICROSCOPIC CROSS
SECTIONS AVERAGED

RESONANCE
GEOMETRY

9

3

YES

YES

CYLINDRICAL

REVISED BROAD GROUP LOWER BOUNDARIES BY ENERGY AND LETHARGY
(GROUP 1 UPPER BOUNDARY IS ENERGY = 1.00+07, LETHARGY = 0.0)

GROUP	DESIRED ENERGY	ENERGY USED	DESIRED LETHARGY	LETHARGY USED	DELTA U
1	1.1700000+04	1.1708796+04	6.7507515+00	6.7500000+00	6.75
2	2.3800000+00	2.3823696+00	1.5250995+01	1.5250000+01	8.50
3	6.8300000-01	6.8256032-01	1.6499356+01	1.6500000+01	1.25

THE SOURCE SPECTRUM USED FOR THIS PROBLEM IS

THE U-235 SPECTRUM (CRANBERG)

U02 - 2 WPC PU02 (8 APC PU240), 0.5 RODS, 0.75 SQ LATTICE

16:09:16

NUMBER NUCLEIDE NAME NUCLEIDE DENSITY
(ATOMS/BARN-CM)

4 016 AL042966 1.51620-02
5 H2O W/UPSCAT A 012469 1.83630-02
10 ZIRCONIUM 0103 3.86440-03
12 U235(W)* C 013169 5.41750-05

RESONANCE DATA FOR U235(W)* C 013169

SIGMA-M SIGMA-P SIGMA-M(EFF) L-BAR TEMPERATURE
1.05228+03 2.54863+03 7.00629+03 1.48907+00 2.93600+02

LUMPED NUCLEIDE ADMIXED SUM OF RESONANCE CONTRIBUTIONS FOR
DENSITY MODERATOR MASS ABSORPTION FISSION

1.50653-04 1.60000+01 2.5250962+02 1.4829886+02

L-TABLE EXTRAPOLATION IS ANALYTIC

RESONANCE ABSORPTION AND FISSION ALLOCATION TO FINE GROUPS

GROUP	ABSORPTION	FISSION	GROUP	ABSORPTION	FISSION
46	0.000000	0.000000	57	4.1997407+01	1.9310150+01
47	0.000000	0.000000	58	7.1879782+01	2.6591515+01
48	1.9589438-01	1.4804598-01	59	2.1219690+01	2.3900291+00
49	7.8728449+01	5.4182301+01	60	4.2980301+01	2.7824173+01
50	5.1919214+01	3.3780293+01	61	7.3657151+00	5.5029401+00
51	9.0003287+01	5.2915836+01	62	1.6400328+01	3.7186820+00
52	6.5262986+01	4.3500074+01	63	6.7851647+00	5.2083306+00
53	1.1244651+02	6.5708876+01	64	4.5295597+01	3.4769155+01
54	5.1115195+01	3.3542679+01	65	3.2417663+01	2.4883980+01
55	1.2089514+02	4.5548226+01	66	7.8051446+00	5.9912730+00
56	1.4770862+02	1.0911115+02	67	0.000000	0.000000

13 U238* C 010968 7.37600-03

RESONANCE DATA FOR U238*					C 010968	
SIGMA-M	SIGMA-P	SIGMA-M(EFF)	L-BAR	TEMPERATURE		
7.72879+00	1.87192+01	5.14598+01	1.48907+00	2.93600+02		
LUMPED NUCLEIDE DENSITY	ADMIXED MODERATOR MASS	SUM OF RESONANCE CONTRIBUTIONS FOR FISSION				
2.05115-02	1.60000+01	1.5398631+01	0.000000			

L-TABLE EXTRAPOLATION IS ANALYTIC					
RESONANCE ABSORPTION AND FISSION ALLOCATION TO FINE GROUPS					
GROUP	ABSORPTION	FISSION	GROUP	ABSORPTION	FISSION
33	0.000000	0.000000	47	1.6999825+00	0.000000
34	4.7405913-01	0.000000	48	2.5727332+00	0.000000
35	6.1077782-01	0.000000	49	0.000000	0.000000
36	6.8186248-01	0.000000	50	1.9583159+00	0.000000
37	6.7880169-01	0.000000	51	6.0282495+00	0.000000
38	9.6486143-01	0.000000	52	8.8656481-01	0.000000
39	9.3319412-01	0.000000	53	1.0728897+01	0.000000
40	1.0882477+00	0.000000	54	0.000000	0.000000
41	9.1300008-01	0.000000	55	0.000000	0.000000
42	9.7057795-01	0.000000	56	1.7590011+00	0.000000
43	1.2364007+00	0.000000	57	1.7270885+01	0.000000
44	1.4247071+00	0.000000	58	6.9357225+00	0.000000
45	1.0578223+00	0.000000	59	1.5639686+00	0.000000
46	3.3658316+00	0.000000	60	0.000000	0.000000

RESONANCE DATA FOR PU239(W)* CR062067

SIGMA-M	SIGMA-P	SIGMA-M(EFF)	L-BAR	TEMPERATURE
4.12887+02	1.00002+03	2.74908+03	1.48907+00	2.93600+02

LUMPED NUCLEIDE DENSITY ADMIXED MODERATOR MASS SUM OF RESONANCE CONTRIBUTIONS FOR FISSION

3.83953-04	1.60000+01	2.6799305+02	1.5889028+02
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L-TABLE EXTRAPOLATION IS ANALYTIC

RESONANCE ABSORPTION AND FISSION ALLOCATION TO FINE GROUPS

GROUP	ABSORPTION	FISSION	GROUP	ABSORPTION	FISSION
41	0.0000000	0.0000000	50	6.5114436+01	1.4943959+01
42	1.0379696+01	5.8757986+00	51	6.3011412+00	3.0476224+00
43	2.4200743+01	1.3868367+01	52	4.9336693+01	2.3499804+01
44	2.1549923+01	1.5874171+01	53	7.1270712+01	4.6773738+01
45	3.5507894+01	1.9944379+01	54	1.8266881+02	1.0574296+02
46	3.5888706+01	2.2136779+01	55	2.0458324+02	1.3443024+02
47	2.6065255+01	2.3810948+01	56	2.1109091+01	1.7377686+01
48	7.8723129+01	5.5133707+01	57	1.3427870+02	6.7875346+01
49	1.1359184+02	7.0359884+01	58	0.0000000	0.0000000

15 PU240* CR062068 1.14800-05

RESONANCE DATA FOR PU240* CR062068

SIGMA-M	SIGMA-P	SIGMA-M(EFF)	L-BAR	TEMPERATURE
4.96561+03	1.20268+04	3.30620+04	1.48907+00	2.93600+02

LUMPED NUCLEIDE DENSITY ADMIXED MODERATOR MASS SUM OF RESONANCE CONTRIBUTIONS FOR FISSION

3.19254-05	1.60000+01	3.4027811+03	1.2111864+00
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L-TABLE EXTRAPOLATION IS ANALYTIC

U02 - 2 WPC PU02 (8 APC PU240), 0.5 RODS, 0.75 SQ LATTICE

16:09:25

RESONANCE DATA FOR PU240*

CR062068

RESONANCE ABSORPTION AND FISSION ALLOCATION TO FINE GROUPS

GROUP	ABSORPTION	FISSION	GROUP	ABSORPTION	FISSION
36	0.0000000	0.0000000	52	0.0000000	0.0000000
37	9.3547214-01	4.3452587-03	53	8.2661264+01	5.4742559-01
38	6.6796035+00	3.1026692-02	54	0.0000000	0.0000000
39	8.2302014+00	3.8229203-02	55	0.0000000	0.0000000
40	1.0098812+01	4.6908880-02	56	0.0000000	0.0000000
41	1.2340425+01	5.7321150-02	57	0.0000000	0.0000000
42	1.5017234+01	6.9754901-02	58	0.0000000	0.0000000
43	1.8199096+01	8.4534616-02	59	0.0000000	0.0000000
44	2.1963912+01	1.0202215-01	60	0.0000000	0.0000000
45	2.6397912+01	1.2261804-01	61	0.0000000	0.0000000
46	7.2614067+01	3.3729162-01	62	0.0000000	0.0000000
47	3.5182814+01	1.6342382-01	63	0.0000000	0.0000000
48	1.0682765+02	4.9621337-01	64	2.5971910+03	4.5010176-01
49	0.0000000	0.0000000	65	1.0897291+04	1.8885364+00
50	1.2967698+02	4.8136684-01	66	1.0661085+03	1.8476011-01
51	0.0000000	0.0000000	67	0.0000000	0.0000000

16 PU241(W)*

CR081966

1.04610-06

RESONANCE DATA FOR PU241(W)*

CR081966

SIGMA-M	SIGMA-P	SIGMA-M(EFF)	L-BAR	TEMPERATURE
5.44931+04	1.31983+05	3.62826+05	1.48907+00	2.93600+02
LUMPED NUCLIDE DENSITY	ADMIXED MODERATOR MASS	SUM OF RESONANCE CONTRIBUTIONS FOR		
		ABSORPTION	FISSION	
2.90916-06	1.60000+01	5.6589565+02	4.1963782+02	

L-TABLE EXTRAPOLATION IS ANALYTIC

16:09:28

U02 - 2 WPC PU02 (8 APC PU240), 0.5 RODS, 0.75 SQ LATTICE

RESONANCE DATA FOR PU241(W)* CR081966
RESONANCE ABSORPTION AND FISSION ALLOCATION TO FINE GROUPS

GROUP	ABSORPTION	FISSION	GROUP	ABSORPTION	FISSION
27	0.000000	0.000000	45	4.2632896+00	3.8036357+00
28	1.0943493+00	9.7636011-01	46	3.2094990+00	2.8634614+00
29	3.6483491+00	3.2549961+00	47	2.3341315+00	2.0824731+00
30	4.7737075+00	4.2590220+00	48	1.6398686+00	1.4630633+00
31	6.0346781+00	5.3835036+00	49	1.9353509+01	1.7436121+01
32	7.3682074+00	6.5737915+00	50	4.6454305+01	3.8324349+01
33	8.6917759+00	7.7546572+00	51	6.0558333+01	5.2646130+01
34	9.9049217+00	8.8370055+00	52	1.2142268+02	1.0696770+02
35	1.0904090+01	9.7284464+00	53	8.9938009+01	3.6222496+01
36	1.1596412+01	1.0346125+01	54	3.0729437+02	2.4120598+02
37	1.1913893+01	1.0629376+01	55	1.6440448+02	1.0831540+02
38	1.1824414+01	1.0549545+01	56	2.1722934+02	1.7375858+02
39	1.1337087+01	1.0114759+01	57	2.3254830+02	1.8924896+02
40	1.0500721+01	9.3685682+00	58	2.6445553+02	2.5240600+02
41	9.3957762+00	8.3827545+00	59	5.5510096+02	2.9463532+02
42	8.1216078+00	7.2459628+00	60	9.7694923+00	9.3937427+00
43	6.7818344+00	6.0506393+00	61	2.4675456+01	2.3726401+01
44	5.4707660+00	4.8809260+00	62	0.0000000	0.0000000

17 PU242 C 052869 4.46490-09

THE FLUXES AND CURRENT TERMS ARE CALCULATED USING THE P-1 APPROXIMATION

GROUP	NET LEAKAGE TERM
1	-9.9999998-11
2	-9.9999998-11
3	-9.9999998-11

U02 - 2 WPC PU02 (8 APC PU240), 0.5 RODS, 0.75 SQ LATTICE

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FLUX AND CURRENT NORMALIZATION FACTOR. = 3.0163461*01

GROUP	FLUX	CURRENT TERM	GROUP	FLUX	CURRENT TERM
1	9.4592441-03	3.0645174-12	35	4.1163976-02	2.7020581-12
2	2.8672582-02	1.0042356-11	36	4.0926772-02	2.6694163-12
3	6.0632758-02	1.7372257-11	37	4.0762226-02	2.5536942-12
4	9.2938252-02	2.1795554-11	38	4.0544697-02	2.5969168-12
5	1.2814221-01	2.6514999-11	39	4.0229013-02	2.5344159-12
6	1.8735041-01	4.5254552-11	40	4.0100285-02	2.6342290-12
7	1.6300713-01	3.3384325-11	41	3.9975855-02	2.6551294-12
8	1.7055378-01	3.0504789-11	42	3.8692931-02	2.0043737-12
9	1.4946350-01	2.2883728-11	43	3.9556439-02	2.4563164-12
10	1.4446613-01	1.8556139-11	44	3.8082619-02	1.5660428-12
11	1.6823715-01	2.3014382-11	45	3.9528348-02	2.4886651-12
12	1.3998551-01	1.8944968-11	46	3.6501988-02	1.2852566-12
13	9.2764176-02	9.6548131-12	47	3.8911378-02	2.4305159-12
14	1.2295028-01	1.2884125-11	48	3.6343376-02	1.5640097-12
15	1.0972186-01	1.1123379-11	49	3.7679824-02	2.3195050-12
16	9.5638587-02	9.8644444-12	50	3.5861846-02	2.0505898-12
17	8.4815722-02	8.5602039-12	51	3.2394666-02	7.5347290-13
18	7.6118917-02	7.3413984-12	52	3.7254143-02	2.1605740-12
19	6.7386761-02	6.3255807-12	53	3.1435554-02	1.1702225-12
20	6.0150781-02	5.3989458-12	54	3.4420250-02	2.0625284-12
21	5.5168997-02	4.7734298-12	55	3.3432332-02	2.0431449-12
22	5.1711405-02	4.3639848-12	56	3.3582075-02	2.1000264-12
23	4.9180616-02	4.0415908-12	57	2.8373850-02	1.3634126-12
24	4.7352540-02	3.7892686-12	58	3.0897564-02	1.9697040-12
25	4.5970932-02	3.5642298-12	59	3.2102177-02	2.0869556-12
26	4.4933731-02	3.3861883-12	60	3.2696485-02	2.1570308-12
27	4.4233364-02	3.3078210-12	61	3.2999449-02	2.1957052-12
28	4.3518572-02	3.2011601-12	62	3.3253143-02	2.2180647-12
29	4.2940941-02	3.0993390-12	63	3.3635388-02	2.2366361-12
30	4.2447899-02	2.9980566-12	64	3.2636343-02	2.1030695-12
31	4.2122392-02	2.9398313-12	65	2.8919680-02	1.6920538-12
32	4.1712565-02	2.8231076-12	66	3.2789572-02	2.0226787-12
33	4.1408771-02	2.7708723-12	67	3.4050865-02	2.0178775-12
34	4.1378190-02	2.7693345-12	68	3.3526345-02	1.8352079-12

U02 - 2 WPC PU02 (8 APC PU240), 0.5 RODS, 0.75 SQ LATTICE

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GROUP	PHI(0,0) TERM	PHI(1,1) TERM	PHI(2,0) TERM	AGE
1	2.8532354-01	2.7730936+00	1.1055253+01	3.8746375+01
2	8.7089702-01	9.0873664+00	3.8415149+01	4.4109863+01
3	1.8288938+00	1.5720222+01	6.2428958+01	3.4134818+01
4	2.8033394+00	1.9722881+01	7.2195654+01	2.5753448+01
5	3.8652126+00	2.3993525+01	8.7190884+01	2.2557849+01
6	5.6511367+00	4.0951019+01	1.5794873+02	2.7949904+01
7	4.9168590+00	3.0209604+01	1.1525218+02	2.3440206+01
8	5.1444922+00	2.7603901+01	1.1669394+02	2.2683277+01
9	4.5083364+00	2.0707574+01	9.6244258+01	2.1348065+01
10	4.3575985+00	1.6791522+01	9.1902096+01	2.1090079+01
11	5.0746358+00	2.0825803+01	1.1834684+02	2.3321247+01
12	4.2224476+00	1.7143374+01	1.0248151+02	2.4270642+01
13	2.7980886+00	8.7366777+00	6.4462297+01	2.3037975+01
14	3.7086061+00	1.1658895+01	9.0340538+01	2.4359702+01
15	3.3095910+00	1.0070113+01	8.3233316+01	2.5149125+01
16	2.8847908+00	8.9263739+00	7.4353886+01	2.5774447+01
17	2.5583357+00	7.7461615+00	6.7116179+01	2.6234312+01
18	2.2960100+00	6.6432597+00	6.1040538+01	2.6585484+01
19	2.0326180+00	5.7240424+00	5.4650335+01	2.6886673+01
20	1.8143557+00	4.8855269+00	4.9212623+01	2.7124021+01
21	1.6640879+00	4.3194950+00	4.5550403+01	2.7372595+01
22	1.5597950+00	3.9489868+00	4.3108215+01	2.7637103+01
23	1.4834576+00	3.6572511+00	4.1379912+01	2.7894232+01
24	1.4283165+00	3.4289237+00	4.0198673+01	2.8144093+01
25	1.3866424+00	3.2252853+00	3.9351846+01	2.8379230+01
26	1.3553568+00	3.0641749+00	3.8775323+01	2.8608940+01
27	1.3342313+00	2.9932600+00	3.8500642+01	2.8856046+01
28	1.3126707+00	2.8967422+00	3.8213637+01	2.9111365+01
29	1.2952474+00	2.8046038+00	3.7995607+01	2.9334632+01
30	1.2803755+00	2.7129530+00	3.7832735+01	2.9548156+01
31	1.2705571+00	2.6602647+00	3.7821997+01	2.9768042+01
32	1.2581953+00	2.5546410+00	3.7701591+01	2.9964816+01
33	1.2490318+00	2.5073730+00	3.7687139+01	3.0173081+01
34	1.2481094+00	2.5059815+00	3.7937415+01	3.0395904+01
35	1.2416480+00	2.4451028+00	3.7992095+01	3.0598121+01
36	1.2344931+00	2.4155651+00	3.8029239+01	3.0805551+01
37	1.2295298+00	2.3108477+00	3.8094371+01	3.0982877+01
38	1.2229684+00	2.3499600+00	3.8161478+01	3.1203978+01
39	1.2134463+00	2.2934028+00	3.8097708+01	3.1396288+01
40	1.2095634+00	2.3837240+00	3.8268124+01	3.1637965+01

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U02 - 2 *PC PU02 (8 APC PU(240), 0.5 RQDS, 0.75 SQ LATTICE

GROUP	PHI(0,0) TERM	PHI(1,1) TERM	PHI(2,0) TERM	AGE
41	1.2058101+00	2.4026368+00	3.84233154+01	3.1865010+01
42	1.1671127+00	1.8137654+00	3.7183215+01	3.1859146+01
43	1.1931591+00	2.2227302+00	3.8383637+01	3.2169756+01
44	1.1487036+00	1.4171181+00	3.6841877+01	3.2072570+01
45	1.1923118+00	2.2520027+00	3.8759159+01	3.2507571+01
46	1.1010263+00	1.1630336+00	3.5578041+01	3.2313526+01
47	1.1737018+00	2.1993832+00	3.8501153+01	3.2803180+01
48	1.0962420+00	1.4152784+00	3.5879502+01	3.2729545+01
49	1.1365539+00	2.0989290+00	3.7645993+01	3.3122928+01
50	1.0817174+00	1.8555866+00	3.5961948+01	3.3245234+01
51	9.7713525-01	6.8182054+01	3.2187077+01	3.2940247+01
52	1.1237139+00	1.9551117+00	3.7631454+01	3.3488465+01
53	9.4820511-01	1.0589388+00	3.1628927+01	3.3356629+01
54	1.0382339+00	1.8663899+00	3.5083588+01	3.3791604+01
55	1.0084348+00	1.8488497+00	3.4285463+01	3.3998690+01
56	1.0129516+00	1.9003220+00	3.4658813+01	3.4215665+01
57	8.5585351-01	1.2337574+00	2.9202634+01	3.4121065+01
58	9.3197745-01	1.7823927+00	3.2147113+01	3.4493444+01
59	9.6831276-01	1.8884941+00	3.3652667+01	3.4753923+01
60	9.8623915-01	1.9519055+00	3.4514944+01	3.4996525+01
61	9.9537759-01	1.9869021+00	3.5068435+01	3.5231289+01
62	1.0030902+00	2.0071352+00	3.5571278+01	3.5461694+01
63	1.0145597+00	2.0239406+00	3.6211060+01	3.5691402+01
64	9.8442504-01	1.9030757+00	3.5299502+01	3.5857988+01
65	8.7231763-01	1.5311460+00	3.1309608+01	3.5892440+01
66	9.8904699-01	1.8303297+00	3.5803916+01	3.6200419+01
67	1.0270920+00	1.8259851+00	3.7395275+01	3.6408867+01
68	1.0112706+00	1.6606867+00	3.6946062+01	3.6534298+01

16:09:29

U02 - 2 WPC PU02 (8 APC PU240), 0.5 RODS, 0.75 SQ LATTICE

ONE-GROUP PARAMETERS FOR THE ENERGY RANGE 10 MEV TO 6.8256032-01 EV

SIGMA ABSORPTION	=	1.0808321-02	DIFFUSION COEFFICIENT	=	1.1625530+00
SIGMA CAPTURE	=	8.1367093-03	SIGMA TRANSPORT	=	2.8672527-01
SIGMA FISSION	=	2.6716117-03	P(0)-TRANSFER	=	2.2955924-02
NU-SIGMA FISSION	=	7.4188013-03	P(1)-TRANSFER	=	3.9142849-03
AVERAGE NU	=	2.7769011+00	INELASTIC TRANSFER	=	2.9179230-12
D/SIG(REMOVAL)	=	3.4431484+01	N-2N TRANSFER	=	0.0000000
NU*SIG(FISS)/SIG(ABS)	=	6.8639721-01	TOTAL SIGMA REMOVAL	=	3.3764244-02
SIG(OUT)/SIG(REMOVAL)	=	6.7988856-01	TOTAL SIGMA OUT	=	2.2955924-02

BROAD GROUP SUMS AND AVERAGE VELOCITIES

GROUP	FLUX	CURRENT	LEAKAGE*FLUX	SOURCE	VBAR/V(2200 M/SEC)
1	2.4912076+00	3.6971694-10	-2.4912077-10	9.9999429-01	3.2090817+03
2	1.2799793+00	7.7175605-11	-1.2799793-10	0.0000000	4.6425064+01
3	1.6123612-01	1.0272502-11	-1.6123612-11	0.0000000	7.0143725+00

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UO2 - 2 WPC PU02 (8 APC PU240), 0.5 RODS, 0.75 SQ LATTICE

MACROSCOPIC CROSS-SECTIONS

GROUP	ABSORPTION	CAPTURE	FISSION	NU*FISSION	NU	OUT	REMOVAL
1	3.0926759-03	1.4162147-03	1.6744612-03	4.7323076-03	2.261674+00	5.0204800-02	5.3297476-02
2	2.1552412-02	1.7434637-02	4.1177755-03	1.1318535-02	2.7487013+00	7.6141406-02	9.7693817-02
3	4.4727900-02	3.6130063-02	6.5978368-03	1.7968772-02	2.7234337+00	4.0040831-01	4.4513621-01
GROUP	FLUX WT	CURRENT WT	TOTAL P1 TRANSFER		TRANSPORT		DIFFUSION COEFFICIENT
			IN	OUT	STANDARD	CONSISTENT	
1	4.5991246-01	3.7714023-01	1.5253558-01	1.6402624-01	2.1311309-01	2.2460496-01	1.4840871+00
2	1.1190710+00	1.0674417+00	5.1459953-01	4.9023493-01	5.7720678-01	5.5284277-01	6.0294417-01
3	1.0471331+00	1.0440632+00	5.2086672-01	4.6455346-01	5.7950860-01	5.2319650-01	6.3710926-01
GROUP FROM TO	P(0) TRANSFER	P(1) TRANSFER	INELASTIC TRANSFER		N-2N TRANSFER	TOTAL TRANSFER	
1	1	3.9209392-01	1.5253558-01	1.4454472-02	6.6186355-05	4.0668117-01	
	2	5.0146844-02	1.1489898-02	4.8013347-05	1.6356801-05	5.0194889-02	
	3	7.1152185-06	3.4188682-07	1.1470525-11	0.0000000	7.1152299-06	
	4	2.8124946-06	4.2446423-07	4.6060020-12	0.0000000	2.8124993-06	
2	2	1.0213763+00	4.5955611-01	8.6029653-07	0.0000000	1.0213772+00	
	3	5.6058960-02	2.6932646-02	0.0000000	0.0000000	5.6058960-02	
	4	2.0082445-02	3.7461821-03	0.0000000	0.0000000	2.0082445-02	
3	3	6.0199087-01	3.1851391-01	0.0000000	0.0000000	6.0199087-01	
	4	4.0040831-01	1.4604069-01	0.0000000	0.0000000	4.0040831-01	

U02 - 2 *PC PU02 (8 APC PU240), 0.5 RODS, 0.75 SQ LATTICE

16:09:30

MICROSCOPIC CROSS-SECTIONS FOR 016 AL042966

ISOTOPE ID NUMBER = 4 NUCLEI DENSITY = 1.51620-02 ATOMS/BARN*CM

GROUP	ABSORPTION	C/PTURE	FISSION	NU*FISSION	NU	OUT	REMOVAL
1	4.2247915-03	4.2247915-03	0.0000000	0.0000000	0.0000000	3.1200346-02	3.5425137-02
2	3.1983884-06	3.1983884-06	0.0000000	0.0000000	0.0000000	4.6161383-02	4.6164582-02
3	2.5377303-05	2.5377303-05	0.0000000	0.0000000	0.0000000	3.6411928-01	3.6414466-01

GROUP	FLUX WT	TOTAL	CURRENT	WT	TOTAL P1	TRANSFER	OUT	STANDARD	TRANSPORT	CONSISTENT
1	3.1668333+00	2.7476117+00	2.9544411-01	2.9065374-01	2.4569540+00	2.4521676+00				
2	3.6922995+00	3.6410719+00	1.4775100-01	1.5517638-01	3.5358956+00	3.5433210+00				
3	3.7000250+00	3.7000249+00	1.4635545-01	1.5555182-01	3.5444731+00	3.5536695+00				

GROUP	FROM	TO	P(0)	TRANSFER	P(1)	TRANSFER	INELASTIC	TRANSFER	N-2N	TRANSFER	TOTAL	TRANSFER
1	1	1	3.1294803+00	2.9544411-01	2.9544411-01	1.9277964-03	0.0000000	0.0000000	0.0000000	3.1314082+00		
	2	2	3.1197989-02	-4.7903769-03	2.356340A-06	0.0000000	0.0000000	0.0000000	0.0000000	3.1200346-02		
	3	3	0.0000000	0.0000000	3.4214839-10	0.0000000	0.0000000	0.0000000	0.0000000	3.4214839-10		
	4	4	0.0000000	0.0000000	1.3739007-10	0.0000000	0.0000000	0.0000000	0.0000000	1.3739007-10		
2	2	2	3.6461349+00	1.7069975-01	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	3.6461349+00		
	3	3	4.6161383-02	-1.5523367-02	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	4.6161383-02		
	4	4	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000		
3	3	3	3.3358804+00	2.6297993-01	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	3.3358804+00		
	4	4	3.6411928-01	-1.0742811-01	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	3.6411928-01		

U02 - 2 WPC PU02 (8 APC PU240), 0.5 RODS, 0.75 SQ LATTICE

16:09:30

MICROSCOPIC CROSS-SECTIONS FOR H2O W/UPSCAT A 012469

ISOTOPE ID NUMBER = 5 NUCLEI DENSITY = 1.83630-02 ATOMS/BARN*CM

GROUP	ABSORPTION	CAPTURE	FISSION	NU*FISSION	NU	OUT	REMOVAL
1	4.4318410-03	4.4318410-03	0.0000000	0.0000000	0.0000000	2.7003004+00	2.7047322+00
2	1.4306842-02	1.4306842-02	0.0000000	0.0000000	0.0000000	4.1026741+00	4.1169809+00
3	9.4694941-02	9.4694941-02	0.0000000	0.0000000	0.0000000	2.1455853+01	2.1550548+01

GROUP	FLUX WT	TOTAL CURRENT WT	TOTAL P1 TRANSFER IN	OUT	STANDARD	TRANSPORT CONSISTENT
1	1.7223344+01	1.3482392+01	6.8225270+00	7.4530406+00	6.0293509+00	6.6598646+00
2	4.3625620+01	4.3662473+01	2.7865774+01	2.6531073+01	1.7031400+01	1.5696699+01
3	4.6490003+01	4.6462823+01	2.8223775+01	2.5149636+01	2.1313187+01	1.8239049+01

GROUP FROM	TO	P(0) TRANSFER	P(1) TRANSFER	INELASTIC TRANSFER	N-2N TRANSFER	TOTAL TRANSFER
1	1	1.4516684+01	6.8225270+00	1.9277964-03	0.0000000	1.4518612+01
	2	2.6997574+00	6.3047195-01	2.3563408-06	0.0000000	2.6997598+00
	3	3.8747583-04	1.8618245-05	3.4214839-10	0.0000000	3.8747617-04
	4	1.5316096-04	2.3115190-05	1.3739007-10	0.0000000	1.5316109-04
2	2	3.9508639+01	2.4845439+01	0.0000000	0.0000000	3.9508639+01
	3	3.0090376+00	1.4816266+00	0.0000000	0.0000000	3.0090376+00
	4	1.0936365+00	2.0400709-01	0.0000000	0.0000000	1.0936365+00
3	3	2.4939455+01	1.7091890+01	0.0000000	0.0000000	2.4939455+01
	4	2.1455853+01	8.0577459+00	0.0000000	0.0000000	2.1455853+01

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U02 - 2 WPC PU02 (8 APC PU(240), 0.5 RDS, 0.75 SQ LATTICE

16:09:30

MICROSCOPIC CROSS-SECTIONS FOR ZIRCONIUM 0103

ISOTOPE ID NUMBER = 10 NUCLEI DENSITY = 3.86440-03 ATOMS/BARN*CM

GROUP	ABSORPTION	CAPTURE	FISSION	NU*FISSION	NU	OUT	REMOVAL
1	1.1008631-04	1.1008631-04	0.0000000	0.0000000	0.0000000	8.9997610-03	9.1098473-03
2	1.2627333-01	1.2627333-01	0.0000000	0.0000000	0.0000000	1.3993622-02	1.4026695-01
3	4.1014696-02	4.1014696-02	0.0000000	0.0000000	0.0000000	1.1042861-01	1.5144331-01

GROUP	FLUX WT	TOTAL CURRENT WT	TOTAL P1 TRANSFER IN	OUT	STANDARD	TRANSPORT CONSISTENT
1	6.6350202+00	6.0016376+00	1.3112474+00	1.3097698+00	4.6918678+00	4.6903902+00
2	6.9138817+00	6.9498552+00	4.8381471-02	5.0381215-02	6.8994741+00	6.9014739+00
3	6.2217186+00	6.2214090+00	4.2460544-02	4.5577914-02	6.1758311+00	6.1789485+00

GROUP FROM TO	P(0) TRANSFER	P(1) TRANSFER	INELASTIC TRANSFER	N-2N TRANSFER	TOTAL TRANSFER
1 1	6.2098002+00	1.3112474+00	4.1607060-01	3.9593840-03	6.6259500+00
1 2	8.9026380-03	-1.4775835-03	9.7120415-05	2.6296481-09	8.9997637-03
1 3	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
1 4	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
2 2	6.7736147+00	5.5459971-02	0.0000000	0.0000000	6.7736147+00
2 3	1.3993622-02	-5.0787566-03	0.0000000	0.0000000	1.3993622-02
2 4	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
3 3	6.0702752+00	8.0616400-02	0.0000000	0.0000000	6.0702752+00
3 4	1.1042861-01	-3.5038487-02	0.0000000	0.0000000	1.1042861-01

16:09:30

UO2 - 2 WPC PU02 (8 APC PU240), 0.5 RODS, 0.75 SQ LATTICE

MICROSCOPIC CROSS-SECTIONS FOR U235(W)* C 013169

ISOTOPE ID NUMBER = 12 NUCLEI DENSITY = 5.41750-05 ATOMS/BARN*CM

GROUP	ABSORPTION	CAPTURE	FISSION	NU*FISSION	NU	OUT	REMOVAL
1	1.7286221+00	2.5658591-01	1.4700362+00	3.7540335+00	2.537015+00	1.0673454-02	1.7372956+00
2	3.4168927+01	1.2498195+01	2.1270731+01	5.1687873+01	2.4299999+00	1.0325857-02	3.4179252+01
3	5.1012491+01	1.0203670+01	4.0802821+01	9.9165431+01	2.4299999+00	9.6248480-02	5.1108739+01

GROUP	FLUX WT	TOTAL CURRENT WT	IN	TOTAL P1 TRANSFER	OUT	STANDARD	TRANSPORT CONSISTENT
1	6.9030858+00	8.2274475+00	2.1367768+00	2.1358221+00	6.0916255+00	6.0906707+00	
2	4.5856666+01	4.3128172+01	3.5530519-02	3.6050183-02	4.3092123+01	4.3092642+01	
3	6.4077701+01	6.3071876+01	3.7533102-02	3.7376438-02	6.3034449+01	6.3034344+01	

GROUP FROM TO	P(0) TRANSFER	P(1) TRANSFER	INELASTIC TRANSFER	N-2N TRANSFER	TOTAL TRANSFER
1 1	6.0615084+00	2.1367768+00	1.0983925+00	5.8894159-03	7.1716797+00
1 2	6.5341635-03	-9.5476411-04	4.1381720-03	1.1187471-06	1.0674573-02
1 3	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
1 4	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
2 1	1.1677414+01	4.0104406-02	0.0000000	0.0000000	1.1677414+01
2 2	1.0325857-02	-4.0542236-03	0.0000000	0.0000000	1.0325857-02
2 3	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
2 4	1.2968963+01	6.7991810-02	0.0000000	0.0000000	1.2968963+01
3 1	9.6248480-02	-3.0615373-02	0.0000000	0.0000000	9.6248480-02

UO2 - 2 WPC PU02 (8 APC PU240), 0.5 RODS, 0.75 SQ LATTICE

16:09:31

MICROSCOPIC CROSS-SECTIONS FOR U238* C 010968

ISOTOPE ID NUMBER = 13 NUCLEI DENSITY = 7.37600-03 ATOMS/BARN*CM

GROUP	ABSORPTION	CAPTURE	FISSION	NU*FISSION	NU	OUT	REMOVAL
1	3.4743465-01	1.6715141-01	1.8028323-01	5.0480551-01	2.8000662+00	1.4569065-02	3.6200371-01
2	1.8909910+00	1.8909910+00	0.0000000	0.0000000	0.0000000	6.5153267-03	1.8975063+00
3	4.1406543-01	4.1406543-01	0.0000000	0.0000000	0.0000000	6.1042020-02	4.7510745-01

GROUP	FLUX WT	TOTAL CURRENT W1	TOTAL P1 TRANSFER IN	OUT	STANDARD	TRANSPORT CONSISTENT
1	9.2294725+00	8.5341313+00	2.3385514+00	2.3373444+00	6.1967870+00	6.1955800+00
2	3.0600842+01	2.3812601+01	6.3091639-02	6.6333823-02	2.3746267+01	2.3749509+01
3	8.6897889+00	8.6875775+00	2.5681484-02	2.3869331-02	8.8437082+00	8.8418961+00

GROUP FROM TO	P(0) TRANSFER	P(1) TRANSFER	INELASTIC TRANSFER	N-2N TRANSFER	TOTAL TRANSFER
1 1	7.1521109+00	2.3385514+00	1.7066352+00	8.7228399-03	8.8761916+00
1 2	8.4486710-03	-1.2070520-03	6.1182254-03	2.1684328-06	1.4571233-02
1 3	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
1 4	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
2 2	2.8703336+01	6.8874133-02	0.0000000	0.0000000	2.8703336+01
2 3	6.5153267-03	-2.5403116-03	0.0000000	0.0000000	6.5153267-03
2 4	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
3 3	8.4146815+00	4.4766423-02	0.0000000	0.0000000	8.4146815+00
3 4	6.1042020-02	-2.0897092-02	0.0000000	0.0000000	6.1042020-02

U02 - 2 WPC PU02 (8 APC PU240), 0.5 RODS, 0.75 SQ LATTICE

16:09:31

MICROSCOPIC CROSS-SECTIONS FOR PU239(W)* CR0620F7

ISOTOPE ID NUMBER = 14 NUCLEI DENSITY = 1.38070-04 ATOMS/BARN*CM

GROUP	ABSORPTION	CAPTURE	FISSION	NU*FISSION	NU	OUT	REMOVAL
1	1.9897047+00	1.5867621-01	1.8300285+00	5.5576222+00	3.0369047+00	2.2894430-02	2.0125991+00
2	3.4389347+01	1.3260720+01	2.1120627+01	6.0660765+01	2.0710225+00	9.1117478-03	3.4398458+01
3	4.0544901+01	8.9389577+00	3.1605944+01	9.0740662+01	2.8709999+00	7.5296365-02	4.0620197+01

GROUP	FLUX WT	TOTAL CURRENT WT	IN	OUT	STANDARD	TRANSPORT	CONSISTENT
1	9.4629172+00	8.7506773+00	2.2694276+00	2.2683714+00	6.4823059+00	6.4812497+00	
2	4.6927387+01	4.4628958+01	3.5881185-02	3.7639015-02	4.4591320+01	4.4593078+01	
3	5.1174855+01	5.0404280+01	2.9031831-02	2.9879308-02	5.0374401+01	5.0375248+01	

GROUP FROM TO	P(0) TRANSFER	P(1) TRANSFER	INELASTIC TRANSFER	N-2N TRANSFER	TOTAL TRANSFER
1	6.5554757+00	2.2694276+00	8.8531580-01	9.5264802-03	7.4598445+00
2	7.2198200-03	-1.0561384-03	1.5672582-02	2.0286778-06	2.2896459-02
3	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
4	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
2	1.2522697+01	4.0940715-02	6.2308728-03	0.0000000	1.2528928+01
3	9.1117478-03	-3.3016996-03	0.0000000	0.0000000	9.1117478-03
4	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
3	1.0554658+01	5.3836951-02	0.0000000	0.0000000	1.0554658+01
4	7.5296365-02	-2.3957642-02	0.0000000	0.0000000	7.5296365-02

U02 - 2 WPC PU02 (8 APC PU240), 0.5 RQDS, 0.75 SQ LATTICE

16:09:31

MICROSCOPIC CROSS-SECTIONS FOR PU240* CR062068

ISOTOPE ID NUMBER = 15 NUCLEI DENSITY = 1.14800E-05 ATOMS/BARN*CM

GROUP	Absorption	Capture	Fission	NU*FISSION	NU	OUT	REMOVAL
1	1.1599321+00	2.8851083-01	8.7142130-01	2.6834677+00	3.0794148+00	1.1832718-02	1.1717648+00
2	1.6672914+01	1.6566648+01	1.0626574-01	2.9756026-01	2.0001524+00	1.2502907-02	1.6685417+01
3	2.7345749+03	2.7341009+03	4.7395199-01	1.3270655+00	2.7999999+00	8.9260644-02	2.7346641+03

GROUP	FLUX WT	TOTAL CURRENT WT	TOTAL P1 TRANSFER IN	OUT	STANDARD	TRANSPORT CONSISTENT
1	9.4750521+00	8.7572806+00	2.3799636+00	2.3795752+00	6.3793055+00	6.3779171+00
2	4.5730225+01	4.1027131+01	7.7075424-02	7.9140820-02	4.0947990+01	4.0950056+01
3	3.2361661+03	3.0406382+03	1.2998282+00	1.3055563+00	3.0393326+03	3.0393384+03

GROUP FROM TO	P(0) TRANSFER	P(1) TRANSFER	INELASTIC TRANSFER	N-2N TRANSFER	TOTAL TRANSFER
1 1	7.2691086+00	2.3799636+00	1.0294292+00	4.7496188-03	8.3080369+00
1 2	8.2166072-03	-1.3884092-03	3.6151913-03	9.1988541-07	1.1833638-02
1 3	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
1 4	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
2 2	2.9044809+01	8.3726728-02	0.0000000	0.0000000	2.9044809+01
2 3	1.2502907-02	-4.5859086-03	0.0000000	0.0000000	1.2502907-02
2 4	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
3 3	5.0150195+02	1.3342814+00	0.0000000	0.0000000	5.0150195+02
3 4	8.9260644-02	-2.8725090-02	0.0000000	0.0000000	8.9260644-02

UO2 - 2 WPC PU02 (8 APC PU240), 0.5 RODS, 0.75 SQ LATTICE

16:09:31

MICROSCOPIC CROSS-SECTIONS FOR PU241(W)* CR081966

ISOTOPE ID NUMBER = 16 NUCLEI DENSITY = 1.04610-06 ATOMS/BARN*CM

GROUP	ABSORPTION	CAPTURE	FISSION	NU*FISSION	NU	OUT	REMOVAL
1	2.4424673+00	1.7573791-01	2.2686604+00	7.0059096+00	3.0881141+00	7.4437140-03	2.4499109+00
2	5.9822939+01	1.4094434+01	4.4913506+01	1.3334822+02	2.9690005+00	8.4898267-03	5.9831429+01
3	2.0399550+01	3.4359892+00	1.6963560+01	5.0364808+01	2.9690000+00	9.0792795-02	2.0490342+01

GROUP	FLUX WT	TOTAL		TOTAL P1		TRANSPORT	
		CURRENT	WT	IN	OUT	STANDARD	CONSISTENT
1	9.6324785+00	8.6786675+00	1.1952228+00	1.1945697+00	7.4840977+00	7.4834447+00	
2	6.9253480+01	6.8290617+01	3.8248864-02	3.8231880-02	6.8252385+01	6.8252368+01	
3	3.3168839+01	3.2977718+01	4.1577064-02	3.5658456-02	3.2942060+01	3.2936141+01	

GROUP FROM TO	P(0)		P(1)		INELASTIC		N-2N		TOTAL	
	TRANSFER		TRANSFER		TRANSFER		TRANSFER		TRANSFER	
1	1	6.5289206+00	1.1952228+00	6.4909761-01	4.5493286-03	7.1871168+00				
	2	6.0919407-03	-6.5311798-04	1.3508105-03	9.6285555-07	7.4446768-03				
	3	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000				
	4	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000				
2	2	9.4220513+00	4.1377687-02	0.0000000	0.0000000	9.4220513+00				
	3	8.4898267-03	-3.1458069-03	0.0000000	0.0000000	8.4898267-03				
	4	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000				
	3	1.2678497+01	6.5210988-02	0.0000000	0.0000000	1.2678497+01				
	4	9.0792795-02	-2.9552533-02	0.0000000	0.0000000	9.0792795-02				

16:09:32

UO2 - 2 WPC PU02 (6 APC PU2+U), 0.5 RODS, 0.75 SQ LATTICE

MICROSCOPIC CROSS-SECTIONS FOR PU242 C 052869

ISOTOPE ID NUMBER = 17 NUCLEI DENSITY = 4.46490-09 ATOMS/BARN*CM

GROUP	ABSORPTION	CAPTURE	FISSION	NU*FISSION	NU	OUT	REMOVAL
1	1.1468970+00	2.9451084-01	8.6038617-01	2.6594184+00	3.0909590+00	1.1782935-02	1.1606799+00
2	1.1270153+02	1.1261263+02	8.8902274-02	2.4965474-01	2.8980034+00	2.7551877-01	1.1297705+02
3	2.1104933+01	2.1088319+01	1.6613762-02	4.6651442-02	2.8079999+00	4.2104191-02	2.1147037+01

GROUP	FLUX WT	TOTAL CURRENT WT	TOTAL P1 TRANSFER		TRANSPORT	
			IN	OUT	STANDARD	CONSISTENT
1	9.4640092+00	5.7520505+00	2.3805349+00	2.3792735+00	6.3727772+00	6.3715160+00
2	1.4232060+02	1.5383013+02	1.8638919-01	8.7913863-02	1.5374222+02	1.5364374+02
3	2.5148755+01	2.5695983+01	-7.6020029-01	1.1009360-02	2.5684974+01	2.6456184+01

GROUP FROM TO	P(0)		P(1)		INELASTIC		N-2N		TOTAL	
	TRANSFER	TRANSFER	TRANSFER	TRANSFER	TRANSFER	TRANSFER	TRANSFER	TRANSFER	TRANSFER	TRANSFER
1	1	7.2691686+00	2.3805349+00	1.0294111+00	4.7496109-03	8.3080788+00				
	2	8.1486665-03	-1.2612763-03	3.6333411-03	9.2751285-07	1.1783863-02				
	3	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000				
	4	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000				
2	2	2.9343544+01	1.9243145-01	0.0000000	0.0000000	2.9343544+01				
	3	2.7551877-01	-1.0451759-01	0.0000000	0.0000000	2.7551877-01				
3	4	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000				
	3	4.0017185+00	2.5022986-02	0.0000000	0.0000000	4.0017185+00				
4	4	4.2104191-02	-1.4013625-02	0.0000000	0.0000000	4.2104191-02				

END OF RUN

APPENDIX A

DERIVATION OF EQUATIONS

APPENDIX A

DERIVATION OF EQUATIONSTHE REFERENCE EQUATION

The steady-state Boltzmann transport equation can be written in a familiar form as

$$\begin{aligned} & \bar{\Omega} \cdot \nabla f(\bar{r}, E, \bar{\Omega}) + \Sigma_t(\bar{r}, E) f(\bar{r}, E, \bar{\Omega}) \\ &= \int dE' d\bar{\Omega}' \Sigma_s(\bar{r}; E'; \bar{\Omega}' \rightarrow E, \bar{\Omega}) f(\bar{r}, E', \bar{\Omega}') + \frac{S(\bar{r}, E)}{4\pi} \end{aligned} \quad (A-1)$$

where $f(\bar{r}, E, \bar{\Omega})$ is the angular flux and the source is assumed to be isotropic. The purpose of HRG is to find the energy dependence of $f(\bar{r}, E, \bar{\Omega})$ in the epithermal energy region to sufficient accuracy that adequate energy averages of the cross sections can be made for use in spatial multigroup calculations. In finding this energy dependence, (A-1) must be converted into a form in which the spatial dependence is suppressed. This is done in various ways, all of which involve multiplying (A-1) by a factor which may or may not depend on $\bar{r}$ and integrating over spatial coordinates. The resulting energy dependent function represents some sort of spatial average of the angular flux and the equation can be interpreted as describing the energy dependence of the "real" system given by (A-1) homogenized in some way.

The spherical harmonics form of (A-1) shows that the coupling between the harmonics components occurs only through the first, or "streaming" term of (A-1). For the reactor systems studied most usually, and the ones for which HRG was developed, the geometrical dependence of the streaming term has only a small influence on the spectrum. Therefore, it is reasonable to assume the simplest geometry which exhibits an effect, i.e., slab geometry, to account for the streaming. We will assume slab geometry in further derivations from (A-1).

This should be recognized as a convenience only in evaluating the first term. The other terms have no essential complications resulting from geometries other than slab.

Taking the z direction as the spatial variable, (A-1) becomes

$$\begin{aligned} & \mu \frac{d}{dz} f(z, E, \bar{\Omega}) + \Sigma_t(z, E) f(z, E, \bar{\Omega}) \\ &= \int dE' d\bar{\Omega}' \Sigma_s(z; E', \bar{\Omega}' \rightarrow E, \bar{\Omega}) f(z, E, \bar{\Omega}') + \frac{S(z, E)}{4\pi}. \end{aligned} \quad (A-2)$$

Let us now introduce into (A-2) the expansions

$$\Sigma_s(z; E', \bar{\Omega}' \rightarrow E, \bar{\Omega}) = \sum_{\ell=0}^{\infty} \frac{2\ell+1}{4\pi} \Sigma_{s\ell}(z, E' \rightarrow E) P_{\ell}(\mu_L) \quad (A-3)$$

and

$$f(z, E, \bar{\Omega}) = \sum_{\ell=0}^{\infty} \frac{2\ell+1}{4\pi} \psi_{\ell}(z, E) P_{\ell}(\mu) \quad (A-4)$$

where $\mu_L = \bar{\Omega}' \cdot \bar{\Omega}$ is the cosine of the scattering angle in laboratory coordinates and $\mu = \bar{\Omega} \cdot \bar{k}$ is the cosine of the angle between the direction $\bar{\Omega}$ and the positive z direction given by the unit vector $\bar{k}$. Although we write (A-3) in terms of macroscopic cross sections, we recognize it as a shorthand notation of separate expansions for the microscopic cross section of each component isotope and that inelastic and n_2n , as well as elastic, scattering processes are included. When (A-3) and (A-4) are put in (A-2), the result can be written as

$$\begin{aligned} & \sum_{\ell=0}^{\infty} \frac{2\ell+1}{4\pi} P_{\ell}(\mu) \left[\mu \frac{\partial}{\partial z} \psi_{\ell}(z, E) + \Sigma_t(z, E) \psi_{\ell}(z, E) \right] \\ &= \sum_{\ell=0}^{\infty} \frac{2\ell+1}{4\pi} P_{\ell}(\mu) \left[\int dE' \Sigma_{s\ell}(z, E' \rightarrow E) \psi_{\ell}(z, E') + S(z, E) \delta_{\ell 0} \right]. \end{aligned} \quad (A-5)$$

In obtaining (A-5), we have used the relationship among the Legendre polynomials in μ_L , μ , and $\mu' = \bar{\Omega}' \cdot \bar{k}$ that gives

$$\int d\bar{\Omega}' P_\ell(\mu_L) P_\ell(\mu') = \frac{4\pi}{2\ell+1} P_\ell(\mu) \delta_{\ell\ell'}.$$

Equation (A-5) becomes our reference form of the Boltzmann transport equation.

THE P_1 EQUATIONS

We now multiply (A-5) by $P_m(\mu)$ and integrate over $\bar{\Omega}$ to obtain

$$\begin{aligned} \frac{m+1}{2m+1} \frac{\partial}{\partial z} \psi_{m+1}(z, E) + \frac{m}{2m+1} \frac{\partial}{\partial z} \psi_{m-1}(z, E) + \Sigma_t(z, E) \psi_m(z, E) \\ = \int dE' \Sigma_{sm}(z, E' \rightarrow E) \psi_m(z, E') + S(z, E) \delta_{m,0} \quad m=0,1,\dots \end{aligned} \quad (A-6)$$

Let $m = 0, 1$ in (A-5). The resulting equations are

$$\frac{\partial}{\partial z} \psi_1(z, E) + \Sigma_t(z, E) \psi_0(z, E) = \int dE' \Sigma_{s0}(z, E' \rightarrow E) \psi_0(z, E') + S(z, E) \quad (A-7)$$

$$\frac{2}{3} \frac{\partial}{\partial z} \psi_2(z, E) + \frac{1}{3} \frac{\partial}{\partial z} \psi_0(z, E) + \Sigma_t(z, E) \psi_1(z, E) = \int dE' \Sigma_{s1}(z, E' \rightarrow E) \psi_1(z, E'). \quad (A-8)$$

If we make the further assumption that $\frac{\partial}{\partial z} \psi_2(z, E) = 0$, Equations (A-7) and (A-8) are the P_1 equations in slab geometry. To get the equations used in HRG, we must proceed further. We differentiate (A-8), making the usual assumption that the cross sections are independent of position within a region, to get

$$\frac{1}{3} \frac{\partial^2}{\partial z^2} \psi_0(z, E) + \Sigma_t(z, E) \frac{\partial}{\partial z} \psi_1(z, E) = \int dE' \Sigma_{s1}(z, E' \rightarrow E) \frac{\partial}{\partial z} \psi_1(z, E'). \quad (A-9)$$

Integrating (A-7) and (A-9) over z , we obtain

$$J(E) + \Sigma_t(E) \phi(E) = \int dE' \Sigma_{s0}(E' \rightarrow E) \phi(E') + S(E) \quad (A-10)$$

$$\frac{1}{3} \mathcal{L}(E) \phi(E) + \Sigma'_t(E) J(E) = \int dE' \Sigma_{s1}(E' \rightarrow E) J(E') \quad (A-11)$$

where

$$\phi(E) = \int dz \psi_0(z, E)$$

$$J(E) = \int dz \frac{\partial}{\partial z} \psi_1(z, E)$$

$$\Sigma_t(E) = \int dz \Sigma_t(z, E) \psi_0(z, E) / \phi(E)$$

$$\Sigma'_t(E) = \int dz \Sigma_t(z, E) \frac{\partial}{\partial z} \psi_1(z, E) / J(E)$$

$$\Sigma_{s0}(E' \rightarrow E) = \int dz \Sigma_{s0}(z, E' \rightarrow E) \psi_0(z, E') / \phi(E')$$

$$\Sigma_{s1}(E' \rightarrow E) = \int dz \Sigma_{s1}(z, E' \rightarrow E) \frac{\partial}{\partial z} \psi_1(z, E') / J(E')$$

$$\mathcal{L}(E) = \int dz \frac{\partial^2}{\partial z^2} \psi_0(z, E) / \phi(E)$$

$$S(E) = \int dz S(z, E)$$

Note that $\Sigma_t(E)$ and $\Sigma'_t(E)$ may be different because they are averages of $\Sigma_t(z, E)$ using different spatial weightings.

HRG neglects this difference. To get the actual equations solved by HRG, Equations (A-10) and (A-11) are converted to a discrete set of multigroup equations by integrating over the energies of each HRG fine group. The results can be written

$$J_n + \Sigma_{t,n} \phi_n = \sum_{n'} \Sigma_{s0}(n' \rightarrow n) \phi_{n'} + S_n \quad (A-12)$$

$$\frac{1}{3} L_n \phi_n + \Sigma'_{t,n} J_n = \sum_{n'} \Sigma_{s1}(n' \rightarrow n) J_{n'} \quad (A-13)$$

where the definitions of the quantities follow obviously from (A-10) and (A-11). Again note that $\Sigma_{t,n}$ and $\Sigma'_{t,n}$ may differ because of different energy weighting, even though the spatial weightings of $\Sigma_t(E)$ and $\Sigma'_t(E)$ are equal. HRG also neglects this possible difference. Further note that, although (A-12) and (A-13) were obtained from a slab geometry form of (A-1), a more general derivation yields the same equations.

THE B_1 EQUATIONS

To obtain the B_1 equations we multiply our reference Equation (A-5), by e^{ikz} and integrate over all z . The resulting Fourier transformed equation is

$$\begin{aligned} & \sum_{\ell=0}^{\infty} \frac{2\ell+1}{4\pi} P_{\ell}(\mu) \left[-ik_{\mu} \bar{\psi}_{\ell}(k, E) + \Sigma_{t\ell}(k, E) \bar{\psi}_{\ell}(k, E) \right] \\ &= \sum_{\ell=0}^{\infty} \frac{2\ell+1}{4\pi} P_{\ell}(\mu) \left[\int dE' \Sigma_{s\ell}(k, E' \rightarrow E) \bar{\psi}_{\ell}(k, E') + \bar{S}(k, E) \delta_{\ell 0} \right] \end{aligned} \quad (A-14)$$

$$\begin{aligned}
\text{where } \bar{\psi}_\ell(k, E) &= \int_{-\infty}^{\infty} e^{ikz} \psi_\ell(z, E) dz \\
\bar{S}(k, E) &= \int_{-\infty}^{\infty} e^{ikz} S(z, E) dz \\
\Sigma_{t\ell}(k, E) &= \int_{-\infty}^{\infty} e^{ikz} \Sigma_t(z, E) \psi_\ell(z, E) dz / \bar{\psi}_\ell(k, E) \\
\Sigma_{s\ell}(k, E \rightarrow E) &= \int_{-\infty}^{\infty} e^{ikz} \Sigma_{s\ell}(z, E \rightarrow E) \psi_\ell(z, E) dz / \bar{\psi}_\ell(k, E).
\end{aligned}$$

Other arguments show that $k = B$, the square root of the geometrical buckling. We have also assumed that $\psi_\ell(k, z) \rightarrow 0$ as $z \rightarrow \pm\infty$ for all ℓ and E .

To obtain (A-14) we have assumed that the quantities in (A-5) are known throughout all space. This assumption, plus the energy independence of k , places restrictions on the system to which (A-14) can be applied: the system must be equivalent to a bare, homogeneous reactor with an extrapolation length independent of energy. We can thus interpret the cross sections in (A-5) as being homogenized before the Fourier transformation. The cross sections in (A-14) are therefore the same as those in (A-5); specifically, $\Sigma_{t\ell}(k, E) = \Sigma_t(E)$ and does not in fact depend on either k or ℓ , as its formal definition implies.

We now divide (A-14) by $\Sigma_t(k, E) - ik\mu$ before we multiply by $P_m(\mu)$ and integrate over $\bar{\Omega}$, obtaining

$$\Sigma_t(E) \bar{\psi}_m(k, E) = \sum_{\ell=0}^{\infty} (2\ell+1) A_{\ell m}(\nu) \left[\int dE' \Sigma_{s\ell}(E' \rightarrow E) \bar{\psi}_\ell(k, E') + \bar{S}(k, E) \delta_{\ell 0} \right] \quad (A-15)$$

m=0,1,-----

where

$$A_{\ell m}(\nu) = \frac{\nu}{2} \int_{-1}^1 \frac{P_{\ell}(\mu) P_m(\mu)}{\nu - \mu} d\mu$$

$$\nu = \frac{\Sigma_t(E)}{ik}$$

$A_{\ell m}(\nu)$ can be evaluated analytically; the result is

$$A_{\ell m}(\nu) = \nu P_j(\nu) Q_n(\nu) \quad j = \min(\ell, m) \quad n = \max(\ell, m) \quad (A-16)$$

where $Q_n(\nu)$ is the n th order Legendre function of the second kind, and

$$Q_0(\nu) = \frac{1}{2} \log \frac{\nu+1}{\nu-1} \quad Q_1(\nu) = \frac{1}{2} \nu \log \frac{\nu+1}{\nu-1} - 1$$

The B_L equations are obtained from (A-15) by assuming that $\Sigma_{s\ell}(E' \rightarrow E) = 0$ for $\ell > L$. This assumption truncates the infinite series in (A-15) at $\ell = L$, but places no restriction on m . The first $L+1$ equations of (A-15) couple the $\bar{\psi}_m(k, E)$ for $m = 0, \dots, L$ and can be solved for these $\bar{\psi}_m(k, E)$. The remaining equations of (A-15) express $\bar{\psi}_m(k, E)$ for $m > L$ in terms of the $\bar{\psi}_m(k, E)$ for $m \leq L$. To get the B_1 equations, we set $L = 1$. Let us write only the $m = 0, 1$ equations of (A-15)

$$\Sigma_t(E) \bar{\psi}_0(k, E) = A_{00}(\nu) W_0(k, E) + 3A_{10}(\nu) W_1(k, E) \quad (A-17)$$

$$\Sigma_t(E) \bar{\psi}_1(k, E) = A_{01}(\nu) W_0(k, E) + 3A_{11}(\nu) W_1(k, E) \quad (A-18)$$

where

$$W_0(k, E) = \int dE' \Sigma_{s0}(E' \rightarrow E) \bar{\psi}_0(k, E') + \bar{S}(k, E)$$

$$W_1(k, E) = \int dE' \Sigma_{s1}(E' \rightarrow E) \bar{\psi}_1(k, E')$$

and where, from (16)

$$A_{01} = A_{10} = v(A_{00}-1)$$

$$A_{11} = vA_{01} = v^2(A_{00}-1).$$

By alternately eliminating W_0 and W_1 between (A-17) and (A-18), we can write

$$-\frac{\Sigma_t(E)}{v} \bar{\psi}_1(k,E) + \Sigma_t(E) \bar{\psi}_0(k,E) = W_0(k,E) \quad (A-19)$$

$$-\frac{\Sigma_t(E)}{3v} \bar{\psi}_0(k,E) + \frac{A_{00}(v)}{3v^2(A_{00}(v)-1)} \Sigma_t(E) \bar{\psi}_1(k,E) = W_1(k,E). \quad (A-20)$$

Since v is a pure imaginary quantity,

$$A_{00}(v) = Q_0(v) = \frac{\tan^{-1} x}{x} \quad x = \frac{k}{\Sigma_t(E)}. \quad (A-21)$$

If we let (A-22)

$$\alpha(E) = \frac{x^2 A_{00}}{3(1-A_{00})}$$

$$\phi(E) = \bar{\psi}_0(k,E)$$

$$J(E) = i\bar{\psi}_1(k,E)$$

$$S(E) = \bar{S}(k,E)$$

we can write (A-19) and (A-20) as

$$k J(E) + \Sigma_t(E) \phi(E) = \int dE' \Sigma_{s0}(E' \rightarrow E) \phi(E') + S(E) \quad (A-23)$$

$$-\frac{1}{3}k\phi(E) + \alpha(E) \Sigma_t(E)J(E) = \int dE' \Sigma_{s1}(E' \rightarrow E) J(E') \quad (A-24)$$

which are in a form analogous to the P_1 Equations (A-10) and (A-11).

In further analogy with the derivation of the P_1 equations, we can write the B_1 equations in HRG fine group form as

$$k J_n + \Sigma_{t,n} \phi_n = \sum_{n' \leq n} \Sigma_{s0}(n' \rightarrow n) \phi_{n'} + S_n \quad (A-25)$$

$$-\frac{k}{3} \phi_n + \alpha_n \Sigma_{t,n} J_n = \sum_{n' \leq n} \Sigma_{s1}(n' \rightarrow n) J_{n'} \quad (A-26)$$

As in the definitions of the P_1 parameters, possible differences in $\Sigma_{t,n}$ due to its different energy weightings in (A-25) and (A-26) are neglected. In addition, we assume that α_n is evaluated from the fine group equivalent of (A-22) rather than being weighted by $\Sigma_t(E)J(E)$ as implied in obtaining (A-26) from (A-24).

THE PLANE MOMENTS EQUATIONS

The mean square distance traveled by a neutron is slowing down to a given energy is a familiar measure of the moderating characteristics of a system. We can determine this quantity from our reference equation (A-5) if we assume the cross sections are homogenized and extend throughout all space. Since, for such an infinite system, the results are independent of the location of the source, we will assume a plane source at the origin. We now multiply (A-5) by $z^n/n!$ and integrate over all space, to obtain

$$\begin{aligned}
& \sum_{\ell=0}^{\infty} \frac{2\ell+1}{4\pi} P_{\ell}(\mu) \left[-\mu \psi_{\ell}^{n-1}(E) + \Sigma_t(E) \psi_{\ell}^n(E) \right] \\
&= \sum_{\ell=0}^{\infty} \frac{2\ell+1}{4\pi} P_{\ell}(\mu) \left[\int dE' \Sigma_{s\ell}(E' \rightarrow E) \psi_{\ell}^n(E') + S_0^0(E) \delta_{\ell 0} \delta_{n0} \right] \quad (A-27)
\end{aligned}$$

n=0,1,-----

where

$$\begin{aligned}
\psi_{\ell}^n(E) &= \frac{1}{n!} \int_{-\infty}^{\infty} z^n \psi_{\ell}(z, E) dz \\
S_0^n(E) &= \frac{1}{n!} \int_{-\infty}^{\infty} z^n S(z, E) dz \\
S(z, E) &= S(E) \delta(z)
\end{aligned}$$

We multiply (A-27) by $P_m(\mu)$ and integrate over $\bar{\Omega}$, obtaining

$$\begin{aligned}
& -\frac{m+1}{2m+1} \psi_{m+1}^{n-1}(E) - \frac{m}{2m+1} \psi_{m-1}^{n-1}(E) + \Sigma_t(E) \psi_m^n(E) \\
&= \int dE' \Sigma_{sm}(E' \rightarrow E) \psi_m^n(E') + S(E) \delta_{m0} \delta_{n0} \quad (A-28)
\end{aligned}$$

m=0,1,-----
n=0,1,-----

The quantity we seek, which we will call the "age," is

$$\tau(E) = \frac{\psi_0^2(E)}{\psi_0^0(E)} \quad (A-29)$$

and we must use enough of the Equations (A-28) to obtain this. We find that only a single equation survives for each n for $n = 0, 1, 2$, and that these are

$$\Sigma_t(E) \psi_0^0(E) = \int dE' \Sigma_{so}(E' \rightarrow E) \psi_0^0(E') + S(E) \quad (A-30)$$

$$\Sigma_t(E) \psi_1^1(E) = \int dE' \Sigma_{s1}(E' \rightarrow E) \psi_1^1(E') + \frac{1}{3} \psi_0^0(E) \quad (A-31)$$

$$\Sigma_t(E) \psi_0^2(E) = \int dE' \Sigma_{so}(E' \rightarrow E) \psi_0^2(E') + \psi_1^1(E). \quad (A-32)$$

In HRG fine group form, these equations are

$$\Sigma_{t,n} \psi_{0,n}^0 = \sum_{n' \leq n} \Sigma_{so}(n' \rightarrow n) \psi_{0,n'}^0 + S_n \quad (A-33)$$

$$\Sigma_{t,n} \psi_{1,n}^1 = \sum_{n' \leq n} \Sigma_{s1}(n' \rightarrow n) \psi_{1,n'}^1 + \frac{1}{3} \psi_{0,n}^0 \quad (A-34)$$

$$\Sigma_{t,n} \psi_{0,n}^2 = \sum_{n' \leq n} \Sigma_{so}(n' \rightarrow n) \psi_{0,n'}^2 + \psi_{1,n}^1 \quad (A-35)$$

and

$$\tau_n = \frac{\psi_{0,n}^2}{\psi_{0,n}^0}. \quad (A-36)$$

As in the equations in the P_1 and B_1 approximations, possible differences in the fine group cross sections due to different energy weightings are neglected.

THE MICROSCOPIC CROSS SECTIONS

The macroscopic cross sections required by the fine group equations we have derived are made up of microscopic cross sections which have been averaged over both space and energy, using either the flux or the current as a weighting function. To provide these averages, we must make additional assumptions about the space and energy dependence of the flux and current within each fine group. Continuing in the spirit of our earlier policy of using the simplest spatial model which exhibits the effects we desire, we shall restrict our system to two spatial regions and assume that, at each energy, all quantities are independent of position within a spatial region. Using flux weighting for an example and suppressing the cross-section type for notational convenience, we can write the homogenized fine group cross section we need as

$$\sigma_{n,hom} = \sigma_{n,reg} \frac{\phi_{n,reg}}{\phi_{n,hom}} \quad (A-37)$$

where

$$\sigma_{n,reg} = \int_n dE \sigma(E) \phi_{reg}(E) / \phi_{n,reg}$$

$$\phi_{n,reg} = \int_n dE \phi_{reg}(E)$$

$$\phi_{n,hom} = \int_n dE \phi_{hom}(E).$$

In calculating $\sigma_{n,reg}$, we assume that, with one important exception, we can use a fission spectrum with a $1/E$ tail as the energy spectrum over which to average the $\sigma(E)$. A spectrum of this kind is the correct epithermal flux in an infinite, homogeneous system with constant scattering cross sections and no absorption, and should be a good approximation to the shape of the actual flux in a fine group if we choose the energy range small enough. The same spectrum should similarly serve for fine group averaging of current-weighted cross sections. As a consequence of this assumption, we need to calculate the microscopic fine group cross sections of a nuclide only once for use in all subsequent spectrum calculations. This calculation is done external to HRG3 and the resulting microscopic parameters for each nuclide are placed on an extensive data tape required by the code. In making these calculations, the ^{235}U fission spectrum was used. In general, the results are insensitive to the choice of fission spectrum.

The ratio $\phi_{n,reg}/\phi_{n,hom}$ is called the self-shielding factor in HRG3. Over much of the epithermal energy range, we can assume that this ratio is unity to a good approximation. Again with one exception, the self-shielding factors are not calculated in HRG3, but they may be supplied as input for any nuclide.

The exception to the calculation of both $\sigma_{n,reg}$ and $\phi_{n,hom}$ is in the resonance energy range, where the assumed fine group spectrum and spatial variation may both be significantly wrong. Even in this range, the exception applies only to some cross sections of certain nuclides. The HRG3 resonance treatment, which we will describe below, calculates both $\sigma_{n,reg}$ and $\phi_{n,hom}$ for each resolved resonance of these nuclides to a much better approximation, subject to the restrictions that $\sigma_{n,reg}$

is an absorption cross section and that the self-shielding factor is applied only to $\sigma_{n,reg}$. The corresponding calculation in the unresolved resonance range has similar restrictions on $\sigma_{n,reg}$ and assumes the self-shielding factor is one.

APPENDIX B

THE RESONANCE CALCULATION

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THE RESONANCE CALCULATION

Let $\sigma(E)$ be the energy dependent absorption (or fission) cross section of a single isolated resonance of a nuclide. We wish to calculate the contribution of this resonance to the homogenized cross section of the nuclide for fine group n . The complete resonance contribution to this group will be the sum of the contributions of the individual resonances. We begin by rewriting the Equation (A-37) for $\sigma_{n,hom}$ in the form

$$\begin{aligned}\sigma_{n,hom} &= \frac{\int_{res} dE \sigma(E) \phi_{reg}(E)}{\phi_{n,hom}} \times \frac{\int_n dE \sigma(E) \phi_{reg}(E)}{\int_{res} dE \sigma(E) \phi_{reg}(E)} \quad (B-1) \\ &= \frac{I}{\phi_{n,hom}} \times F_n\end{aligned}$$

where, for notational convenience, any indexing of the resonance has been suppressed. Here I is the resonance integral of the isolated resonance and F_n is the fraction of the resonance integral to be allocated to fine group n . The calculation of each of the quantities in (B-1) for a resolved resonance will now be considered. This will be followed by a description of the modifications made in the method when it is applied to the unresolved region. Finally, a summary description will be given of the input parameters required for the resonance calculation.

THE RESONANCE INTEGRAL

The resonance integral in (B-1) is calculated by a modification of the method of Adler, Hinman, and Nordheim⁽³⁾ (AHN) to include an intermediate resonance approximation for both the resonance absorber and an admixed moderator. We shall first write the results and then show in more detail how they were obtained.

For a single isolated resonance, HRG3 calculates the resonance integral for process x, where x is either absorption or fission, as

$$I_x = \frac{\sigma_o \Gamma_x}{E_o} \left[\beta_{\kappa\lambda} J(\xi, \beta_{\kappa\lambda}) + L(t_{\kappa\lambda}, \xi, \beta_{\kappa\lambda}) \right] \quad (B-2)$$

where

$$\beta_{\kappa\lambda} = \frac{(\kappa - \lambda) \sigma_m + \lambda \sigma_p}{\sigma_o} \frac{\Gamma}{\Gamma_a + \lambda \Gamma_n}$$

$$\sigma_m = \frac{\Sigma_{s, \text{light}}}{N}$$

$$\sigma_p = \sigma_m + \frac{\Sigma_{s, \text{heavy}}}{N}$$

$$t_{\kappa\lambda} = \{(\kappa - \lambda) \sigma_m + \lambda \sigma_p\} N \bar{\ell}$$

$$\xi = \frac{\Gamma}{2} \left(\frac{A}{E_o T} \right)^{1/2}.$$

The regional parameters are $\bar{\ell}$, the equivalent mean chord length, and T, the temperature in eV. The nuclide parameters are A, the mass in neutron mass units, and N, the "lumped" nuclear density in the region. The resonance parameters are Γ_x , Γ_a , Γ_n , Γ , E_o , and σ_o , with the usual definitions. The parameters σ_m and σ_p are respectively the scattering cross section of the light atoms in the region and of all the atoms in the region, each

per atom of the absorber nuclide. The parameters κ and λ are the intermediate resonance parameters for the admixed moderator and the absorber; they are solutions of transcendental equations to be given later. The functions $J(\xi, \beta_{\kappa\lambda})$ and $L(t_{\kappa\lambda}, \xi, \beta_{\kappa\lambda})$ are defined as

$$J(\xi, \beta_{\kappa\lambda}) = \int_0^\infty \frac{\psi(\xi, x)}{\psi(\xi, x) + \beta_{\kappa\lambda}} dx \quad (B-3)$$

$$L(t_{\kappa\lambda}, \xi, \beta_{\kappa\lambda}) = \int_0^\infty \frac{[\psi(\xi, x)]^2}{\psi(\xi, x) + \beta_{\kappa\lambda}} P_0 \left\{ \frac{t_{\kappa\lambda}}{\beta_{\kappa\lambda}} [\psi(\xi, x) + \beta_{\kappa\lambda}] \right\} dx \quad (B-4)$$

where

$$\psi(\xi, x) = \frac{\xi}{\sqrt{4\pi}} \int_{-\infty}^{\infty} \frac{dy}{1+y^2} \exp \left\{ -\frac{\xi^2}{4} (x-y)^2 \right\}$$

$$x = \frac{2}{\Gamma} (E - E_0)$$

is the Doppler broadening function and P_0 is the average escape probability from the absorber region. These J and L functions have been tabulated by AHN and appear on the HRG data tape.

Equation (B-2) was obtained as follows. The AHN method uses the NR approximation for narrow resonances and the NR1A approximation for wide resonances. For absorbing regions containing an admixed moderator, the AHN equations for these two approximations can be combined into a single expression which is (B-2) with $\kappa = 1$, by letting $\lambda = 1$ or 0 for NR or NR1A respectively. This fact suggests that an intermediate resonance (IR) approximation, which assigns λ a value between 0 and 1 , would give improved results. The IR method chosen was that of Ishiguro,⁽⁹⁾ which also extends the method to admixed moderators

through the introduction of additional parameters. Only a single admixed moderator, characterized by the parameter κ , is allowed in HRG3, and other refinements of Ishiguro are neglected. When κ is introduced, (B-2) is the formal result.

The expressions from which these IR parameters are evaluated depend on the resonance integral itself. It is assumed that this dependence is weak enough that a simplified version of the resonance integral can be used for this purpose. Thus, it is customary to use the Wigner rational approximation to the escape probability P_0 and further to use unbroadened cross sections. The Wigner rational approximation can be written as

$$P_0 = \frac{\sigma_e}{\sigma_t + \sigma_e}$$

where $\sigma_e = 1/\bar{\ell}N$ is an effective cross section for escape. When P_0 is expressed in terms of the quantities in (B-2), it can be shown that

$$\beta_{\kappa\lambda} J(\xi, \beta_{\kappa\lambda}) + L(t_{\kappa\lambda}, \xi, \beta_{\kappa\lambda}) = \beta'_{\kappa\lambda} J(\xi, \beta'_{\kappa\lambda}) \quad (B-5)$$

where

$$\beta'_{\kappa\lambda} = \beta_{\kappa\lambda} + \frac{\beta_{\kappa\lambda}}{t_{\kappa\lambda}} = \frac{(\kappa - \lambda)\sigma_m + \lambda\sigma_p + \sigma_e}{\sigma_0} \frac{\Gamma}{\Gamma_a + \lambda\Gamma_n}.$$

When, in addition, unbroadened cross sections are used with (B-5) in evaluating I_x and the IR conditions are applied, we find that κ and λ are solutions of

$$\lambda = 1 - \frac{\tan^{-1} X_{\kappa\lambda}}{X_{\kappa\lambda}}$$

$$\kappa = 1 - \frac{\tan^{-1} Y_{\kappa\lambda}}{Y_{\kappa\lambda}}$$

with

$$X_{\kappa\lambda} = \frac{4A}{(A+1)^2} \frac{E_0}{\Gamma} \left(\frac{\beta'_{\kappa\lambda}}{1+\beta'_{\kappa\lambda}} \right)^{1/2}$$

$$Y_{\kappa\lambda} = \frac{4A_m}{(A_m+1)^2} \frac{E_0}{\Gamma} \left(\frac{\beta'_{\kappa\lambda}}{1+\beta'_{\kappa\lambda}} \right)^{1/2}$$

where A_m is the admixed moderator mass in units of the neutron mass and all other quantities have been defined before. These κ and λ are then used to evaluate (B-2). The AHN assignments of each resonance to either the NR or NRIA approximation are used only in starting the iterative solution of the transcendental equation for λ .

The preceding discussion was confined to nonmetallic fuels, that is, $\sigma_m \neq 0$. For metallic fuels, $\sigma_m = 0$. In the NR approximation ($\lambda = 1$), both $\beta_{\kappa\lambda}$ and $t_{\kappa\lambda}$ are greater than zero and Equation (B-2) is still used by AHN. In the NRIA approximation ($\lambda = 0$), however, both $\beta_{\kappa\lambda}$ and $t_{\kappa\lambda}$ equal zero. Under these conditions,

$$\lim_{\beta \rightarrow 0} \beta J(\xi, \beta) = 0$$

$$\lim_{\substack{\beta \rightarrow 0 \\ t \rightarrow 0}} L(t, \xi, \beta) = L'(t'', \xi) = \int_0^\infty \psi P_0(t'' \psi) dx \quad (B-6)$$

where

$$t'' = \sigma_0 N \bar{\ell} \frac{\Gamma_\lambda}{\Gamma}$$

and the subscripts on $\beta_{\kappa\lambda}$ and $t_{\kappa\lambda}$ have been suppressed for notational convenience. AHN argue that in this limit the "volume" term,

$$\sigma_0 \frac{\Gamma_Y}{E_0} J(\xi, \beta),$$

should approach the slowing down density in the fuel, $2\sigma_{\text{pot}}/A$, rather than zero. For metallic fuels in the NR1A approximation, they replace the form of Equation (B-2) by

$$I = \frac{2\sigma_{\text{pot}}}{A} + \frac{\sigma_0 \Gamma_Y}{E_0} L'(t'', \xi) \quad (\text{B-7})$$

and tabulate the L' -function separately. In the HRG3 modification the $2\sigma_{\text{pot}}/A$ term is omitted; its small effect is already included to some extent in the IR formulation. Since the L' term is a limiting form of the L -function, Equation (B-2) can thus be used in all cases. Numerical problems occur, however, whenever the values of β and t in (B-2) lie sufficiently far below the ranges covered by the L -tables that the extrapolation procedures used in previous versions of HRG are inadequate. To cover this situation, two additional extrapolation formulas have been introduced, one for the L -tables and one for the L' -tables. Both are based on the Wigner rational approximation.

The identity

$$L(t, \xi, \beta) = L(t_m, \xi, \beta) \times \frac{L(t, \xi, \beta)}{L(t_m, \xi, \beta)}$$

can be converted into an extrapolation formula for L by using (B-5) to evaluate the ratio on the right-hand side. The result is

$$L(t, \xi, \beta) = L(t_m, \xi, \beta) \times \frac{(\beta + \beta/t)J(\xi, \beta + \beta/t) - \beta J(\xi, \beta)}{(\beta + \beta/t_m)J(\xi, \beta + \beta/t_m) - \beta J(\xi, \beta)} \quad (\text{B-8})$$

where t_m is the smallest tabulated value of t . Similarly, the identity

$$\beta J(\xi, \beta) + L(t, \xi, \beta) = \lim_{\substack{\beta \rightarrow 0 \\ t \rightarrow 0}} \{ \beta J(\xi, \beta) + L(t, \xi, \beta) \} \\ \times \left(\frac{\beta J(\xi, \beta) + L(t, \xi, \beta)}{\lim_{\substack{\beta \rightarrow 0 \\ t \rightarrow 0}} \{ \beta J(\xi, \beta) + L(t, \xi, \beta) \}} \right)$$

can be converted into an extrapolation formula for L' ; the ratio is evaluated from Equation (B-5) and its limiting form, and the first factor is given by Equation (B-6). The result is

$$\beta J(\xi, \beta) + L(t, \xi, \beta) = L'(t'', \xi) \times \frac{(\beta + \beta/t) J(\xi, \beta + \beta/t)}{1/t'' J(\xi, 1/t'')}. \quad (B-9)$$

Equation (B-9) is used whenever both β and t are well below the ranges covered by the L -tables; this situation naturally arises for those strong, broad resonances in metallic fuels previously evaluated by Equation (B-7). If only t is too small, Equation (B-8) is used.

During the development of this resonance treatment, a version was in use for some time which differed from the above only in the lack of the extrapolation procedure of Equation (B-8). For convenience, this earlier version is still available as an option. The output designates the Equation (B-8) extrapolation as analytic and the previous method as numerical.

THE FINE GROUP ALLOCATION

The Wigner rational approximation and unbroadened cross sections are also used in evaluating the factor F_n of (B-1). This factor is the ratio of two integrals, each with the same integrand but with different limits. The integrand is just that of $J(\xi, \beta'_{\kappa\lambda})$ as the preceding discussion showed. We thus need to evaluate

$$\int_{x_1}^{x_2} \frac{\psi(\xi, x)}{\psi(\xi, x) + \beta'_{\kappa\lambda}} dx$$

where x_1 and x_2 correspond to the energy limits of fine group n for the numerator integral and to $\pm\infty$ for the denominator integral. For unbroadened cross sections

$$\psi(\xi, x) = \frac{1}{1+x^2}$$

and the integrals can be evaluated analytically to give

$$F_n = \frac{1}{\pi} \left(\tan^{-1} \sqrt{\frac{\beta'_{\kappa\lambda}}{1+\beta'_{\kappa\lambda}}} x_{n-1} - \tan^{-1} \sqrt{\frac{\beta'_{\kappa\lambda}}{1+\beta'_{\kappa\lambda}}} x_n \right) \quad (B-10)$$

where

$$x_k = \frac{2}{\Gamma} (E_k - E_0).$$

Although in principle this method gives a contribution to every fine group, in practice some cutoff procedure is needed. For this purpose, two energies equally distant from E_0 are selected such that they include between them a specified fraction of the resonance integral as given by Equation (B-8); this fraction has arbitrarily been chosen as 0.9. The fine groups containing these two energies are then determined and the resonance integral is allocated to these and all intermediate groups, with the contributions beyond the cutoff energies included in the bounding groups.

The F_n depend on geometry and the scattering properties of the admixed moderator through $\beta'_{\kappa\lambda}$. Because unbroadened cross sections are used, the F_n are not dependent on the temperature.

THE HOMOGENIZED FLUX

The quantity in (B-1) remaining to be considered is

$$\phi_{n, \text{hom}} = \int_n dE \phi_{\text{hom}}(E)$$

To evaluate $\phi_{n, \text{hom}}$, we recall that our resonance treatment assumes an equivalent two region model. For convenience we will refer to the absorber region as "fuel", the other region as "moderator", and the homogenized system as "cell". We assume that $\phi_{\text{cell}}(E)$ is the volume weighted average of the two regional fluxes. Thus we can write

$$\phi_{\text{cell}}(E) = \phi_{\text{mod}}(E) - \frac{V_{\text{fuel}}}{V_{\text{cell}}} (\phi_{\text{mod}}(E) - \phi_{\text{fuel}}(E)).$$

The resonance calculation has assumed $\phi_{\text{mod}}(E) = 1/E$ and, with the Wigner rational approximation, the flux in the absorber region becomes

$$\phi_{\text{fuel}}(E) = \frac{\beta'_{\kappa\lambda}}{\psi(\xi, x) + \beta'_{\kappa\lambda}} \cdot \frac{1}{E}.$$

It also follows from the homogenization of the nuclide concentration that $N_{\text{fuel}} V_{\text{fuel}} = N_{\text{cell}} V_{\text{cell}}$. With these assumptions

$$\begin{aligned}
\phi_{n,hom} &= \int_n dE \phi_{cell}(E) \\
&= \int_{E_n}^{E_{n-1}} \frac{dE}{E} - \frac{N_{cell}}{N_{fuel}} \frac{\Gamma}{2E_0} \int_{x_n}^{x_{n-1}} \frac{\psi(\xi, x)}{\psi(\xi, x) + \beta_{\kappa\lambda}} dx \\
&= 0.25 - \frac{\pi}{2} \frac{N_{cell}}{N_{fuel}} \frac{\Gamma}{E_0 \sqrt{\beta_{\kappa\lambda}} (1 + \beta_{\kappa\lambda})} F_n . \quad (B-11)
\end{aligned}$$

UNRESOLVED RESONANCES

In the unresolved range, (B-1) still applies in principle but is modified in detail. We assume first that all resonances in the unresolved range can be calculated by the NR approximation, that the Wigner rational approximation can be used, and that the spatial self-shielding of the absorption can be neglected. As a consequence, once the parameters of a resonance are known, I_x can be calculated using the approximation (B-5) in (B-2) with $\kappa = 1$ and $\lambda = 1$; $\phi_{n,hom}$ is 0.25; and F_n can be set to 1 in the fine group in which the resonance appears, but is 0 otherwise. To determine the parameters of the resonance, we assume $\Gamma_x = \langle \Gamma_x \rangle$, $\Gamma_a = \langle \Gamma_a \rangle$, and $\Gamma_n = \Gamma_n^0 \sqrt{E_0}$ where Γ_n^0 is given by the Porter-Thomas distribution

$$P(y) = \frac{1}{(2\pi y)^{1/2}} e^{-y/2} \quad y = \frac{\Gamma_n^0}{\langle \Gamma_n^0 \rangle} .$$

This assumption requires that (B-2) be integrated over the distribution, to give

$$\bar{I}_x = \frac{\sigma_{m,eff} \langle \Gamma_x \rangle}{E_0} \bar{J} \quad (B-12)$$

where

$$\bar{J} = \int_0^\infty \frac{dy}{(2\pi y)^{1/2}} J[\xi(y), \beta'_{11}(y)] e^{-y/2}$$

$$\sigma_{m,eff} = \sigma_o \beta'_{11} = \sigma_p + \sigma_e.$$

HRG3 evaluates $\bar{J}$ by an adaptation of the GAM-I procedure. The variable of integration is changed to ξ with

$$\xi = B + Gy$$

and

$$B = \frac{\langle \Gamma_a \rangle}{2} \left(\frac{A}{E_o T} \right)^{1/2}$$

$$G = \frac{\langle \Gamma_n^o \rangle}{2} \left(\frac{A}{T} \right)^{1/2}.$$

The integral becomes

$$\bar{J} = \frac{1}{(2\pi G)^{1/2}} \int_B^\infty \frac{d\xi}{\sqrt{\xi-B}} J[\xi, \beta'_{11}(\xi)] e^{-\frac{(\xi-B)}{2G}}. \quad (B-13)$$

The range of integration is further divided into three parts: from B to $B + \Delta$, from $B + \Delta$ to 1 , and from 1 to ∞ . The value of Δ is set somewhat arbitrarily to 0.00095 . The contributions of both the first and last parts are neglected and the middle part is evaluated by numerical integration using Simpson's rule.

According to (B-1) $4 \bar{T}_x$ is the contribution to $\sigma_{n,hom}$ of an average unresolved resonance at E_o . The total contribution of the unresolved resonances in fine group n is found from

$$\begin{aligned}
\sigma_{n,\text{hom}} &= \int_n 4 \bar{\Gamma}_x \frac{dE_o}{<D>} \\
&= 4\sigma_{m,\text{eff}} \frac{<\Gamma_x>}{<D>} \int_n \bar{J} \frac{dE_o}{E_o}.
\end{aligned} \tag{B-14}$$

The evaluation of this integral in HRG3 differs from the GAM-I method and is based on the observation that, over the unresolved range, $\ln \bar{J}$ can be well approximated by a quadratic equation in the lethargy u . $\bar{J}$ need be calculated at only three values of u to evaluate the coefficients in this quadratic; two of these, u_1 and u_3 , are chosen to be the lethargies corresponding to the upper and lower energy limits respectively of the unresolved range for the nuclide and the third, u_2 , is chosen midway between them. If we insert this quadratic in the integral and express it in terms of the mean lethargy u_o of that portion of fine group n which is in the unresolved range, we find

$$\int_n \bar{J} du = \bar{J}_o \int_n e^{(u-u_o)A + (u-u_o)^2 B} du.$$

We make the further assumption that the quadratic term in the exponent can be expanded to give

$$\begin{aligned}
\int_n \bar{J}(u) du &= \bar{J}_o \int_n e^{(u-u_o)A} (1 + (u-u_o)^2 B) du \\
&= \bar{J}_o \left[\frac{1}{A} (e^D - e^{-D}) + \frac{2B}{A^3} \left\{ (1 - D + \frac{1}{2} D^2) e^D - (1 + D + \frac{1}{2} D^2) e^{-D} \right\} \right]
\end{aligned} \tag{B-15}$$

where

$$A = 2u_0 B - C$$

$$B = \frac{2}{\Delta^2} (\ln \bar{J}_1 - 2 \ln \bar{J}_2 + \ln \bar{J}_3)$$

$$C = \frac{2}{\Delta^2} \left\{ (u_2 + u_3) \ln \bar{J}_1 - 2(u_1 + u_3) \ln \bar{J}_2 + (u_1 + u_2) \ln \bar{J}_3 \right\}$$

$$D = \delta_n A/2$$

$$\ln \bar{J}_0 = \frac{2}{\Delta^2} \left\{ (u_0 - u_2)(u_0 - u_3) \ln \bar{J}_1 - 2(u_0 - u_1)(u_0 - u_3) \ln \bar{J}_2 + (u_0 - u_1)(u_0 - u_2) \ln \bar{J}_3 \right\}$$

$$\Delta = u_1 - u_3$$

and δ_n = lethargy width of that portion of fine group n which is in the unresolved range. The B , D , and Δ in (B-15) are, of course, not the same as the B , D , and Δ used earlier.

THE INPUT PARAMETERS

Most of the parameters required for the resonance calculations described above are obtained from the data tape, but others must be supplied as input. A summary description of this latter set of parameters will now be given. These are A_m on Card Type 8 and the six quantities on Card Type 10 of the input instructions: σ_m , σ_p , $\sigma_{m,eff}$, N , $\bar{\ell}$, and T .

Let us first consider $\bar{\ell}$, the equivalent mean chord length. The AHN method assumes an isolated two region system of simple geometry, with the absorber and any admixed moderator in a central region and the external moderator in a surrounding region. In such a system, a neutron which escapes the central region must collide in the surrounding region, and the probability of escaping the central region is a function of $\bar{\ell}$. For this simple system, $\bar{\ell} = \bar{\ell}_0 = 4V_0/S_0$ where V_0 and S_0 are the volume and surface area respectively of the central region. A more complex system must be equivalenced to a system of this

simple form for the resonance calculation, and $\bar{\ell}$ is the principal parameter used in this equivalencing. The most common complexity is that the resonance absorber region, though of simple geometry, is not isolated but rather is an element in a regular lattice array. In this case, it is customary to set

$$\bar{\ell} = \frac{\bar{\ell}_0}{1-C}$$

where C is the familiar Dancoff factor, which corrects for the fact that a neutron escaping one absorber region may still collide in another absorber region after traversing the intervening material without collision. C may be calculated, for example, by the method of Carlvik.⁽¹⁰⁾ An additional complexity is that the element in a lattice array is itself a cluster of subelements, each of simple geometry. In this case, the cluster must be equivalenced to a single simple element, by an analogous calculation of another Dancoff factor, or by astute homogenization, before the lattice correction is made. The treatment of clusters is discussed for example by Leslie and Jonsson.⁽¹¹⁾ Complexities associated with the presence of cladding and coolant regions, in addition to the surrounding moderator region, affect $\bar{\ell}$ only through C , and can usually be treated by appropriate homogenization outside the central region.

As for the other parameters, the temperature T is input in °K. The absorber nuclide density, N , is the number per barn-cm (10^{-24} cm^3) in the equivalent central region; for a simple element, this number is the physical number density, but for a cluster element the number must represent any homogenization which may have been made in the $\bar{\ell}$ equivalencing. The parameter $\sigma_m = \Sigma_{s,\text{light}}/N$, the scattering cross section per absorber nuclide of the admixed light atoms, and A_m is their mass. For a pure metal absorber, $\sigma_m = 0.0$ and the value of A_m is

immaterial. If the resonance absorber is in a simple element as an oxide or as an alloy with a light metal diluent, the value of A_m is clear. If several light atoms of different mass are admixed, there is no simple correct value of A_m . A suggested A_m in this case is that value corresponding to $\bar{\xi}$, the average logarithmic energy decrement of the light atoms. The parameter $\sigma_p = \sigma_m + \Sigma_{s,\text{heavy}}/N$, the off-resonance scattering cross section per absorber nuclide of all the atoms in the absorber region. The parameter $\sigma_{m,\text{eff}} = \sigma_p + 1/\bar{\xi}N$.

Finally, in the opposite direction of complexity from the AHN model is the truly homogeneous system. Analytically, the homogeneous system is the limiting case of the AHN model as $\bar{\xi} \rightarrow \infty$. Therefore in this case $\sigma_{m,\text{eff}} = \sigma_p$. However, $\bar{\xi}$ itself should be entered as 0.0 as a signal to the code to omit the "surface" term, $L(t, \xi, \beta)$, in (B-2). A large value of $\bar{\xi}$ should not be used; such a value leads to extrapolating the L or L' tables well beyond their normal range and gives incorrect results.

APPENDIX C

S_n PARAMETERS IN THE EXTENDED TRANSPORT APPROXIMATION

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S_n PARAMETERS IN THE EXTENDED TRANSPORT APPROXIMATION

Among the punch options available in HRG3, some will provide 2-table sets of parameters for use in S_n codes such as DTF-IV. The sets represent different approximations to the Boltzmann transport equation that can be characterized by the entry for group g in the σ_g position of the first table. In one approximation, $\sigma_g = \sigma_{t,g}(0)$ the flux weighted total cross section. In the other,

$$\sigma_g = \sigma_{t,g}^{(2)} - \sigma_{2g}^{(2)} \quad (C-1)$$

where the subscript 2 refers to the second Legendre moment of the scattering cross section in the laboratory system and the 2 in parentheses indicates the cross sections should be weighted over the energies of group g by the second Legendre moment of the angular flux. In the terminology of Bell et al.,⁽¹²⁾ this latter is the 2-table version of the extended transport approximation, which they show is generally preferable. Because evaluation of Equation (C-1) requires knowledge of the second Legendre moments of both the angular flux and the scattering cross section, neither of which is directly available in HRG3, the σ_g in (C-1) can only be approximated. The auxiliary calculations to provide this approximation are described here.

Bell et al.⁽¹²⁾ show that, for the unknown flux moment, an adequate approximation is

$$\phi_2(E) \propto \phi_1(E)/\Sigma_{tr}(E) \quad (C-2)$$

where $\phi_1(E)$ is the first Legendre moment of the flux, i.e., the current, and $\Sigma_{tr}(E)$ is the macroscopic transport cross section. These latter quantities are available in HRG for each fine group, so that the fine group analog of (C-2) can readily be found.

Finding the second Legendre moment of the scattering cross section is more difficult, but sufficient information is available so that a reasonable approximation can be made if we can assume that the only anisotropy is that of elastic scattering and that this is linearly anisotropic in the center of mass system. In this case, the microscopic cross section in energy and solid angle for a particular isotope is, in usual notation,

$$\sigma_S(E, \mu_C) = \frac{\sigma_S(E)}{4\pi} (1 + \omega_1^C(E) \mu_C). \quad (C-3)$$

In the laboratory system, the cross section for this isotope is

$$\sigma_S(E, \mu_L) = \frac{\sigma_S(E)}{4\pi} \sum_{\ell=0}^{\infty} \omega_{\ell}^L(E) P_{\ell}(\mu_L). \quad (C-4)$$

The transformation matrix relating these two sets of ω 's is well-known; we only need values for $\ell = 0, 1, 2$. For $\gamma = 1/A \ll 1$, These are

$$\omega_0^L(E) = 1 \quad (C-5)$$

$$\omega_1^L(E) = 2\gamma + (1 - \frac{3}{5} \gamma^2) \omega_1^C(E) \quad (C-6)$$

$$\omega_2^L(E) = \gamma^2 [1 + 0(\gamma^2)] + 2\gamma [1 + 0(\gamma^2)] \omega_1^C(E) \quad (C-7)$$

where only terms to order γ^2 are given explicitly for $\omega_2^L(E)$. The angular moments we seek are not the ω_{ℓ}^L themselves, but instead the coefficients of the expansion

$$\sigma_S(E, \mu_L) = \sum_{\ell=0}^{\infty} \frac{2\ell+1}{4\pi} \sigma_{\ell}(E) P_{\ell}(\mu_L). \quad (C-8)$$

From (C-4) it follows that

$$\sigma_{\ell}(E) = \frac{\omega_{\ell}^L(E) \sigma_S(E)}{2\ell+1}. \quad (C-9)$$

Now $\omega_1^C(E)$ can be eliminated between (C-6) and (C-7), and (C-9) can be used to express $\sigma_2(E)$ in terms of $\sigma_1(E)$ and $\sigma_0(E)$. In fine group form, the result can be written

$$\sigma_{2,n} = \frac{6}{5} \frac{\gamma[1+0(\gamma^2)]}{1 - \frac{3}{5}\gamma^2} \left(\sigma_{1,n} - \frac{2}{3} \gamma \sigma_{0,n} \right) + \frac{1}{5} \gamma^2 [1+0(\gamma^2)] \sigma_{0,n} \quad \gamma \ll 1. \quad (C-10)$$

For an individual isotope, Equation (C-8) gives the second Legendre moment we seek.

Many HRG nuclides are individual isotopes and $\sigma_{0,n}$ and $\sigma_{1,n}$ are available for them, so that $\sigma_{2,n}$ can be found if γ is known. We can readily find γ from the knowledge that the scattering is isotropic in the center of mass system at sufficiently low energies. Thus, we can choose a low energy fine group m for which scattering is isotropic and find γ from

$$\frac{\sigma_{1,m}}{\sigma_{0,m}} = \frac{2}{3} \gamma. \quad (C-11)$$

For these nuclides, σ_g in Equation (C-1) can be found by averaging $\sigma_{t,n} - \sigma_{2,n}$ over all fine groups n in g , where $\sigma_{2,n}$ is found from (C-10) and (C-11), and where, from (C-2), the weighting function is $J_n/\Sigma_{tr,n}$.

It is assumed that this same procedure can also be used for the remaining HRG nuclides and for the macroscopic cross section. This extension of the application of (C-10) and (C-11) needs justification. What is obtained from (C-11) is an average value $\bar{\gamma}$, where

$$\bar{\gamma} = \frac{\sum_i \gamma_i N_i \sigma_{o,m}^i}{\sum_i N_i \sigma_{o,m}^i} \quad (C-12)$$

and the index i refers to the component isotopes. It is not immediately clear that $\bar{\gamma}$ is appropriate for use in (C-10). For one thing, other averages such as $\bar{\gamma}^2$ are needed in (C-10), and $\bar{\gamma}^2 = \overline{\gamma^2}$ may be a poor approximation even for group m . In addition, if the ratios of the σ_o of the component isotopes vary from group to group, $\bar{\gamma}_m = \bar{\gamma}_n$ may also be a poor approximation. If the γ_i are nearly equal, however, as in those HRG nuclides which represent elements, it is clear from (C-12) and its analogs for higher powers of γ_i that $\bar{\gamma}^p \sim \overline{\gamma^p}$ and $\bar{\gamma}$ can be used in (C-10) with little error. Where the γ_i are widely different, as in the HRG nuclides H_2O and D_2O and as is usual for the components of macroscopic cross sections for a cell, the accuracy of the approximation can best be determined by testing actual data. Because $\gamma = \bar{\gamma} \ll 1$ is not true for these cases, another problem arises in using (C-10): the leading terms in γ do not reduce to the correct limit as $\gamma \rightarrow 1$. This deficiency can be largely overcome by adding terms in γ^2 in (C-10), with adjustable coefficients chosen to give the correct values as $\gamma \rightarrow 1$. When this is done, (C-10) is replaced by

$$\sigma_{2,n} = \frac{6}{5} \gamma \frac{\left(1 - \frac{3}{8} \gamma^2\right)}{\left(1 - \frac{3}{5} \gamma^2\right)} \left(\sigma_{1,n} - \frac{2}{3} \gamma \sigma_{0,n}\right) + \frac{1}{5} \gamma^2 \left(1 + \frac{1}{4} \gamma^2\right) \sigma_{0,n} \quad (C-13)$$

Tests indicate that an uncertainty of the order of 10% is introduced by extending (C-11) and (C-13) to macroscopic cross sections. This accuracy is usually well within that of the basic assumption that the scattering is linearly anisotropic in the center-of-mass system and therefore a more elaborate treatment of the available data is not warranted at this time.

APPENDIX D

THE HRG3 DATA TAPE

APPENDIX D

THE HRG3 DATA TAPE

The HRG3 data tape contains the fine group microscopic parameters for the individual nuclides, the fine group sources, and several tabulated functions used in resonance calculations. The logical structure of the tape will be described immediately below. Some information is then given about the sources of the data. Input instructions for NUTAPE, a code for updating and editing an HRG3 data tape, are given in Appendix E.

STRUCTURE

The logical structure of an HRG3 data tape is summarized in Table D-1, which for the most part is self-explanatory. A more complete description of the storage of the scattering matrices in the cross section array for a nuclide is advisable, however. Four such matrices are possible for each nuclide: inelastic, $n2n$, P_0 elastic, and P_1 elastic, and they are stored in the order named. Consider such a matrix arranged so that the columns represent the originating groups in order of decreasing energy; the matrix is then stored by columns. Since no upscattering is permitted, the matrix is lower triangular and each column can be truncated so that the first (within group) element in Column $i+1$ can directly follow the last element in Column i . Further, since most nuclides will not downscatter to the maximum number of groups, another truncation is usually possible. To define this procedure explicitly, let LA be the maximum number of originating groups and LD be the maximum number of groups to which downscattering can occur. Then $\text{Max}(LD+1, 69-i)$ values are stored for Group i if $i \leq LA$ and no values are stored if $i > LA$. LA is 68 for P_0 and P_1 scattering but generally is much smaller for inelastic and $n2n$ scattering. Further, let $LOL = LA*(LD+1) - LX*(LX-1)/2$,

where $LX = \text{Max}(0, LA+LD-68)$. The three numbers, LOL, LA, and LD are the integer descriptions for the matrix which appear in logical record N+1 of Table D-1. The numbers are zero if the matrix is absent.

TABLE D-1. Structure of HRG3 Data Tape

<u>Logical Record</u>	<u>Contents</u>	<u>Words per Record</u>	<u>Remarks</u>
1	Tape Identification	3	NTID is 6-digit number, normally the updating date in month-day-year form; NOI is total number of nuclides on tape; NFS is number of source spectra, currently 8.

The next five logical records contain tabulated functions used in the resonance calculations. See Appendix B for additional definitions of functions and parameters. Unless otherwise noted, k and β are related by $\beta = 2^k \times 10^{-5}$.

In the notation below, the quantity (x,y) indicates that the array is dimensioned x by y . Also, the notation $k = x(y)z$ indicates that the variable k has the range of values x to z in steps of magnitude y .

<u>Logical Record</u>	<u>Contents</u>	<u>Words per Record</u>	<u>Remarks</u>
2	$J(k, \xi)$	1012	$(44, 23)$. Values: $k=4.0(0.5)20.0(1.0)31.0$; $\xi=0.0(0.005)0.02(0.01)0.05(0.05)0.5(0.1)1.0, \infty$
3	$C(n, k)$	165	$(5, 33)$. Values: $n=1(1)5$; $k=4.0(0.5)20.0$. $J(k, \xi) = \sum_n C(n, k) * \xi^{-2n}$, $\xi > 1.0$.
4-6	$F(n, k, \xi)$	4158	4, 5, 6 for slab, cylinder, sphere. $(9, 33, 14)$. Values: $n=1(1)9$; $k=4.0(0.5)20.0$; $\xi=0.02(0.01)0.05(0.05)0.5, \infty$.

TABLE D-1. (Continued)

<u>Logical Record</u>	<u>Contents</u>	<u>Words per Record</u>	<u>Remarks</u>
			For $1 \leq n \leq 8$, $F(n, k, \xi) = L(z, k, \xi)$, with $z = 0.025 \times 2^n$; $t = 2z$ for 4, 5; $t = 4/3z$ for 6. For $n = 9$, $F(n, k, \xi) = L'(z', \xi)$, with $z' = 64 \times 10^4 \times 2^{-k}$; $t' = 2z'$ for 4, 5; $t' = 4/3 z'$ for 6.
6+I (I=1, NFS)	Source Spectrum	80	12 word alphanumeric name followed by 68 fine group values.

The logical records for the individual nuclides follow the preceding 6+NFS records, for a total of NOI nuclides. The nuclides appear in increasing, not necessarily consecutive, numerical order of NID. Each nuclide requires either 3 or 5 logical records, according to the following structure for data for a nuclide, assumed to begin with logical record N.

<u>Logical Record</u>	<u>Contents</u>	<u>Words per Record</u>	<u>Remarks</u>
N	Nuclide Name	4	Alphanumeric
N+1	Integer Descriptors	17	First word is NID, nuclide identification number; second word is LTOT, length of data array; fifth word is IWR, = 1 if resonance data given, = 0 otherwise.
N+2	Cross Section Array	LTOT	Code separates array into its component parts by use of the remaining integers of the preceding record.

TABLE D-1. (Continued)

<u>Logical Record</u>	<u>Contents</u>	<u>Words per Record</u>	<u>Remarks</u>
N+3	Unresolved Resonance Parameters	11	Present only if IWR = 1. First word is NRGYS, the number of resolved resonances; reminder are floating point.
N+4	Resolved Resonance Parameters	6*NRGYS	Present only if IWR = 1. Six values per resonance, first five floating point, last an integer.

SOURCES OF DATA

The J- and L-tables and the 8 source spectra on the HRG3 data tape were obtained from the data tape GAM101. A few obvious numerical errors have been corrected. The L'-tables were recalculated, using the routine of Reference (13). The C-table was added to improve the ξ -extrapolation in the J-table in the range $\xi > 1.0$, $4.0 \leq k \leq 20.0$, by using a power series in ξ^{-2} . Such a power series is indicated by the analytic asymptotic behavior of the ψ function appearing in the integrand of J. The C-table entries for each k were derived from the corresponding J-table entries for the six ξ values, 0.6(0.1)1.0 and ∞ , by an orthogonal polynomial least squares fitting procedure in which the degree of the polynomial was varied between 1 and 4 to obtain the least residual at these points. Thus, for a given k, the entries in the J-table and the C-table are in different modes: the J-table entries are values of J at specific ξ , and J values for other ξ are obtained by interpolation; the C-table entries are coefficients of a power series and J values are obtained by evaluating the power series.

The nuclide data on the HRG3 data tape will be described in general terms. The name of the nuclide broadly identifies the source of the data. The basic policy regarding names is that, when the data for a nuclide are changed in any way on the data tape, the name of that nuclide should also be changed, so that the data can be specifically identified.

Data for most of the nuclides have come from the Battelle Master Library⁽¹⁴⁾ (BML) by way of its processor code, BARNS-II.⁽¹⁵⁾ For these nuclides, the ^{235}U fission spectrum with a $1/E$ tail was used in finding the fine group averages. For those BML isotopes with resonance parameter tables, the resonance region calculations were done with a $1/E$ flux, using the superposition of contributions from all the resonances. A temperature of 300 °K was used for Doppler broadening, and interference between resonance and potential scattering was assumed. Some of these BML isotopes also appear on the HRG3 data tape as nuclides with resonance parameter tables; for these nuclides the fine group averages for absorption and fission in the resonance range include only the background contribution of the resonances. The transfer matrices were calculated by considering the scattering cross sections to be constant over each fine group and analytically integrating the flux-weighted energy-dependent transfer probabilities. A $1/E$ flux was used for elastic scattering and a constant flux was used for inelastic and $n2n$ scattering in this calculation. The elastic scattering model used the fine group averages of Legendre coefficients of anisotropy through order 4. The inelastic and $n2n$ scattering model neglected energy-angle correlation. The transfer probabilities for inelastic scattering were those of the BML, which assumes either discrete energy levels or the evaporation model; $n2n$ scattering was treated as inelastic scattering with two neutrons appearing at the final energy.

Those HRG nuclides with names consisting only of an isotope designation, for example DY164, were taken from the BML in Mid-1963. An extensive updating of the BML occurred in 1965 and the revised data were reprocessed for HRG. To identify the revised data, a numerical code of the form IIJJ was added to the isotope designation to give, for example, H2 0103. Here the II refers to the version of BML data, the JJ to the

version of the BARNS-II processing code. If either a change in the BML data or a revision in BARNS-II occurred which could influence the values on the HRG library, the data for that nuclide were reprocessed with the appropriate II or JJ incremented by 1. The surviving nuclides of this type on current HRG tapes reflect only JJ incrementation (changes in BARNS-II). Also present from this era of evolution are nuclides representing elements, and designated by the element name in full, for example ZIRCONIUM 0103. These were obtained by composition weighting the data of the constituent isotopes by their percent abundance in the natural element as given by the then current KAPL Chart of the Nuclides. The numerical code used for an element was that of the most recently updated constituent isotope. By early 1965, the BML data for an isotope included the date of last revision. The nuclide identification procedure in HRG was concurrently revised to its present form. The six digit number at the extreme right of the name is a date, which is usually that of the BML revision but may be that of a reprocessing of unchanged BML data, as in H2O W/UPSCAT and 304 SS. The letter two spaces ahead of the date indicates the version of the BARNS-II processing code which was used; the most recent isotope data have a D designation. In some cases, there is another letter in the space just ahead of the date word. An entry here indicates that some departure from the normal processing procedure has occurred. These departures represent solutions to special problems which could not be ignored but which at the time did not warrant revision of either BML data or processing code. For further identification, the nuclide names for ^{233}U , ^{235}U , ^{239}Pu , and ^{241}Pu also contain parenthetical information designating one of several BML versions of those isotopes.

The data for H2O W/UPSCAT contains hydrogen cross sections modified⁽¹⁶⁾ by adapting the corrections of the model of Cady et al.⁽¹⁷⁾ to the HRG group structure. Briefly, the model treats the hydrogen scattering as that of a gas of mass 1 at an elevated temperature, but restricts the upscattering to the originating group. The following tabulation gives the composition used to produce the 304 SS nuclide.

<u>Element</u>	<u>wt%</u>	<u>at. wt</u>	<u>wt%/at. wt</u>	<u>at.%</u>
Cr	19.00	51.996	0.3654	19.945
Mn	2.00	54.938	0.0364	1.987
Fe	68.345	55.847	1.2238	66.797
Ni	9.5	58.71	0.1618	8.832
Si	1.0	28.068	0.0356	1.945
S	0.03	32.064	0.000936	0.051
C	0.08	12.0111	0.00666	0.364
P	0.045	30.9738	0.00145	0.079
			<u>1.8321</u>	

$$\overline{\text{at. wt}} = 100/1.8321 = 54.5823$$

$$\text{at\%} = \overline{\text{at. wt}} (\text{wt\%/at. wt})$$

This composition is that of the Reactor Handbook,⁽¹⁸⁾ with the low concentration elements taken at their maximum values chromium and nickel at the average of their ranges, and iron as the remainder.

As for the remaining nuclides, data for most of the fission products have come from a 68-group version of a 99-group GAM-II tape obtained from ORNL,⁽¹⁹⁾ and data for a few other nuclides have been added by cards. The fission product data from GAM-II all have OR-G2 at the extreme right of the name. The PSEUDO FPROD nuclides with identification Numbers 37-44 are Nephew⁽²⁰⁾ data adapted to the HRG group structure, those with identification Numbers 45 and 46 are single pseudoelement values obtained by weighting the appropriate 4 pseudoelements of Nephew with their given yields.

APPENDIX E

INPUT INSTRUCTIONS FOR NUTAPE-II

APPENDIX E

INPUT INSTRUCTIONS FOR NUTAPE-II

NUTAPE-II is a code for updating and editing an HRG data tape. The code can update nuclide data on an HRG data tape directly from the Battelle Master Library, by operating as a part of the BARNS-II system for processing BML data. It can also operate independently, in which case nuclide data can be updated from either tape or cards. To provide for updating by cards, the General Atomics routine for updating a GAM-I Data Tape has been incorporated essentially intact.⁽²¹⁾

The updating operations permitted are addition, insertion, change, and deletion. The operations apply to the complete set of data for a nuclide, with the exception of changes via card input, in which case subsets consisting of data of a single reaction type can be changed. The requirements on card input are given in detail in the instructions. The requirements on tape input are that the complete sets of data for a nuclide are in the HRG logical structure. The TRANS link of BARNS-II produces a tape in this structure. In addition, the ENDF/B data processing code ETOG has been modified locally⁽²²⁾ to produce such a tape. NUTAPE-II will also accept another HRG data tape as input. It is also possible to change both the identification number and the name of a nuclide on the tape input at updating time.

The output supplied with a normal run is a listing of the complete set of data for those nuclides which have been added, inserted, or changed, and a listing of the names and identification numbers of those nuclides which have been deleted. In addition, listings of the names of all the nuclides are supplied, both numerically by identification number and alphabetically by name. It is also possible to list the data for any or all of the nuclides, as well as the tabulated resonance functions and source spectra.

The source spectra can only be modified by card input. There is no provision for modifying the tabulated resonance functions.

NUTAPE-II is written in FORTRAN-IV with the exception of the INCLUDE statement. The code operates on a 64k UNIVAC, using either the CSCX or EXEC-II system. The functions of INCLUDE and SETIO, the only system subroutine explicitly called, are described on page 8 and 12. The only machine-dependent programming is the alphabetization logic at the end of subroutine PRTAPE. Normal input and output are on logical Units 2 and 3, respectively. The listing of nuclide data in the output can alternatively be written to a variable logical unit, specified in the input. The logical units for the old and new HRG tapes and the updating tape are also specified in the input.

<u>Card Type</u>	<u>Columns</u>	<u>Format</u>	<u>Variable</u>	<u>Description</u>
1	1-12	I12	NFSP	Are source spectra to be changed: 0 = No 1 = Yes
	13-24	I12	NPRT	What part of tape on Logical Unit KN should be printed? 0 - Data for nuclides added or revised, along with alphabetical and numerical listing of all nuclides. N - After KN is produced, write the output to Logical Unit N according to instructions on Card Types 24 and 25.

<u>Card Type</u>	<u>Columns</u>	<u>Format</u>	<u>Variable</u>	<u>Description</u>
1	13-24	I12	NPRT (contd)	-N - KN is an existing tape and this is a 'print only' run. Write the output to Logical Unit N according to instructions on Card Types 24 and 25.
	25-36	I12	NOKI	Number of nuclides on tape on Logical Unit KI. Note: Set sign negative if KI is an HRG data tape. (Entry needed only if data from KI to be used in updating. All nuclides on KI need not be transferred to the new tape and nuclide order need not be in increasing HRG identification number).
	37-48	I12	KN	Logical Unit number for new HRG tape.
	49-60	I12	KG	Logical Unit number for old HRG tape.
	61-72	I12	KI	Logical Unit for intermediate tape to be used in updating. Set to 0 if not used.

The following card is not needed if NPRT (Columns 13-24 of Card Type 1) is negative.

2	1-12	I12	NTID	New Tape Identification Number. No more than 6 digits.
	13-24	I12	NOI	Number of nuclides on new tape.
	25-36	I12	NFS	Number of source spectra on new tape (now 8)

Card Type	Columns	Format	Variable	Description
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Source Spectra Modification Cards

Note: Card Types 3-5 are needed only if source spectra to be added or changed, i.e., NFSP (Columns 1-12 of Card Type 1) is non-zero.

3	1-72	6I12	L(I)	Spectrum change table: Each entry determined as follows: 0 - No change in this spectrum 1 - This spectrum to be added 2 - This spectrum to be changed Repeat with 6 entries per card, for a total of NFS values.
---	------	------	------	---

For each spectrum to be added or changed, supply a set consisting of one Type 4 and twelve Type 5 cards.

4	1-72	12A6	BCDX(I)	Alphanumeric title card for this spectrum.
5	1-72	6E12	SA(I)	Fine group values for this spectrum, 6 per card, 68 total.

Nuclide Modification Cards

Note: For each nuclide to be added, changed or deleted, supply a Type 6 card followed by Type 7-23 cards as needed. All cards for a nuclide must precede the Type 6 card of the following nuclide. Nuclides must be arranged in ascending numerical order of identification number.

6	1-12	I12	NUMU	Identification number of nuclide to be modified.
	13-24	I12	NAOC	Modification indicator Data for this nuclide are to be 1 - Added or inserted 2 - Changed 3 - Deleted

<u>Card Type</u>	<u>Columns</u>	<u>Format</u>	<u>Variable</u>	<u>Description</u>
6	25-36	I12	LOID	Location of nuclide data 0 - Tape on Logical Unit KI 1 - Input cards
	37-48	I12	ISEND	Termination indicator -1 - This is last nuclide to be modified 0 - Otherwise
	49-60	I12	NIDOLD	Identification number on KI for this nuclide (Permits change of KI identification number and/or name of this nuclide at updating time. Number on new Tape will be NUMU) 0 - No change in number or name <0 - Change name to that on following Type 7 card.

No further cards are needed for this nuclide if LOID = 0 and NIDOLD $\geq$ 0. If LOID = 0 and NIDOLD < 0, only the following additional card is needed.

7	1-12	12X		Not used
	13-36	4A6	BCD(I)	New alphanumeric name for this nuclide.

Card Types 8-23 are used, as needed, if LOID = 1

The following card is needed if NAOC = 2, i.e., if data for this nuclide are being changed. (If NAOC = 1 the table entries are set to 1 internally.)

8	1-72	6I12	LTK(I)	Nuclide change table: For each of the six sets of parameters identified below, enter a 1 in the indicated columns if a change is to be made, a 0 otherwise.
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<u>Card Type</u>	<u>Columns</u>	<u>Format</u>	<u>Variable</u>	<u>Description</u>
8	1-72	6I12	LTK(I) (contd)	12 Absorption 24 Fission 36 Inelastic scattering 48 n2n scattering 60 Elastic scattering 72 Resonance parameters

Card Types 9-14 are required for each nuclide to be added or changed.

9	1-24	4A6	BCD(I)	Alphanumeric name for this nuclide.
10	1-12	I12	NID	Nuclide identification number.
	13-24	I12	LTOT	Total length of data list (Resonance parameters excluded)
	25-36	I12	IWA	Are absorption cross sections present 0 - No 1 - Yes
	37-48	I12	IWF	Are fission cross sections present 0 - No 1 - Yes
	49-60	I12	IWR	Are resonance parameters present 0 - No 1 - Yes
11	1-12	I12	LOL(1)	Total number of inelastic cross sections given (0 if no inelastic cross sections)
	13-24	I12	LA(1)	Group number of lowest energy fine group in which inelastic scattering occurs.
	25-36	I12	LD(1)	Maximum number of groups to which inelastic down-scattering may occur (originating group not counted)

<u>Card Type</u>	<u>Columns</u>	<u>Format</u>	<u>Variable</u>	<u>Description</u>
12	1-36	3I12	LOL(2) LA(2) LD(2)	Same as Card Type 11, but for n2n scattering
13	1-36	3I12	LOL(3) LA(3) LD(3)	Same as Card Type 11, but for P ₀ elastic scattering
14	1-36	3I12	LOL(4) LA(4) LD(4)	Same as Card Type 11, but for P ₁ elastic scattering. (Entries should be identical to those of Card Type 13 for P ₀ scattering).

Card Types 15-23 are required to supply the cross sections and/or resonance parameters to be changed or added for this nuclide. An entire set of data must be supplied for each set of parameters.

15	1-72	6E12		Absorption cross sections, 6 per card, 68 total (Needed only if IWA = 1 and LTK(1) = 1)
16	1-72	6E12		Fission cross sections, 6 per card, 68 total (Needed only if IWF = 1 and LTK(2) = 1)
17	1-72	6E12		Neutrons per fission, 6 per card, 68 total (Needed only if IWF = 1 and LTK(2) = 1)
18	1-72	6E12		Inelastic scattering array, 6 per card, for a total of LOL(1) values, ordered as described in Appendix D. (Needed only if LOL(1) > 0 and LTK(3) = 1)

<u>Card Type</u>	<u>Columns</u>	<u>Format</u>	<u>Variable</u>	<u>Description</u>
19	1-72	6E12		n2n scattering array, 6 per card, for a total of LOL(2) values, ordered as described in Appendix D. (Needed only if LOL(2) > 0 and LTK(4) = 1).

The following card type is used to enter the P_0 and P_1 scattering arrays simultaneously. Each card contains the P_0 and P_1 transfer cross sections between two groups. A total of LOL(3) cards is needed, ordered as described in Appendix D. (Needed only if LOL(3) > 0 and LTK(5) = 1)

20	1-12			Not used
	13-27	E15		P_0 transfer cross section between two groups
	28-42	E15		P_1 transfer cross section between two groups

Card Types 21-23 are used to enter the resonance table data.
(Needed only if IWR = 1 and LTK(6) = 1)

21	1-12	I12	NRGYS	Number of resolved resonances in this table
	13-24	E12	SMAS	Mass of resonance absorber in units of the neutron mass
	25-36	E12	EC	Energy of transition between resolved and unresolved resonance ranges, in eV
	37-48	E12	DLEV	Average level spacing in unresolved range, in eV
	49-60	E12	GAMNO	Average reduced neutron width in unresolved range, in eV
	61-72	E12	GAMGA	Average capture width in unresolved range, in eV

<u>Card Type</u>	<u>Columns</u>	<u>Format</u>	<u>Variable</u>	<u>Description</u>
22	1-12	E12	GAMFIS	Average fission width in unresolved range, in eV
	13-24	E12	ET	Upper limit of energies to be included in unresolved range, in eV
	25-36	E12	GUNR	Average statistical weight of resonances in unresolved range
	37-48	E12	ELow	Lower limit of energies to be included in resolved range, in eV (used only in NUTAPE-II editing)
	49-60	E12	PNUNR	Average number of neutrons per fission in unresolved range (not used at present)

One card of the following type is needed for each resolved resonance, for a total of NRGYS cards. The ordering of the cards is immaterial.

23	1-12	E12	EN(I)	Resonance energy in eV
	13-24	E12	GAMN(I)	Neutron width in eV
	26-36	E12	GAMGAM(I)	Capture width in eV
	37-48	E12	GAMFI(I)	Fission width in eV
	49-60	E12	G(I)	Statistical weight of this resonance
	61-72	I12	L(I)	Narrow or wide resonance? 1 - Wide 2 - Narrow

Card Types 24 and 25 are needed if and only if NPRT (Columns 13-24 of Card Type 1) differs from zero.

<u>Card Type</u>	<u>Columns</u>	<u>Format</u>	<u>Variable</u>	<u>Description</u>
24	1-4	I4	NLIST	Total number of nuclides to be listed. Set to 999 to list all NOI nuclides, otherwise NLIST < NOI
	5-8	I4	NTAB	Should the tabulated resonance functions and source spectra be listed? 0 - No 1 - Yes (Set internally to 1 if NLIST = 999)
25	1-72	18I4	LIST(I)	Identification numbers of nuclides to be listed, in increasing order, 18 per card, for a total of NLIST numbers. (Not needed if NLIST = 0 or NLIST = 999)

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