525
FEB 28 1962

MASTER

ORNL-3198
UC-32 - Mathematics and Computers
TID-4500 (17th ed.)

NIGHTMARE - AN IBM 7090 CODE FOR THE
CALCULATION OF GAMMA HEATING IN
CYLINDRICAL GEOMETRY

M. L. Tobias
D. R. Vondy
Marjorie P. Lietzke

OAK RIDGE NATIONAL LABORATORY

operated by

UNION CARBIDE CORPORATION

for the

U.S. ATOMIC ENERGY COMMISSION

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

Printed in USA. Price \$1.00. Available from the

Office of Technical Services
Department of Commerce
Washington 25, D. C.

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

A. Makes any warranty or representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or

B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor, to the extent that such employee or contractor of the Commission, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.

Contract No. W-7405-eng-26

REACTOR DIVISION

NIGHTMARE — AN IBM 7090 CODE FOR THE CALCULATION
OF GAMMA HEATING IN CYLINDRICAL GEOMETRY

M. L. Tobias
D. R. Vondy
Marjorie P. Lietzke

DATE ISSUED

FEB 26 1962

OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee
operated by
UNION CARBIDE CORPORATION
for the
U.S. ATOMIC ENERGY COMMISSION

**THIS PAGE
WAS INTENTIONALLY
LEFT BLANK**

CONTENTS

Abstract	1
Introduction	1
Mathematical Basis of the Program	2
Procedure for Use of Codes	7
Notation	14
Appendix A - Comparison of Results with Experiment (BSR)	23
Appendix B - Properties of Materials for Use in Reactor Heat- Generation Calculations	28
Appendix C - Example of Extension of a NIGHTMARE Result to Obtain Additional Information	37

NIGHTMARE - AN IBM 7090 CODE FOR THE CALCULATION
OF GAMMA HEATING IN CYLINDRICAL GEOMETRY

M. L. Tobias

D. R. Vondy

Marjorie P. Lietzke

ABSTRACT

The NIGHTMARE program calculates the gamma-dose rate at any point in or near a reactor by means of the NDA buildup-factor method. The source distribution is obtained from a two-group, two-dimensional diffusion code (EQUIPOISE-2). Seven gamma-energy groups are used. As many as nine different concentric cylindrical regions may be considered, but only radial variation of attenuation and buildup properties is permitted. Two schemes of estimating buildup factors through a succession of materials are built into the code, and results may be obtained by using either or both methods. An IBM 7090 computer with seven tape units is required. Computations are performed at the approximate rate of $10,000/n$ mesh points per minute, where n is the number of concentric regions, and the number of mesh points is the product of the number of axial, radial, and angular increments. The program is run under the control of the IBM 7090 MONITOR system.

INTRODUCTION

By use of the FORTRAN-II programming system, the NIGHTMARE code for the IBM 7090 was devised; it will estimate the gamma dose at an arbitrary point in or near a reactor in cylindrical coordinates. The basic procedure, which combines the NDA buildup-factor method with numerical integration, was applied some years ago by Claiborne¹ to problems in x , y , z geometry. In the Oracle program used at that time, the photon source distribution was provided as input from a hand-punched paper tape. In the present program the source information is obtained by a prior calculation using a special version of the EQUIPOISE code,^{2,3} which computes the photons produced per volume element of the two-dimensional EQUIPOISE

¹H. C. Claiborne and T. B. Fowler, The Calculation of Gamma Heating in Reactors of Rectanguloid Geometry, ORNL CF-56-7-97 (July 20, 1956).

²M. L. Tobias and T. B. Fowler, EQUIPOISE - An IBM-704 Code for the Solution of Two-Group, Two-Dimensional, Neutron Diffusion Equations in Cylindrical Geometry, ORNL-2967 (Oct. 17, 1960).

³T. B. Fowler and M. Tobias, EQUIPOISE-2 - A Two-Dimensional, Two-Group, Neutron Diffusion Code for the IBM-7090 Computer, ORNL CF-60-11-67 (Nov. 21, 1960).

mesh. These results, distributed among seven energy groups, are written by the machine on a magnetic tape which is used as NIGHTMARE input. The normalization is to the arbitrary power level computed in the EQUIPOISE part of the program. The photon sources are those which are proportional to either the neutron-capture rate or the fission density distribution, such as prompt fission gammas and capture gammas. Delayed gammas from fission products may be included if it can be reasonably assumed that the fission products will not move about after they are produced.

In succeeding sections, the mathematical and physical basis of the program is described, followed by a description of input forms and operating instructions. Capture-gamma data, attenuation coefficients, and buildup-factor data which have been used in various calculations are also supplied. An illustration of how a NIGHTMARE result may be extended to yield additional information is presented in Appendix C.

The results obtained from this code have been compared with experimental data obtained in the Bulk Shielding Reactor (BSR)⁴ and are in reasonable agreement. A discussion of this comparison may be found in Appendix A.

MATHEMATICAL BASIS OF THE PROGRAM

The problem treated by the NIGHTMARE code is (with certain restrictions) the estimation of the gamma-dose rate at an arbitrary point produced by a source of arbitrary distribution in space and energy. The principal assumption is that this estimate can be made by the buildup-factor method. Given a source of $s(E, \vec{r})$ gammas per unit energy range per unit volume per second, the dose at a point whose position vector is $\vec{r}_T$ is

$$\int_{\text{energy}} \int_{\text{space}} \text{EBU}(\vec{r}, \vec{r}_T, E) \mu_e(E) \frac{s(E, \vec{r}) e^{-\int_{\vec{r}}^{\vec{r}_T} \mu(\vec{r}', E) d\vec{r}'}}{4\pi(\vec{r} - \vec{r}_T)^2} dE dV \quad (1)$$

in units of power per cubic centimeter.

⁴F. T. Binford, E. S. Bettis, and J. T. Howe, Gamma Heating Measurements in the Bulk Shielding Reactor, ORNL CF-56-3-72 (Mar. 7, 1956).

For calculation purposes the energy range is broken into seven energy groups, in each of which the buildup factors and attenuation coefficients are taken at an average energy. In space the integral is evaluated numerically by breaking up the reactor into elements of volume bounded by surfaces of a cylindrical coordinate system. In the R-Z directions the mesh spacing is the same as that used in the EQUIPOISE calculation; in the θ direction the spacing is uniform at any given radius, but is usually changed with increasing radius to prevent excessive calculation (see "Procedure for Use of Codes"). The appearance of the mesh is as shown in Fig. 1. The distribution of materials is arbitrary in the R-Z coordinates as far as calculation of the sources is concerned and is uniform in the θ direction. In calculating the attenuation, however, the material properties are considered to be uniform in the Z direction; that is, as far as gamma-ray attenuation and buildup factors are concerned, the material distribution appears as in Fig. 2a and not as in Fig. 2b.

The form of expression (1), which is used in the numerical integration, is as follows for each energy group:

$$\frac{\mu_e(E)}{2\pi} \sum_{Z=Z_1}^{Z_2} \sum_{R=R_1}^{R_2} \sum_{\theta=\theta_1}^{\theta_2} \frac{BU(\vec{r}, \vec{r}_T, E) e^{-\sum_i \mu_i d_i}}{|\vec{r} - \vec{r}_T|^2} S_P(R, Z) \Delta V. \quad (2)$$

The ranges of integration (that is, summation) are specified from one row of mesh points to another row of mesh points, but the actual summation occurs from halfway in between rows and columns. Target points never coincide with source points. The target point may be placed anywhere on the R-Z mesh, but in the θ coordinate the target is always half of an angle increment away from the nearest mesh point.

If no correction is made to formula (2), the amount of the dose from the volume elements closest to the target point is underestimated. Provision is made in the input to reduce the source-target distance for the closest mesh points by subtracting an amount $\epsilon R_T \Delta\theta/2$ from this distance, where R_T is the target radius, $\Delta\theta/2$ is the angular increment from the source point to the target, and ϵ is a number between 0 and 1. It has

Fig. 1. Typical Mesh Spacing Which Might Be Used in NIGHTMARE; Material Distribution Uniform in θ Direction and Arbitrary in R Direction. In Z direction, distribution is arbitrary with respect to the sources but uniform with respect to attenuation properties.

been found that $\epsilon = 0.25$ is usually adequate, but the user may employ any desired value in the range $0 \leq \epsilon < 1$. The results for $\epsilon = 0$ are also printed out for comparison with the results for $\epsilon \neq 0$.

The buildup factor for radiation passing through layers of different materials is handled by an empirical device which has the merit of fulfilling certain physical requirements. Referring to Fig. 3, for the case of four layers, the buildup factor is estimated by either of the following formulas:

$$BU(S \rightarrow T) = \left(\left[BU_I \left(\sum_1^4 \mu_i d_i \right) \right]^a \left[BU_{II} \left(\sum_1^4 \mu_i d_i \right) \right]^{1-a} \right)^b \times \left[BU_{III} \left(\sum_1^4 \mu_i d_i \right) \right]^{1-b}{}^c \times \left[BU_{IV} \left(\sum_1^4 \mu_i d_i \right) \right]^{1-c} \quad (3)$$

or

$$BU(S \rightarrow T) = \left(\left[BU_I \left(\mu_1 \sum_1^4 d_i \right) \right]^a \left[BU_{II} \left(\mu_2 \sum_1^4 d_i \right) \right]^{1-a} \right)^b \times \left[BU_{III} \left(\mu_3 \sum_1^4 d_i \right) \right]^{1-b}{}^c \times \left[BU_{IV} \left(\mu_4 \sum_1^4 d_i \right) \right]^{1-c}, \quad (4)$$

where

$$a = e^{-\mu_2 P_2},$$

$$b = e^{-\mu_3 P_3},$$

$$c = e^{-\mu_4 P_4}.$$

Figure 3 shows a plane passing through a source point S and the target point T which is parallel to the common axis of the concentric cylindrical regions I, II, III, and IV. Lines m, n, p, q, and r are the lines of intersection of the plane with the concentric regions. (The axis of the cylinders need not lie in the plane of the picture.) Both formulas have the following characteristics. First, the further the target point is from the boundary of the region in which it is, the closer the over-all buildup factor corresponds to the buildup factor for that region. Second,

UNCLASSIFIED
ORNL-LR-DWG 64198

Fig. 2. Material Distribution Considered in NIGHTMARE. The actual material distributions may be as in (b), and the radiation sources are calculated on that basis. Attenuations must be calculated on the basis of a distribution such as that shown in (a).

UNCLASSIFIED
ORNL-LR-DWG 64199

Fig. 3. Diagram Illustrating Method of Estimating Buildup Factor for a Layered System.

if all the regions are of the same material, the over-all buildup factor will be the buildup factor for that material. Formula (3) is preferred because the buildup factors tend to become unreasonably large at long distances in formula (4). More realistic answers are also obtained with (3) if a thin region of heavy material lies between the target and the source. The user has the option of obtaining answers by either or both methods of buildup factor computation. In the program, formulas (3) and (4) may be extended to as many as nine regions.

PROCEDURE FOR USE OF CODES

Figures 4-7 show the input forms used in NIGHTMARE. The first step in a NIGHTMARE calculation is the running of an EQUIPOISE-2^{2,3} case. The manner of writing input for EQUIPOISE-2 is described in full elsewhere^{2,3} and will not be repeated here. A special program deck for EQUIPOISE-2 is used which requires, in addition to the information given in Fig. 4, the data shown in Fig. 5. These numbers are the number of gammas in each of the seven energy groups produced per capture (P_c) and per neutron produced (P_f) in each region. The information is given as decimal floating-point numbers starting from the inmost region and proceeding outward. One blank card follows the regular EQUIPOISE input and one after each set of P_c and P_f values.

At the conclusion of the EQUIPOISE run the source distribution is placed on tape ready for the NIGHTMARE calculation. The source tape (actual tape 6) may be used repeatedly for gamma-heating calculations in the same reactor. (The description of other tapes is given in the EQUIPOISE-2 memorandum.)

It is important to remember that the EQUIPOISE and NIGHTMARE meshes coincide. Further, the target point must, as a rule, lie on or within the next to the last row and column of the EQUIPOISE mesh. If the target point lies above or below the reactor but within the next to last column, the attenuation coefficient and buildup factor will be based upon that region above or below which the target point is located. If the target point is outside the next to last column, the attenuation coefficient and buildup factor will be based on the outermost region of the reactor.

KEY PUNCHING INSTRUCTIONS:
Punch only those cards which have
data in columns 73 - 80.

EQUIPOISE INPUT FORM

REQUEST NO. 1804A0

TITLE																																																																								73	80
SAMPLE PROBLEM FOR NIGHTMARE -- BSR GAMMA-HEATING																																																																									
IMAX	JMAX	NORI	NORJ	F.L	S.L	C.L	L.L	T.L	R.L	B.L	T	Φ_F	T	Φ_S	R	Φ_F	R	Φ_S	B	Φ_F	B	Φ_S	ϵ	β	73	80																																															
1	4	7	10	13	15	17	19	21	23	25	27		33		39		45		51		57		63		69	73	80																																														
12	12	14	2		4	4					1												001	1.6		2																																															
Δz	ROW	Δz	ROW	Δz	ROW	Δz	ROW	Δz	ROW	Δz	ROW	Δz	ROW	Δz	ROW	Δz	ROW	Δz	ROW	Δz	ROW	Δz	ROW	Δz	ROW	73	80																																														
15.24	4	7.62	5	4.689	12																					3																																															
ΔR	COL	ΔR	COL	ΔR	COL	ΔR	COL	ΔR	COL	ΔR	COL	ΔR	COL	ΔR	COL	ΔR	COL	ΔR	COL	ΔR	COL	ΔR	COL	ΔR	COL	73	80																																														
4.978	6	3.46	8	7.4	9	14.8	10	20.1	12																	4																																															
ROW 1	ROW 2	COL 1	COL 2	D_F	D_S	Σ_F	Σ_S	$\nu \Sigma_F$	$\nu \Sigma_S$	P	Φ_F	Φ_S	73	80																																																											
1	4	1	12	2.0	.16188	.040	.01838			.9898	.1	1.0	OUTERH2O																																																												
4	5	1	9	1.5	.16188	.0523	.01838			.9898	8.0	25.0	INNERH2O																																																												
5	8	1	6	1.435	.2533	.02745	.070662	.003125	.10387	.9142	240.0	80.0	OUT CORE																																																												
8	12	1	4	1.434	.2533	.02718	.070662	.003109	.10387	.9138	300.0	100.0	INN CORE																																																												
8	12	4	6	1.435	.2533	.02745	.070662	.003125	.10387	.9142	240.0	80.0	OUT CORE																																																												
5	12	6	9	1.5	.16188	.0523	.01838			.9898	8.0	25.0	INN H2O																																																												
4	12	9	12	2.0	.16188	.040	.01838			.9898	.1	1.0	OUT H2O																																																												
													END																																																												

UCM-1338
(2 2-60)

Fig. 4. EQUIPOISE Input Form.

REQUEST

NIGHTMARE INPUT ONE

WRITTEN BY

DATE

BLOCK 1

TITLE																																										# Δ θ	R TARGET						Z TARGET						*																												
BSR GAMMA HEATING AL-I TARGET																																										AUG-60						8 24.13						83.8185						*																							
μ/p (E1)									μ/p (E2)									μ/p (E3)									μ/p (E4)									μ/p (E5)									μ/p (E6)									μ/p (E7)									$0 \leq \epsilon < 1.0$																				
.03885									.073									.1252									.2172									.3072									.399									.1153									.25																				
ROW 1					ROW 2					COL 1					COL 2					θ 1 (RADIAN)										θ 2										TB																																											

BLOCK 2

TITLE																																										# Δ θ	R TARGET						Z TARGET						*																												
BSR GAMMA HEATING AL-I FRONT HALF OF REAC																																										4 24.13						83.8185						*																													
μ/p (E1)									μ/p (E2)									μ/p (E3)									μ/p (E4)									μ/p (E5)									μ/p (E6)									μ/p (E7)									$0 \leq \epsilon < 1.0$																				
.03885									.073									.1252									.2172									.3072									.399									.1153									.25																				
ROW 1					ROW 2					COL 1					COL 2					θ 1 (RADIAN)										θ 2										TB																																											

BLOCK 3

TITLE																																										# Δ θ	R TARGET						Z TARGET						*																												
BSR GAMMA HEATING AL-I CORE ONLY																																										8 24.13						83.8185						*																													
μ/p (E1)									μ/p (E2)									μ/p (E3)									μ/p (E4)									μ/p (E5)									μ/p (E6)									μ/p (E7)									$0 \leq \epsilon < 1.0$																				
.03885									.073									.1252									.2172									.3072									.399									.1153									.25																				
ROW 1					ROW 2					COL 1					COL 2					θ 1 (RADIAN)										θ 2										TB																																											

BLOCK 4

TITLE																																										# Δ θ	R TARGET						Z TARGET						*																												
μ/p (E1)									μ/p (E2)									μ/p (E3)									μ/p (E4)									μ/p (E5)									μ/p (E6)									μ/p (E7)									$0 \leq \epsilon < 1.0$																				
ROW 1					ROW 2					COL 1					COL 2					θ 1 (RADIAN)										θ 2										TB																																											

NOTE: IF CARD 01 OF ANY BLOCK IS FILLED IN CARDS 02 AND 03 MUST BE PUNCHED.

*: IF COL. 72 OF ANY CARD 01 IS BLANK OR 0, NIGHTMARE INPUT TWO MUST FOLLOW CARD 03 OF THAT BLOCK.

UCN-1851
(2 7-60)

Fig. 6. NIGHTMARE INPUT ONE Form.

NIGHTMARE INPUT TWO

REQUEST										WRITTEN BY										DATE																																																											
JR1	JR2	JR3	JR4	JR5	JR6	JR7	JR8	JR9	JR10	JC1	JC2	JC3	JC4																																																																		
0	1	1																	0																																																												
μ										μ/p										A																																																											
1										9										18										27										36										45										73										80									
0.150																				1.04										.402																				E1										REG1																			
0.0945																				0.84										.60																				E1										REG2																			
0.0																																																		SIGNAL																													
0.109																				1.04										.123																				E2										REG1																			
0.0692																				.97										.175																				E2										REG2																			
0.0																																																		SIGNAL																													
0.076																				0.76										.047																				E3										REG1																			
0.0482																				0.83										.037																				E3										REG2																			
0.0																																																		SIGNAL																													
0.0541																				0.56										.004																				E4										REG1																			
0.0333																				0.589										.0045																				E4										REG2																			
0.0																																																		SIGNAL																													
0.0454																				0.43										.002																				E5										REG1																			
0.027																				0.46										-.0035																				E5										REG2																			
0.0																																																		SIGNAL																													
0.0409																				0.34										.001																				E6										REG1																			
0.0236																				0.381										-.005																				E6										REG2																			
0.0																																																		SIGNAL																													
0.0816																				0.82										.065																				E7										REG1																			
0.052																				0.88										.06																				E7										REG2																			
0.0																																																		SIGNAL																													

UCN-1851A
(2 7-60)

Fig. 7. NIGHTMARE INPUT TWO Form.

If a plane of symmetry is used in the EQUIPOISE mesh, it must be placed at the bottom of the mesh. The gamma-heating result will be for the top half of the reactor.

The input system used permits the running of an arbitrary number of gamma-heating calculations in succession. The NIGHTMARE input cards which describe the number of angular increments, the target position, attenuation coefficients, etc., are divided into two parts. NIGHTMARE INPUT ONE (Fig. 6) consists of three cards filled out as follows:

Card 01:

Columns 1-42 are the title positions and may contain any information.

Columns 43-48 must be blank.

Columns 49-50 represent the number of $\Delta\theta$'s; if the target is on the axis of the reactor, this number should be 1.

Columns 51-60 represent the radius of target, in centimeters, measured from axis of cylinder.

Columns 61-70 represent the height of target, in centimeters, measured from top row of EQUIPOISE mesh.

Column 71 is blank.

Column 72, if blank or zero, NIGHTMARE INPUT TWO must follow card 03 of NIGHTMARE INPUT ONE. If 1, the next block of three cards may follow the running of this case.

Card 02:

Columns 1-9, 10-18, 19-27, 28-36, 37-45, 46-54, and 55-63 are the values of the energy absorption coefficient times the group average energy divided by the density for the target material for each of the seven energy groups.

Columns 64-72 describe the fraction ϵ which is used to reduce the distance from source to target for the (at most four) source points nearest to the target.

Card 03:

Columns 1-3, 6-8, and 11-13 are blank.

Columns 4-5, 9-10, 14-15, and 19-20 are the upper and lower rows and right and left columns in the EQUIPOISE mesh bounding the source region.

Columns 21-30 and 31-40 are the angular positions in radians of the bounding surfaces in the θ coordinate of the source region. If these numbers are omitted, θ_1 is set to zero and θ_2 is set to π . In any case, the answer reported is for twice the angular increment $\theta_2 - \theta_1$, so that the full reactor is calculated for $\theta_2 - \theta_1 = \pi$. Note that the angular coordinate of the target itself is always zero.

Columns 41-42 indicate the method used for calculating buildup factors. If zero is used, the buildup factor for each material is based on the mean free path for attenuation between source point and target. If -1 is used, the buildup factor for each material is computed by using the distance in mean free paths of that material as the argument in the buildup-factor formula. If +1 is used, the results are printed out for both methods. (The calculation time is nearly doubled.)

Note that the boundaries of the source regions are halfway between rows, columns, and circles of mesh points. Care must therefore be taken when the dose from a particular EQUIPOISE region is desired, for if the P_c and P_f values in adjacent regions are not zero, sources outside the region of interest will be included.

NIGHTMARE INPUT TWO must follow card 03 of a block of NIGHTMARE INPUT ONE cards if column 72 of card 01 of that block is blank or zero. INPUT TWO locates the column numbers in the EQUIPOISE mesh where the attenuation and buildup properties change, as well as locates the changes in angular increments. Buildup and attenuation data are also supplied here (see Appendix B). Figure 7 shows this input form, which is to be filled out as follows:

Card 04:

Columns 4-5, 9-10, 14-15, 19-20, 24-25, 29-30, 34-35, 39-40, and 44-45 are, respectively, the column numbers of the outside radii of as many as 9 regions, each having different attenuation and buildup characteristics, as described on succeeding cards.

Columns 54-55, 59-60, 64-65, and 69-70 are the column numbers at which the radial increment is decreased by a factor of 3 from its value in the previous column. That is, if the number of $\Delta\theta$'s noted on card 01 of INPUT ONE were 8, it would be changed to 24 after JC1, to 72 after JC2, and so on. The succeeding cards give information in as many blocks as there are regions. The first block concerns energy group 1, the next group 2, and so on. Each block must be separated by a blank card.

Columns 1-9 give the attenuation coefficient of the region in units of reciprocal centimeters.

Columns 10-18 give the energy absorption coefficient divided by the density for the region. (This information is usually omitted, as it refers only to the target.)

Columns 19-27, 28-36, and 37-45 are the coefficients A, B, and C, respectively, in the empirical buildup-factor formula

$$BU_i(X) = 1 + AX + BX^2 + CX^3 ,$$

where $BU_i(X)$ is the buildup factor after a distance of X mean free paths in material i . A blank card must be used at the end of NIGHTMARE INPUT TWO.

The program output consists of the following items:

1. Title given on card 01 of INPUT ONE.
2. Target radius, target height, and total number of source points.
3. Total number of rows and columns in EQUIPOISE-2 mesh.
4. Column number and radial positions of inner and outer surfaces enclosing source region over which integration occurs.
5. Row numbers and heights measured from top of EQUIPOISE-2 mesh of upper and lower surfaces enclosing source region.
6. Angular positions of remaining two surfaces of the region of integrations; the target is always at the zero-angle position.
7. Tabulation of gamma dose at target point in whatever energy units per unit mass were employed on card 02 of INPUT ONE. Tabulation is from groups 1 to 7, and the total is given at the end. The results for $\epsilon = 0$ are compared with the results for whatever value of ϵ was used on card 02. Also, if columns 41-42 of card 03 were filled with +1, the results obtained with both buildup factors are displayed. If zero or blank were used, the "preferred" method results alone are displayed, and if -1 were used, the alternate method results alone are given.

The above describes only the NIGHTMARE gamma-heating output. The usual EQUIPOISE output is obtained off-line at the time of the running of the EQUIPOISE-2 part of the program (see Figs. 8-10).

NOTATION

A, B, C	Coefficients in empirical equation for buildup factors (energy dependent)
$BU(\vec{r}, \vec{r}_T, E)$	Buildup factor at energy level, E , between the source location, $\vec{r}$, and the target location, $\vec{r}_T$
d_i	Distance in i th material, cm
$E_1, E_2, \dots, E_7$	Energy of groups 1 to 7 respectively
p_i	Distance in i th material, cm, projected on a horizontal plane
P_c, P_f	Number of photons produced per capture and per fission respectively
$\vec{r}, \vec{r}_T$	Source and target locations respectively
R	Radial distance, cm

$s(E, \vec{r})$	Source strength, photons per unit energy range per cm^3 per sec
$S_p(R, Z)$	Source strength over an energy range, photons $\text{cm}^{-3} \text{sec}^{-1}$
$V, \Delta V$	Volume and volume increment, cm^3
Z	Axial distance measured from the top of the EQUIPOISE mesh
ϵ	A number $0 \leq \epsilon < 1$ used to correct source-to-target distances
$\mu_e(E)$	Energy absorption coefficient at energy level, E , for target material, cm^{-1}
μ_i	Attenuation coefficient, cm^{-1}
ρ	Density, g/cm^3
$\theta, \Delta\theta$	Angular measurement and angular increment, radians

Fig. 8. Sample Problem; EQUIPOISE Output.

SAMPLE PROBLEM FOR NIGHTMARE -- BSR GAMMA HEATING

REACTOR SPECIFICATIONS

1 (ROWS) #12	1 (COLS) #12	NO. REG. # 7	BND. COND. (1, R, B) #0, 0, 1	1 (NORM) #11	1 (NORM) #2	EPI #10.000E-04
--------------	--------------	--------------	-------------------------------	--------------	-------------	-----------------

MESH SPECIFICATIONS

I DELZ

1 15.240 4 7.620 5 4.689 12

J DELR

1 4.978 6 3.460 8 7.400 9 14.800 10 20.100 12

REGION SPECIFICATIONS

REG	I1	I2	J1	J2	DT	DT	STG1	STG2	NUSF1	NUSF2	RES.ESCAPE	PHI1	PHI2
1	1	4	1	12	2.000E-00	1.619E-01	4.000E-02	1.838E-02	-0.	-0.	9.898E-01	10.000E-02	1.000E-00
2	4	5	1	9	1.500E-00	1.619E-01	5.230E-02	1.838E-02	-0.	-0.	9.898E-01	8.000E-00	2.500E-01
3	5	8	1	6	1.435E-00	2.533E-01	2.745E-02	7.066E-02	3.125E-03	1.039E-01	9.142E-01	2.400E-02	8.000E-01
4	8	12	1	4	1.434E-00	2.533E-01	2.718E-02	7.066E-02	3.109E-03	1.039E-01	9.138E-01	3.000E-02	1.000E-02
5	8	12	4	6	1.435E-00	2.533E-01	2.745E-02	7.066E-02	3.125E-03	1.039E-01	9.142E-01	2.400E-02	8.000E-01
6	5	12	6	9	1.500E-00	1.619E-01	5.230E-02	1.838E-02	-0.	-0.	9.898E-01	8.000E-00	2.500E-01
7	4	12	9	12	2.000E-00	1.619E-01	4.000E-02	1.838E-02	-0.	-0.	9.898E-01	10.000E-02	1.000E-00

SAMPLE PROBLEM FOR NIGHTMARE -- BSR GAMMA HEATING.

FLUX CALCULATION BEGINS - BETAF# 1.600 BETAS# 1.600

IT	ID	SUMRESF#5.015E-03	SUMRESS#7.364E-04	MAXRESF(5, 3)#1.503E-03	MAXRESS(10, 6)#1.720E-04	PHI R# 9.984E-01
10		CONVR(NUCRIT), MAX PT. MIN PT.		CONVR(FLUX) MAX PT. MIN PT.		NU CRITICAL
10		1.864E-01 (5, 2) (10, 6)		7.071E-02 (6, 11) (2, 2)		1.00717E-00
20		1.499E-02 (11, 6) (5, 2)		6.105E-01 (2, 11) (3, 11)		1.00770E-00
30		7.083E-04 (5, 5) (5, 6)		4.467E-02 (3, 11) (2, 11)		1.00389E-00
11	30	SUMRESF#1.116E-05	SUMRESS#1.711E-05	MAXRESF(7, 5)#9.579E-06	MAXRESS(5, 7)#4.666E-06	PHI R# 9.999E-01

SAMPLE PROBLEM FOR NIGHTMARE -- BSR GAMMA HEATING

30 ITERATIONS CONVR(NUCRIT)# 7.083E-04 CONVR(FLUX)# 4.467E-02 NU CRITICAL# 1.00396E-00 PHI R# 9.99947E-01

FAST FLUX(I, J)

	1	2	3	4	5	6	7	8	9	10
1	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
2	2.628E-01	2.628E-01	2.450E-01	2.121E-01	1.695E-01	1.245E-01	9.615E-02	7.163E-02	3.380E-02	6.970E-03
3	2.085E-00	2.085E-00	1.930E-00	1.642E-00	1.267E-00	8.717E-01	6.327E-01	4.382E-01	1.764E-01	3.103E-02
4	1.652E-01	1.652E-01	1.521E-01	1.275E-01	9.472E-02	5.882E-02	3.802E-02	2.301E-02	7.392E-03	1.109E-03
5	7.973E-01	7.973E-01	7.335E-01	6.129E-01	4.472E-01	2.445E-01	1.263E-01	6.200E-02	1.485E-02	1.959E-03
6	1.418E-02	1.418E-02	1.305E-02	1.092E-02	8.005E-03	4.339E-03	2.074E-03	9.537E-04	2.088E-04	2.582E-05
7	1.897E-02	1.897E-02	1.746E-02	1.462E-02	1.073E-02	5.836E-03	2.786E-03	1.269E-03	2.693E-04	3.215E-05
8	2.294E-02	2.294E-02	2.112E-02	1.769E-02	1.299E-02	7.075E-03	3.380E-03	1.538E-03	3.231E-04	3.791E-05
9	2.605E-02	2.605E-02	2.398E-02	2.009E-02	1.476E-02	8.041E-03	3.843E-03	1.749E-03	3.661E-04	4.261E-05
10	2.818E-02	2.818E-02	2.595E-02	2.174E-02	1.597E-02	8.704E-03	4.160E-03	1.893E-03	3.959E-04	4.592E-05
11	2.926E-02	2.926E-02	2.695E-02	2.258E-02	1.659E-02	9.041E-03	4.321E-03	1.967E-03	4.112E-04	4.762E-05
12	2.926E-02	2.926E-02	2.695E-02	2.258E-02	1.659E-02	9.041E-03	4.321E-03	1.967E-03	4.112E-04	4.762E-05

Fig. 8 (continued)

SAMPLE PROBLEM FOR NIGHTMARE -- BSR GAMMA HEATING

FAST FLUX(I,J)

	11	12
1	0.	0.
2	2.776E-04	0.
3	3.488E-03	0.
4	1.083E-02	0.
5	1.744E-02	0.
6	2.205E-02	0.
7	2.668E-02	0.
8	3.095E-02	0.
9	3.447E-02	0.
10	3.696E-02	0.
11	3.825E-02	0.
12	3.825E-02	0.

SAMPLE PROBLEM FOR NIGHTMARE -- BSR GAMMA HEATING

SLOW FLUX(I,J)

	1	2	3	4	5	6	7	8	9	10
1	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
2	6.826E-01	6.826E-01	6.365E-01	5.517E-01	4.412E-01	3.253E-01	2.517E-01	1.880E-01	8.870E-02	1.812E-02
3	5.316E 00	5.316E 00	4.922E 00	4.194E 00	3.255E 00	2.272E 00	1.671E 00	1.170E 00	4.693E-01	8.184E-02
4	3.908E 01	3.908E 01	3.601E 01	3.030E 01	2.287E 01	1.527E 01	1.071E 01	6.903E 00	2.137E 00	2.956E-01
5	7.590E 01	7.590E 01	6.986E 01	5.862E 01	4.449E 01	3.583E 01	3.046E 01	1.918E 01	4.667E 00	5.327E-01
6	5.450E 01	5.450E 01	5.019E 01	4.226E 01	3.311E 01	3.606E 01	4.269E 01	2.799E 01	6.531E 00	7.040E-01
7	6.606E 01	6.606E 01	6.086E 01	5.131E 01	4.046E 01	4.581E 01	5.590E 01	3.672E 01	8.396E 00	8.767E-01
8	7.885E 01	7.885E 01	7.267E 01	6.143E 01	4.858E 01	5.523E 01	6.755E 01	4.438E 01	1.007E 01	1.034E 00
9	8.905E 01	8.905E 01	8.210E 01	6.956E 01	5.513E 01	6.273E 01	7.676E 01	5.042E 01	1.141E 01	1.163E 00
10	9.629E 01	9.629E 01	8.879E 01	7.525E 01	5.966E 01	6.790E 01	8.310E 01	5.458E 01	1.234E 01	1.253E 00
11	10.000E 01	10.000E 01	9.221E 01	7.816E 01	6.197E 01	7.053E 01	8.632E 01	5.670E 01	1.281E 01	1.300E 00
12	10.000E 01	10.000E 01	9.221E 01	7.816E 01	6.197E 01	7.053E 01	8.632E 01	5.670E 01	1.281E 01	1.300E 00

SAMPLE PROBLEM FOR NIGHTMARE -- BSR GAMMA HEATING

SLOW FLUX(I,J)

	11	12
1	0.	0.
2	2.256E-03	0.
3	9.240E-03	0.
4	2.826E-02	0.
5	4.588E-02	0.
6	5.809E-02	0.
7	7.038E-02	0.
8	8.169E-02	0.
9	9.100E-02	0.
10	9.757E-02	0.
11	1.010E-01	0.
12	1.010E-01	0.

Fig. 8 (continued)

SAMPLE PROBLEM FOR NIGHTMARE -- BSR GAMMA HEATING

TOTAL FAST GROUP PRODUCTION #	2.10817E 04
TOTAL SLOW GROUP PRODUCTION #	2.94462E 05
TOTAL FAST GROUP ABSORPTION #	1.72317E 04
TOTAL SLOW GROUP ABSORPTION #	2.99394E 05
TOTAL FAST GROUP TOP LEAKAGE #	7.77789E 01
TOTAL SLOW GROUP TOP LEAKAGE #	1.64304E 01
TOTAL FAST GROUP RIT LEAKAGE #	6.05367E 01
TOTAL SLOW GROUP RIT LEAKAGE #	1.29097E 01
TOTAL FAST GROUP BOT LEAKAGE #	0.
TOTAL SLOW GROUP BOT LEAKAGE #	0.

REGION ABSORPTIONS

REGION	FAST ABSORP	SLOW ABSORP
1	1.07949E 02	1.24812E 04
2	2.52168E 02	1.33371E 04
3	5.38050E 03	7.46742E 04
4	4.46532E 03	4.62711E 04
5	6.04230E 03	7.93753E 04
6	8.69935E 02	5.79279E 04
7	1.13547E 02	1.53271E 04

SAMPLE PROBLEM FOR NIGHTMARE -- BSR GAMMA HEATING

SOURCE(I,J)

	1	2	3	4	5
1	0. 0.	0. -0.	0. -0.	0. -0.	0. -0.
2	0. 0.	-0. -0.	-0. -0.	-0. -0.	-0. -0.
3	0. 0.	-0. -0.	-0. -0.	-0. -0.	-0. -0.
4	0. 0.	-0. -0.	-0. -0.	-0. -0.	-0. -0.
5	0. 0.	-0. 8.133E 00	-0. 8.133E 00	-0. 8.133E 00	-0. 8.133E 00
6	0. 0.	6.104E 00 6.104E 00	6.104E 00 6.104E 00	6.104E 00 6.104E 00	6.104E 00 6.104E 00
7	0. 0.	7.455E 00 7.455E 00	7.455E 00 7.455E 00	7.455E 00 7.455E 00	7.455E 00 7.455E 00
8	0. 0.	8.907E 00 8.903E 00	8.907E 00 8.903E 00	8.907E 00 8.903E 00	8.907E 00 8.903E 00
9	0. 0.	1.006E 01 1.006E 01	1.006E 01 1.006E 01	1.006E 01 1.006E 01	1.006E 01 1.006E 01
10	0. 0.	1.088E 01 1.088E 01	1.088E 01 1.088E 01	1.088E 01 1.088E 01	1.088E 01 1.088E 01
11	0. 0.	1.130E 01 1.130E 01	1.130E 01 1.130E 01	1.130E 01 1.130E 01	1.130E 01 1.130E 01
12	0. 0.	1.130E 01 0.	1.130E 01 0.	1.130E 01 0.	1.130E 01 0.

Fig. 8 (continued)

SAMPLE PROBLEM FOR NIGHTMARE -- BSR GAMMA HEATING

SOURCE(I,J)

	6	7	8	9	10
1	0. -0.	0. -0.	0. -0.	0. -0.	0. -0.
2	-0. -0.	-0. -0.	-0. -0.	-0. -0.	-0. -0.
3	-0. -0.	-0. -0.	-0. -0.	-0. -0.	-0. -0.
4	-0. -0.	-0. -0.	-0. -0.	-0. -0.	-0. -0.
5	-0. 3.798E 00-0.	-0. -0.	-0. -0.	-0. -0.	-0. -0.
6	3.881E 00-0. 3.881E 00-0.	-0. -0.	-0. -0.	-0. -0.	-0. -0.
7	4.941E 00-0. 4.941E 00-0.	-0. -0.	-0. -0.	-0. -0.	-0. -0.
8	5.958E 00-0. 5.958E 00-0.	-0. -0.	-0. -0.	-0. -0.	-0. -0.
9	6.767E 00-0. 6.767E 00-0.	-0. -0.	-0. -0.	-0. -0.	-0. -0.
10	7.325E 00-0. 7.325E 00-0.	-0. -0.	-0. -0.	-0. -0.	-0. -0.
11	7.609E 00-0. 7.609E 00-0.	-0. -0.	-0. -0.	-0. -0.	-0. -0.
12	7.609E 00-0. 0.	-0. 0.	-0. 0.	-0. 0.	-0. 0.

SAMPLE PROBLEM FOR NIGHTMARE -- BSR GAMMA HEATING

SOURCE(I,J)

	11	12
1	0. -0.	0. 0.
2	-0. -0.	0. 0.
3	-0. -0.	0. 0.
4	-0. -0.	0. 0.
5	-0. -0.	0. 0.
6	-0. -0.	0. 0.
7	-0. -0.	0. 0.
8	-0. -0.	0. 0.
9	-0. -0.	0. 0.
10	-0. -0.	0. 0.
11	-0. -0.	0. 0.
12	-0. 0.	0. 0.

Fig. 9. Sample Problem; NIGHTMARE Output.

SAMPLE PROBLEM FOR NIGHTMARE -- BSR GAMMA HEATING				
BSR GAMMA HEATING AL-1 CORE ONLY				
TARGET RADIUS	2.4130E 01	TARGET HEIGHT	8.3818E 01	TOTAL POINTS 240
11 COLUMNS, RADIUS 71.62 CM. 11 ROWS, HEIGHT 81.47 CM.				
CALCULATED BETWEEN				
COLUMN 2 RADIUS	2.49 CM.	AND COLUMN 6 RADIUS	22.40 CM.	
ROW 6 HEIGHT	58.03 CM.	AND ROW 11 HEIGHT	81.47	
-0. DEGREES AND 180.000 DEGREES				
X = SUMMATION OF MU(I)*D(I) X = MU(I)*D(AC)				
EPSILON = 0 EPSILON = 0.25 EPSILON = 0 EPSILON = 0.25				
GAMMA DOSE FROM ENERGY GROUP 1	0.	0.	3.35519E-01	3.35519E-01
GAMMA DOSE FROM ENERGY GROUP 2	0.	0.	1.60011E 00	1.79302E 00
GAMMA DOSE FROM ENERGY GROUP 3	0.	0.	2.10043E 00	2.36292E 00
GAMMA DOSE FROM ENERGY GROUP 4	0.	0.	7.70667E-01	8.47608E-01
GAMMA DOSE FROM ENERGY GROUP 5	0.	0.	2.34558E-01	2.57353E-01
GAMMA DOSE FROM ENERGY GROUP 6	0.	0.	1.89903E-01	2.08210E-01
GAMMA DOSE FROM ENERGY GROUP 7	0.	0.	1.30865E-01	1.45160E-01
TOTAL GAMMA DOSE FROM ALL GROUPS	0.	0.	5.36205E 00	5.94979E 00

SAMPLE PROBLEM FOR NIGHTMARE -- BSR GAMMA HEATING				
BSR GAMMA HEATING AL-1 FRONT HALF OF REAC				
TARGET RADIUS	2.4130E 01	TARGET HEIGHT	8.3818E 01	TOTAL POINTS 400
11 COLUMNS, RADIUS 71.62 CM. 11 ROWS, HEIGHT 81.47 CM.				
CALCULATED BETWEEN				
COLUMN 2 RADIUS	2.49 CM.	AND COLUMN 11 RADIUS	71.62 CM.	
ROW 2 HEIGHT	15.24 CM.	AND ROW 11 HEIGHT	81.47	
-0. DEGREES AND 89.997 DEGREES				
X = SUMMATION OF MU(I)*D(I) X = MU(I)*D(AC)				
EPSILON = 0 EPSILON = 0.25 EPSILON = 0 EPSILON = 0.25				
GAMMA DOSE FROM ENERGY GROUP 1	3.08894E-01	3.08894E-01	2.97168E-01	2.97168E-01
GAMMA DOSE FROM ENERGY GROUP 2	1.50262E 00	1.69553E 00	1.50655E 00	1.69947E 00
GAMMA DOSE FROM ENERGY GROUP 3	2.79686E 00	3.17747E 00	2.81287E 00	3.19349E 00
GAMMA DOSE FROM ENERGY GROUP 4	6.84962E-01	7.61903E-01	6.90912E-01	7.67852E-01
GAMMA DOSE FROM ENERGY GROUP 5	2.06819E-01	2.29615E-01	2.08426E-01	2.31222E-01
GAMMA DOSE FROM ENERGY GROUP 6	1.67070E-01	1.85377E-01	1.68171E-01	1.86478E-01
GAMMA DOSE FROM ENERGY GROUP 7	1.19422E-01	1.33718E-01	1.20390E-01	1.34685E-01
TOTAL GAMMA DOSE FROM ALL GROUPS	5.78665E 00	6.49251E 00	5.80449E 00	6.51036E 00

Fig. 9 (continued)

SAMPLE PROBLEM FOR NIGHTMARE -- BSR GAMMA HEATING				
BSR GAMMA HEATING AL-1 TARGET		AUG-60		
TARGET RADIUS	2.4130E 01	TARGET HEIGHT	8.3818E 01	TOTAL POINTS 800
11 COLUMNS, RADIUS	71.62 CM.	11 ROWS, HEIGHT	81.47 CM.	
CALCULATED BETWEEN				
COLUMN 2 RADIUS	2.49 CM.	AND COLUMN 11 RADIUS	71.62 CM.	
ROW 2 HEIGHT	15.24 CM.	AND ROW 11 HEIGHT	81.47	
-0. DEGREES AND 180.000 DEGREES				
X = SUMMATION OF MU(I)*D(I)			X = MU(I)*D(AC)	
	EPSILON = 0	EPSILON = 0.25	EPSILON = 0	EPSILON = 0.25
GAMMA DOSE FROM ENERGY GROUP 1	3.57432E-01	3.57432E-01	0.	0.
GAMMA DOSE FROM ENERGY GROUP 2	1.61049E 00	1.80340E 00	0.	0.
GAMMA DOSE FROM ENERGY GROUP 3	3.01059E 00	3.39121E 00	0.	0.
GAMMA DOSE FROM ENERGY GROUP 4	7.74288E-01	8.51229E-01	0.	0.
GAMMA DOSE FROM ENERGY GROUP 5	2.36044E-01	2.58840E-01	0.	0.
GAMMA DOSE FROM ENERGY GROUP 6	1.91363E-01	2.09670E-01	0.	0.
GAMMA DOSE FROM ENERGY GROUP 7	1.31262E-01	1.45558E-01	0.	0.
TOTAL GAMMA DOSE FROM ALL GROUPS	6.31147E 00	7.01734E 00	0.	0.

UNCLASSIFIED
ORNL-LR-DWG 64465

Fig. 10. Geometric Mesh for EQUIPOISE and NIGHTMARE Calculations of Sample Heating in the BSR. Regions shown were used to specify nuclear properties (the core consists of regions marked 3, 4, and 5). NIGHTMARE mesh is I from 2 to 11, J from 2 to 11.

Appendix A

COMPARISON OF RESULTS WITH EXPERIMENT (BSR)

In the course of checking out the NIGHTMARE code, heat-generation rates were calculated in targets in the BSR for which experimental determinations⁵ are available. The rectangular core was simulated with a cylindrical core as follows: actual core: 18 in. deep $\times$ 15 in. wide $\times$ 24 in. high; nuclear equivalent cylinder: 8.82-in. radius $\times$ 24-in. height.

A critical, homogeneous core was established for a fuel concentration of 9.4×10^{19} atoms of U^{235} per cm^3 , using the GNU⁶ one-dimensional, multigroup code. Homogeneous poison was added to reduce k_{eff} to 1.0 from a clean value of 1.0734. A perpendicular buckling of 0.00171 was applied to the fuel region only, equivalent to adding an extrapolation distance of 7.5 cm on this region; axial leakage in the reflector was neglected.

An EQUIPOISE two-dimensional, two-group calculation was made, employing the two-group nuclear constants generated by GNU. Since the fuel region and reflector had each been subdivided into two regions for the GNU calculation, variation with radial position of the fast-group properties was in part taken into account; this same variation was assumed to apply axially. It was found that k_{eff} was 0.99606 without modification of the nuclear properties.

The following assumptions were made for the heat-generation calculations:

1. A fission product delayed-gamma source of 6.75 Mev/fission was distributed (geometrically) in the same way as the prompt-plus-capture gamma source in the fuel region.

2. Delayed gammas from aluminum of 1.782 Mev (core and Al target) and delayed betas having an average energy of 1.249 Mev ($E_{max} = 2.856$) were assumed.

⁵T. B. Fowler and M. Tobias, EQUIPOISE-2 - A Two-Dimensional, Two-Group, Neutron Diffusion Code for the IBM-7090 Computer, ORNL CF-60-11-67 (Nov. 21, 1960).

⁶C. L. Davis, J. M. Bookston, and B. E. Smith, GNU-II - A Multigroup One-Dimension Diffusion Program, GMR-101 (Nov. 12, 1957).

3. The target was assumed to be sufficiently small for flux depression at the target to be neglected.

4. Heating from radiation generated in the target itself is calculated by using an escape probability for a cylinder having a uniform isotropic source, and neglecting buildup.

5. It was assumed that there were 1.25 photons per capture in H_2O of 2.0 Mev as opposed to the more accurate 1.0 photon per capture of 2.2 Mev.

The fluxes of photons having discrete energies were established at three radial locations from prompt-plus-capture gamma-ray sources by the NIGHTMARE code. This calculation was made for the whole reactor and also for the core only, using 800 and 280 mesh points respectively.

Heat-generation rates in targets of aluminum, iron, and lead were calculated from these photon flux values and EQUIPOISE neutron flux levels at the target locations. Results of calculations are compared with experimental results⁵ in Table A.1 and in Fig. A.1. Certain data used are given in Table A.2.

The actual radial positions of targets have been used in these calculations. In the reactor the targets were located opposite the narrow side; therefore the distances used in the calculation from the reactor edge to the targets are greater than in the actual experimental situation. This difference would be expected to cause the calculated heating rates to be somewhat low.

It is worth noting that a relatively large mesh spacing is associated with only 800 mesh points; with each point is associated an appreciable volume. The calculated result may be expected to be slightly on the low side due to this large mesh spacing, even though a value of ϵ was used to account for the effect of a finite mesh.

In this calculation it was found that only 7.3% of the captures in the fuel region occurred in fission products and control rods. Therefore the high-energy gamma-ray source associated with capture in the rod is not very significant. If there were an appreciable amount of cadmium in the reactor at the time in question, then this additional contribution would increase the heat-generation rates by an amount which would increase in significance with distance from the core.

The calculated results are considered to be sufficiently in agreement with observations to warrant general application of this code to problems of local heat generation in reactors.

Table A.1. Heat Generation in Targets in the BSR

Radius (cm)	Source	Heat Generation (w g ⁻¹ Mw ⁻¹)		
		Aluminum Target	Iron Target	Lead Target
Calculated				
24.13	Prompt + capture + activation gamma	0.1219	0.1256	0.2202
	Delayed fission product gamma	0.0657	0.0656	0.1214
	Target gamma + beta	0.0108	0.0393	0.0015
	Total	0.1984	0.2305	0.3431
33.02	Prompt + capture + activation gamma	0.05001	0.05155	0.08427
	Delayed fission product gamma	0.02155	0.02152	0.03893
	Target gamma + beta	0.00370	0.0131	0.00045
	Total	0.07526	0.08617	0.12365
45.72	Prompt + capture + activation gamma	0.01663	0.01850	0.02734
	Delayed fission product gamma	0.00670	0.00671	0.01175
	Target gamma + beta	0.00037	0.00131	0.00005
	Total	0.02370	0.02652	0.03914
Experimental				
24.13		0.219	0.271	0.332
26.95		0.132	0.173	
30.48				0.175
33.02		0.0745	0.105	
38.10				0.090
45.72				0.043

UNCLASSIFIED
ORNL-LR-DWG 64200

Fig. A.1. Comparison of Code Calculation Results with Experimentally Measured Structural Heating in the BSR. Calculated result includes prompt and capture gammas, fission product delayed gammas, and target capture and decay gammas and betas.

Table A.2. Data for Target Heating Calculation in the BSR

Energy (Mev)	Photons Produced per Neutron Production	Photons Produced per Neutron Capture in Fuel Region	Fission Product Delayed Gamma (photons $\text{Mw}^{-1} \text{sec}^{-1}$)	$\mu_e E^{(a)}$ (Mev/cm)			$\mu_T^{(b)}$ (cm^{-1} at 60°C)			
				Al ($\rho=2.7$)	Fe ($\rho=7.85$)	Pb ($\rho=11.353$)	H ₂ O	Al	Al/H ₂ O = 1.0	Al/H ₂ O = 0.7
0.5	1.56	0.3924	10×10^{16}	0.03875	0.1155	0.564	0.0323	0.228	0.130	0.1129
1	0.82	0.4287	10×10^{16}	0.0733	0.207	0.454	0.0305	0.165	0.0978	0.0859
2	0.484	0.2726	3.18×10^{16}	0.1244	0.366	0.66	0.0257	0.116	0.0708	0.0629
4	0.102	0.0596	0.12×10^{16}	0.2168	0.704	1.524	0.0210	0.0838	0.0524	0.0469
6	0.0193	0.0156		0.3072	1.092	2.604	0.0185	0.0716	0.0450	0.0404
8	0.00131	0.0052		0.399	1.52	3.848	0.0171	0.0656	0.0414	0.0371
10	0	0		0.494	1.96	5.27	0.0163	0.0620	0.0392	0.0351

(a) Linear energy absorption coefficient times energy.

(b) Linear total absorption coefficient.

Appendix B

PROPERTIES OF MATERIALS FOR USE IN REACTOR
HEAT-GENERATION CALCULATIONS

Definitions

Z = atomic numbers; for mixtures, the equivalent Z used must correspond to the actual attenuation properties of the mixture

μ = total linear attenuation coefficient, cm^{-1} , proportional to density for a material

μ_e = linear energy absorption coefficient, cm^{-1} , proportional to density for a material

$\mu/\rho \equiv \mu_e/\rho$ = mass energy absorption coefficient, cm^2/g , independent of density

Note: for $\mu/\rho \equiv \mu_e/\rho$ input, it may be desirable to use one of the following:

μ_e/ρ , in which case heat-generation rate calculated is in photons/g, but the NIGHTMARE total is meaningless because the results for each energy group must be multiplied by the energy before they can be summed;

μ_e , in which case heat-generation rate calculated is in photons/ cm^3 , but the NIGHTMARE total is meaningless;

$E\mu_e/\rho$, in which case heat-generation rate calculated is in Mev/g, and the total is correct;

$E\mu_e$, in which case heat-generation rate calculated is in Mev/ cm^3 , and the total is correct (here E is the group photon energy, Mev).

Conversion Factors

$$1.603 \times 10^{-13} \text{ w-sec/Mev} = 1.0$$

$$3.38 \times 10^{16} \text{ fissions/Mw-sec} = 1.0$$

$$3.6 \times 10^8 \text{ (rads/hr)/(w/g)} = 1.0$$

Table B.1. Linear Total Attenuation Coefficients, μ

Target Material	Density (g/cm ³)	Atoms per barn-cm	μ (cm ⁻¹) at Energies of						
			0.5 Mev	1 Mev	2 Mev	4 Mev	6 Mev	8 Mev	10 Mev
H		(0.06682)	0.0193	0.0141	0.00982	0.00648	0.00502	0.00418	0.00363
Be	1.846	0.1233	0.143	0.104	0.0726	0.0491	0.0391	0.0334	0.0300
B	2.0	0.1113	0.161	0.118	0.082	0.0559	0.0448	0.0387	0.0349
C	1.671	0.0838	0.146	0.106	0.0742	0.0509	0.0411	0.0359	0.0326
O		(0.03341)	0.0772	0.0565	0.0394	0.0275	0.0226	0.0200	0.0184
Mg	1.74	0.0431	0.150	0.109	0.0767	0.0547	0.0465	0.0423	0.0399
Al	2.70	0.0602	0.228	0.165	0.116	0.0838	0.0716	0.0656	0.0620
Ti	4.50	0.0566	0.0368	0.265	0.187	0.142	0.129	0.123	0.121
Fe	7.854	0.0847	0.660	0.470	0.334	0.259	0.240	0.234	0.232
Ni	8.90	0.0913	0.772	0.547	0.389	0.305	0.285	0.279	0.279
Cu	8.09	0.0842	0.741	0.523	0.372	0.294	0.275	0.271	0.272
Zr	6.44	0.0425	0.557	0.373	0.266	0.222	0.217	0.211	0.226
Cd	8.65	0.0463	0.792	0.500	0.357	0.308	0.308	0.318	0.330
I	4.94	0.0234	0.470	0.285	0.202	0.178	0.181	0.188	0.196
Xe		(0.0024)	0.050	0.030	0.021	0.019	0.019	0.020	0.021
Pm		(0.030)	0.783	0.444	0.309	0.278	0.289	0.300	0.318
Sm	7.7	0.0308	0.832	0.465	0.323	0.292	0.304	0.317	0.333
Eu	5.24	0.0208	0.580	0.322	0.225	0.202	0.210	0.220	0.231
Ta	16.6	0.0553	2.15	1.08	0.730	0.669	0.708	0.741	0.785
Pb	11.347	0.0330	1.73	0.795	0.521	0.485	0.505	0.535	0.571
Th	11.5	0.0298	2.04	0.873	0.554	0.513	0.533	0.563	0.599
U	18.7	0.0473	3.47	1.46	0.913	0.842	0.880	0.927	0.998
Pu	16.1	0.0406	3.17	1.32	0.816	0.747	0.775	0.824	0.877
H ₂ O, $\rho = 1.00$ at 20°C			0.0965	0.0706	0.0492	0.0340	0.0276	0.0242	0.0220
$\rho = 0.974$ at 80°C			0.0939	0.0687	0.0480	0.0331	0.0269	0.0235	0.0215
$\rho = 0.917$ at 150°C			0.0887	0.0648	0.0453	0.0312	0.0254	0.0222	0.0202
Concrete, $\rho = 2.3$			0.201	0.147	0.102	0.073	0.062	0.056	0.053
$\rho = 2.6$			0.226	0.165	0.114	0.083	0.072	0.066	0.063
$\rho = 3.0$			0.259	0.188	0.131	0.096	0.084	0.078	0.075
Barytes, $\rho = 3.5$			0.326	0.217	0.152	0.120	0.112	0.109	0.109
D ₂ O, $\rho = 0.826$ at 280°C			0.0719	0.0526	0.0367	0.0253	0.0206	0.0180	0.0164

Table B.2. Linear Energy Absorption Coefficients, μ_e , for Target Material

Target Material	Density (g/cm ³)	Atoms per barn-cm	μ_e (cm ⁻¹) at Energies of						
			0.5 Mev	1 Mev	2 Mev	4 Mev	6 Mev	8 Mev	10 Mev
H		(0.06682)	0.00660	0.00622	0.00523	0.00395	0.00328	0.00284	0.00255
Be	1.846	0.1233	0.0491	0.0457	0.0387	0.0305	0.0263	0.0235	0.0220
B	2.0	0.1113	0.0550	0.0520	0.0440	0.0349	0.0300	0.0276	0.0259
C	1.671	0.0838	0.0505	0.0465	0.0397	0.0319	0.0279	0.0258	0.0245
O		(0.03341)	0.0263	0.0249	0.0210	0.0174	0.0156	0.0147	0.0141
Mg	1.74	0.0431	0.0509	0.0478	0.0412	0.0351	0.0330	0.0320	0.0315
Al	2.70	0.0602	0.0777	0.0730	0.0626	0.0543	0.0512	0.0499	0.0494
Ti	4.50	0.0566	0.127	0.117	0.102	0.0949	0.0965	0.0981	0.101
Fe	7.854	0.0847	0.231	0.207	0.183	0.176	0.182	0.190	0.196
Ni	8.90	0.0913	0.272	0.242	0.213	0.208	0.218	0.228	0.238
Cu	8.89	0.00842	0.681	0.492	0.355	0.201	0.213	0.222	0.233
Zr	6.44	0.0425	0.216	0.168	0.148	0.158	0.173	0.187	0.198
Cd	8.65	0.0463	0.338	0.230	0.203	0.224	0.250	0.274	0.294
I	4.94	0.0234	0.235	0.146	0.116	0.135	0.151	0.165	0.178
Xe		(0.0024)	0.0231	0.0142	0.0120	0.0141	0.0156	0.0174	0.0189
Pm		(0.030)	0.398	0.219	0.181	0.209	0.241	0.252	0.288
Sm	7.7	0.0308	0.428	0.230	0.190	0.220	0.254	0.279	0.302
Eu	5.24	0.0208	0.302	0.161	0.133	0.152	0.176	0.194	0.210
Ta	16.6	0.0553	1.273	0.577	0.450	0.516	0.602	0.660	0.720
Pb	11.347	0.0330	1.128	0.454	0.330	0.381	0.434	0.481	0.527
Th	11.5	0.0298	1.428	0.532	0.363	0.410	0.463	0.509	0.556
U	18.7	0.0473	2.47	0.903	0.602	0.684	0.766	0.840	0.928
Pu	16.1	0.0406	2.29	0.831	0.543	0.600	0.676	0.748	0.815
H ₂ O, $\rho = 1.00$ at 20°C			0.0329	0.0311	0.0262	0.0214	0.0189	0.0175	0.0166
$\rho = 0.974$ at 80°C			0.0319	0.0302	0.0254	0.0208	0.0183	0.0169	0.0161
$\rho = 0.917$ at 150°C			0.0302	0.0286	0.0241	0.0197	0.0174	0.0161	0.0153
Concrete, $\rho = 2.3$			0.069	0.065	0.056	0.047	0.044	0.042	0.040
$\rho = 2.6$			0.065	0.062	0.052	0.044	0.042	0.040	0.038
$\rho = 3.0$			0.060	0.058	0.048	0.041	0.039	0.037	0.036
Barytes, $\rho = 3.5$			0.119	0.087	0.074	0.073	0.077	0.080	0.084
ThO ₂ (5000 g of Th per liter)			0.642	0.251	0.174	0.192	0.214	0.233	0.253

Table B.3. Total Linear Attenuation Coefficients, μ , for Some Mixtures at 80°C

Target Material	μ (cm ⁻¹) at Energies of						
	0.5 Mev	1 Mev	2 Mev	4 Mev	6 Mev	8 Mev	10 Mev
Be (5% H ₂ O)	0.141	0.102	0.0714	0.0483	0.0385	0.0329	0.0296
Al/H ₂ O = 0.75	0.151	0.110	0.0771	0.0548	0.0461	0.0416	0.0388
= 1.0	0.161	0.117	0.0820	0.0584	0.0493	0.0446	0.0417
= 1.25	0.168	0.122	0.0858	0.0613	0.0517	0.0469	0.0440
= 4.0	0.201	0.146	0.102	0.0737	0.0627	0.0572	0.0539
Fe/H ₂ O = 1.0	0.377	0.269	0.191	0.146	0.133	0.129	0.127
= 4.0	0.547	0.390	0.277	0.214	0.197	0.192	0.190
Ni/H ₂ O = 1.0	0.433	0.308	0.218	0.169	0.156	0.151	0.150
= 4.0	0.636	0.451	0.321	0.251	0.233	0.228	0.227

Table B.4. Parameters A, B, and C for Energy Absorption Buildup Factor in the Equation

$$BU_{i,n}(\mu d) = 1.0 + A_{i,n}(\mu d) + B_{i,n}(\mu d)^2 + C_{i,n}(\mu d)^3$$

for a Point Isotropic Source

Material	Parameters A, B, and C for Energies of						
	0.5 Mev	1 Mev	2 Mev	4 Mev	6 Mev	8 Mev	10 Mev
	$A_{i,n}$						
H ₂ O ($\mu d < 15$)	0.840	0.970	0.830	0.589	0.460	0.381	0.312
Z							
2	0.22	0.97	0.76	0.65	0.54	0.45	0.39
4	0.44	0.98	0.76	0.63	0.51	0.42	0.36
6	0.64	0.99	0.76	0.60	0.48	0.40	0.34
8	0.83	1.00	0.76	0.58	0.46	0.37	0.31
10	1.01	1.01	0.76	0.56	0.43	0.34	0.29
12	1.19	1.02	0.76	0.54	0.41	0.32	0.26
14	1.32	1.03	0.76	0.52	0.38	0.30	0.24
16	1.42	1.04	0.76	0.51	0.36	0.28	0.22
18	1.50	1.05	0.76	0.49	0.34	0.26	0.20
20	1.55	1.06	0.75	0.47	0.33	0.24	0.18
22	1.59	1.07	0.75	0.46	0.31	0.22	0.17
24	1.62	1.08	0.75	0.44	0.30	0.21	0.16
26	1.64	1.09	0.75	0.43	0.28	0.20	0.15
28	1.64	1.10	0.74	0.42	0.27	0.19	0.14
30	1.64	1.11	0.74	0.41	0.26	0.18	0.14
32	1.63	1.11	0.74	0.39	0.25	0.17	0.13
34	1.61	1.12	0.73	0.38	0.24	0.17	0.13
36	1.59	1.12	0.73	0.37	0.23	0.16	0.13
38	1.56	1.13	0.72	0.36	0.22	0.16	0.12
40	1.53	1.13	0.72	0.36	0.22	0.15	0.12
42	1.49	1.13	0.71	0.35	0.21	0.15	0.12
44	1.44	1.13	0.71	0.34	0.21	0.15	0.12
46	1.39	1.13	0.70	0.33	0.20	0.14	0.11
48	1.34	1.12	0.70	0.32	0.20	0.14	0.11
50	1.29	1.11	0.69	0.32	0.19	0.14	0.11
52	0.24	1.10	0.68	0.31	0.19	0.13	0.11
54	1.19	1.09	0.67	0.30	0.18	0.13	0.10
56	1.15	1.08	0.67	0.30	0.18	0.13	0.10
58	1.10	1.06	0.66	0.29	0.17	0.12	0.10
60	1.05	1.04	0.65	0.29	0.17	0.12	0.10
62	1.01	1.02	0.65	0.28	0.16	0.12	0.10
64	0.96	1.00	0.64	0.27	0.16	0.11	0.10
66	0.91	0.98	0.64	0.27	0.16	0.11	0.09
68	0.87	0.96	0.63	0.26	0.15	0.11	0.09
70	0.82	0.94	0.62	0.26	0.15	0.11	0.09
72	0.78	0.92	0.62	0.25	0.15	0.11	0.09
74	0.73	0.90	0.61	0.25	0.14	0.11	0.09
76	0.69	0.87	0.61	0.24	0.14	0.10	0.09
78	0.65	0.85	0.60	0.24	0.14	0.10	0.09

Table B.4 (continued)

Material	Parameters A, B, and C for Energies of						
	0.5 Mev	1 Mev	2 Mev	4 Mev	6 Mev	8 Mev	10 Mev
	$B_{i,n}$						
H ₂ O ($\mu d < 15$)	0.600	0.175	0.037	0.0015	-0.0035	-0.005	-0.0055
Z							
2	0.53	0.126	0.055	0.05	0.05	0.05	0.05
4	0.50	0.125	0.053	0.04	0.04	0.04	0.04
6	0.464	0.125	0.051	0.03	0.03	0.03	0.03
8	0.436	0.124	0.049	0.015	0.015	0.015	0.015
10	0.402	0.123	0.047	0.010	0.010	0.010	0.010
12	0.367	0.121	0.045	0.005	0.003	0.002	0.001
14	0.336	0.120	0.043	0.007	0.005	0.003	0.002
16	0.305	0.118	0.041	0.008	0.006	0.004	0.003
18	0.275	0.116	0.039	0.011	0.008	0.006	0.005
20	0.244	0.113	0.038	0.013	0.010	0.008	0.007
22	0.215	0.109	0.037	0.015	0.012	0.010	0.009
24	0.188	0.105	0.036	0.017	0.014	0.010	0.009
26	0.160	0.100	0.036	0.019	0.015	0.011	0.009
28	0.142	0.094	0.036	0.021	0.017	0.011	0.009
30	0.103	0.088	0.036	0.022	0.018	0.011	0.009
32	0.091	0.082	0.036	0.023	0.019	0.010	0.008
34	0.070	0.079	0.036	0.023	0.019	0.010	0.008
36	0.050	0.067	0.036	0.023	0.019	0.009	0.007
38	0.031	0.058	0.036	0.022	0.018	0.009	0.007
40	0.014	0.050	0.036	0.022	0.018	0.008	0.006
42	0.0	0.041	0.036	0.021	0.017	0.007	0.005
44	-0.013	0.032	0.036	0.021	0.017	0.006	0.004
46	-0.025	0.022	0.036	0.020	0.016	0.005	0.003
48	-0.035	0.013	0.036	0.020	0.016	0.004	0.002
50	-0.043	0.004	0.036	0.019	0.015	0.004	0.002
52	-0.048	-0.005	0.035	0.018	0.015	0.003	0.001
54	-0.053	-0.013	0.032	0.018	0.014	0.003	0.001
56	-0.056	-0.020	0.028	0.017	0.013	0.002	0.001
58	-0.058	-0.027	0.025	0.017	0.012	0.002	0.0
60	-0.060	-0.033	0.022	0.016	0.011	0.001	-0.001
62	-0.062	-0.037	0.018	0.015	0.010	0.001	-0.001
64	-0.063	-0.040	0.015	0.015	0.009	0.001	-0.002
66	-0.064	-0.043	0.012	0.014	0.008	0.0	-0.003
68	-0.065	-0.045	0.008	0.014	0.007	-0.001	-0.003
70	-0.066	-0.047	0.005	0.013	0.006	-0.001	-0.004
72	-0.067	-0.048	0.002	0.013	0.005	-0.002	-0.005
74	-0.067	-0.050	-0.002	0.012	0.004	-0.002	-0.005
76	-0.068	-0.051	-0.004	0.011	0.003	-0.003	-0.006
78	-0.068	-0.052	-0.006	0.010	0.002	-0.004	-0.006

Table B.4 (continued)

Material	Parameters A, B, and C for Energies of						
	0.5 Mev	1 Mev	2 Mev	4 Mev	6 Mev	8 Mev	10 Mev
	$C_{i,n}$						
H ₂ O ($\mu d < 15$)	0	0	0	0	0	0	0
Z							
2	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0
26	0	0	0	0	0	0	0
28	0.0001	0	-0.0001	0.0001	0.0001	0.0001	0.0001
30	0.0002	0	-0.0002	0.0002	0.0002	0.0002	0.0002
32	0.0003	0	-0.0002	0.0004	0.0003	0.0003	0.0003
34	0.0005	0.0001	-0.0003	0.0005	0.0004	0.0005	0.0005
36	0.0008	0.0001	-0.0004	0.0006	0.0005	0.0008	0.0008
38	0.0010	0.0002	-0.0005	0.0007	0.0006	0.0010	0.0010
40	0.0012	0.0002	-0.0005	0.0008	0.0006	0.0012	0.0012
42	0.0014	0.0003	-0.0006	0.0008	0.0007	0.0013	0.0014
44	0.0015	0.0004	-0.0006	0.0009	0.0008	0.0014	0.0015
46	0.0016	0.0005	-0.0006	0.0009	0.0009	0.0015	0.0016
48	0.0017	0.0006	-0.0007	0.0010	0.0010	0.0016	0.0017
50	0.0018	0.0007	-0.0007	0.0010	0.0010	0.0017	0.0018
52	0.0019	0.0008	-0.0006	0.0010	0.0011	0.0017	0.0019
54	0.0020	0.0009	-0.0006	0.0010	0.0012	0.0018	0.0020
56	0.0021	0.0010	-0.0006	0.0010	0.0013	0.0018	0.0020
58	0.0022	0.0010	-0.0005	0.0010	0.0013	0.0019	0.0020
60	0.0023	0.0011	-0.0004	0.0010	0.0014	0.0019	0.0020
62	0.0023	0.0012	-0.0004	0.0009	0.0014	0.0020	0.0020
64	0.0024	0.0013	-0.0003	0.0009	0.0015	0.0020	0.0020
66	0.0025	0.0014	-0.0002	0.0009	0.0015	0.0020	0.0020
68	0.0025	0.0015	-0.0001	0.0009	0.0015	0.0020	0.0020
70	0.0026	0.0016	0.0	0.0008	0.0016	0.0020	0.0020
72	0.0026	0.0017	0.0001	0.0008	0.0016	0.0021	0.0020
74	0.0026	0.0018	0.0002	0.0008	0.0017	0.0021	0.0020
76	0.0027	0.0018	0.0003	0.0007	0.0017	0.0021	0.0019
78	0.0027	0.0019	0.0004	0.0007	0.0018	0.0021	0.0019

Table B.5. U^{235} Capture and Fission Gamma Source

($\nu = 2.44$, $\sigma_a = 513$ barns, $\nu\sigma_f = 1070$ barns,
 $\sigma_c = 74.5$ barns, thermal at $80^\circ\text{C}.$)

Energy (Mev)	Prompt Fission		Prompt Capture (photons/nonfission neutron capture)	Prompt Fission + Delayed Fission Product ^b (photons ^a /neutron production)
	Photons per Fission	Photons ^a per Neutron Production		
0.5	3.80	1.56	3.50	3.02
1	2.00	0.82	2.837	2.23
2	1.18	0.484	0.383	0.90
4	0.25	0.102	0.0374	0.12
6	0.047	0.0193	0.0048	0.021
8	0.0032	0.00131	0	0.00131
10	0	0	0	0
	7.2802	2.98661	6.7622	6.29231

^a P_f input.

^bSee Table B.6.

Table B.6. Typical Fission Product Delayed Gamma Source

Energy (Mev)	Photons per Fission	Photons per Mw-sec ^a
		$\times 10^{16}$
0.5	3.0	10
1	3.0	10
2	1.0	3.4
4	0.04	0.14
6 ^b	0.003	0.01
	7.043	23.55

^aEquivalent to 6.68 Mev/fission, or 94% of infinite time level of 7.1 Mev/fission.

^b6 Mev is above the usual energy limit of delayed fission product gammas, and this source therefore can be used as an upper bound.

Table B.7. Capture Photons^a

Element	Average Binding Energy in Product Nucleus (Mev)	Capture Gamma-Ray Photons per Neutron Capture at Energies of						
		0.5 Mev	1 Mev	2 Mev	4 Mev	6 Mev	8 Mev	1.0 Mev
H	2.22			(1.25)				
D	6.26					1.1		
Be	6.81				0.50	0.80		
B ¹⁰	11.45				1.20	0.30	0.06	0.01
C	4.94		0.30		0.41	0.50		
Mg	9.24	0.70	0.40	0.59	1.10	0.25	0.11	0.01
Al	7.72			0.23	0.77	0.21	0.35	
Ti	8.25	0.50	1.00	0.29	0.20	0.90	0.03	
Fe	7.72	0.68	0.40	0.35	0.30	0.25	0.41	0.03
Ni	8.41	0.20	0.04	0.05	0.14	0.30	0.60	0.10
Cu	7.76	1.73	0.40	0.20	0.23	0.22	0.48	
Zr	7.94		1.20	0.60	0.40	0.40	0.05	
Ag	6.78	0.79	0.62	1.37	0.58	0.16		
Cd	9.05	0.5	0.10	0.40	1.45	0.30	0.02	
Xe ¹³⁵								
Sm ¹⁴⁹	8.00	3.59	0.60	1.50	0.45	0.05	0.01	
Eu	6.45	0.81	0.70	1.76	0.38	0.05		
Dy	(6.5)		0.50	1.90	0.50	0.20		
Ta	6.05		0.50	1.80	0.40	0.10		
Au	6.45		0.50	1.20	0.35	0.35		
Pb	7.29					0.15	0.80	
Th	5.2	0.86	0.93	1.66	0.13			

^aComplete experimental data are not available in the literature for many of these elements; therefore a reasonable distribution of the binding energy has been made herein.

Table B.8. Beta-Particle Energy Associated with Decay of Product(s)
Formed upon Neutron Capture^a

Material (Isotope of Principal Capture)	Energy (Mev)			
	Principal Beta of Any Product, Maximum	Principal Beta of Main Product	Main Product Disintegration (total)	Average Beta per Capture
Boron (B^{10})	13.4	0	0	~ 0
Sodium (Na^{23})	1.39	1.39	5.51	0.555^b
Aluminum (Al^{27})	2.87	2.87	4.65	1.25^c
Titanium (Ti^{48})	2.1	0	0	0.01
Iron (Fe^{56})	0.462	0	0	~ 0
Nickel (Ni^{58})	2.1	0	0	~ 0
Zirconium (Zr^{90})	1.91	0	0	0.01
Silver ($Ag^{107} + Ag^{109}$)	2.24	1.77, 2.24	1.77, 2.88	0.88
Cadmium (Cd^{113})	1.61	0	0	~ 0
Europium (Eu^{151})	1.88	0, 1.88	0, 1.88	0.1
Dysprosium (Dy^{164})	0.8 + 0.42	0.8 + 0.42	2.1	0.41
Gold (Au^{197})	0.96	0.96	1.37	0.32
Thorium (Th^{232})	1.23	1.23	1.23	0.42
Uranium (U^{238})	1.21	1.21	1.28	0.41

^aExcludes transitions of long half-life. In a material such as Eu, the beta energy increases with exposure (on a basis of one capture in the material). Also the gamma rays produced in decay may make available significant energy for local heat generation. Deactivation energy is not included in the main product disintegration energy (causing capture gamma rays).

^bAlso one 2.75- and one 1.37-Mev decay gamma per capture.

^cAlso one 1.78-Mev decay gamma per capture.

Appendix C

EXAMPLE OF EXTENSION OF A NIGHTMARE RESULT
TO OBTAIN ADDITIONAL INFORMATIONProblem

The heat-generation rate at the inside edge of a pressure vessel (which is located outside a thick water blanket) is known as a function of energy from a NIGHTMARE calculation. It is desired to obtain the heat-generation rate at the outside edge of this steel pressure vessel, which is 7 in. thick. The effective distance from the core source to the blanket edge is estimated at 66 in. (The core source is all-important at remote distances, except when appreciable neutron absorption occurs in another region such as a steel shield or control rod, resulting in high-energy capture, activation, or decay gammas.)

Solution

The ratio of the gamma flux at the outside surface to that at the inside surface will be determined and applied to the heat generation rate at the inside surface for each energy group. A preliminary calculation using the energy buildup-factor equation indicates that this factor is dependent only on the material adjacent to the point of interest in this situation.

Table C.1a. Summary of Calculations To Extend NIGHTMARE Result

Energy (Mev)	Heat-Generation Rate at a ^(a) (w/g)	μ (cm ⁻¹)		μd (mean free paths)		
		H ₂ O	Fe	H ₂ O	Fe	Total
0.5	8.743×10^{-6}	0.0939	0.660	15.74	12.58	28.32
1	1.104×10^{-4}	0.0687	0.470	11.52	8.96	20.48
2	1.014×10^{-3}	0.0480	0.334	8.05	6.36	14.41
4	1.557×10^{-3}	0.0331	0.259	5.55	4.93	10.49
6	2.174×10^{-3}	0.0269	0.240	4.51	4.57	9.08
8	6.439×10^{-4}	0.0235	0.234	3.94	4.46	8.40
Total	5.51×10^{-3}					

(a)_a = inside edge of pressure vessel.

Table C.1b. Summary of Calculations To Extend NIGHTMARE Result

Energy (Mev)	BU		BU _{Fe} /BU _{H₂O}	$e^{-\mu d_{H_2O}}$	BU _{Fe} /BU _{H₂O} $\times e^{-\mu d_{H_2O}}$	Heat-Generation Rate at b ^(a) (w/g)
	H ₂ O	Fe				
0.5	180	180	1.0	290,000	3.44×10^{-6}	~0
1	35	60	1.74	7,770	2.24×10^{-4}	~0
2	10	18.7	1.87	578	3.24×10^{-3}	3.28×10^{-6}
4	4.3	7.5	1.74	139	1.26×10^{-2}	1.95×10^{-5}
6	3.0	4.9	1.63	96.4	1.69×10^{-2}	3.68×10^{-5}
8	2.43	3.55	1.46	86.4	1.69×10^{-2}	1.09×10^{-5}
Total						7.05×10^{-5}

(a)_b = outside edge of pressure vessel.

ORNL-3198
UC-32 - Mathematics and Computers
TID-4500 (17th ed.)

INTERNAL DISTRIBUTION

1. L. G. Alexander	32. C. W. Nestor, Jr.
2. V. E. Anderson (K-25)	33. C. E. Newlon (K-25)
3. L. L. Bennett	34. A. M. Perry
4. A. L. Boch	35. P. H. Pitkanen
5. W. L. Breazeale	36. C. A. Preskitt
6. R. S. Carlsmith	37. B. E. Prince
7. W. L. Carter	38. M. W. Rosenthal
8. R. D. Cheverton	39. T. H. Row
9. H. C. Claiborne	40. J. E. Rowe (K-25)
10. A. L. Colomb	41. E. G. Silver
11. R. R. Coveyou	42. J. G. Sullivan
12. J. G. Delene	43. J. A. Swartout
13. A. C. Downing	44-48. M. Tobias
14-18. T. B. Fowler	49. Marina Tsagaris
19. E. H. Gift	50. R. Van Winkle
20. D. R. Gilfillan	51. D. R. Vondy
21. E. E. Gross	52. D. W. Vroom
22. A. S. Householder	53. A. M. Weinberg
23. W. H. Jordan	54. F. G. Welfare (Y-12)
24. P. R. Kasten	55-56. Reactor Division Library
25. W. E. Kinney	57. HRP Director's Office, Rm. 259,
Bldg. 9204-1
26. J. A. Lane	58-59. Central Research Library
27. M. P. Lietzke	60-61. Document Reference Library
28. R. N. Lyon	62-82. Laboratory Records Department
29. H. G. MacPherson	83. Laboratory Records, ORNL R.C.
30. B. Maskowitz (K-25)	84. SHARE Library (K-25)
31. E. A. Nephew	

EXTERNAL DISTRIBUTION

- 85-86. General Atomics, P. O. Box 608, San Diego, Calif. (1 copy each to W. Sangren and Seymour Jaye)
87. D. H. Groelsema, AEC, Washington
88. W. Cartwell, System Analysis and Computation, IBM, Owego, New York
89. D. Jacobson, Argonne National Laboratory
- 90-91. Westinghouse Electric Corp., Bettis Plant, Pittsburgh, Pa. (1 copy each to B. H. Mount and E. M. Gelbard)
92. Division of Research and Development, AEC, ORO
93. L. R. Blue, Atomic International, Canoga Park, Calif.
94. Donald M. Shapiro, Internuclear Company, 7 North Brentwood Blvd., Clayton 5, Mo.
95. Thomas F. McKiernan, Engineering 1 North, Pratt and Whitney Aircraft, East Hartford 8, Conn.

96. D. J. Mallon, Nuclear Engineering, Allison Division, General Motors Corp., Indianapolis 6, Ind.
- 97-702. Given distribution as shown in TID-4500 (17th ed.) under Mathematics and Computers category (75 copies - OTS)