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AEC RESEARCH AND DEVELOPMENT REPORT
JANUARY 1973

LMFBR SHIELDING DESIGN EXPERIMENTS AND METHODS EVALUATION

FOURTH QUARTERLY PROGRESS REPORT
OCTOBER-DECEMBER 1972

U. S. ATOMIC ENERGY COMMISSION
CONTRACT AT(04-3)-189 PROJECT AGREEMENT 62

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AND METHODS EVALUATION
FOURTH QUARTERLY REPORT
OCTOBER-DECEMBER 1972**

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ABSTRACT

This report is the fourth in a series of quarterly progress reports published under the LMFBR shielding development program (PA-62). Both experimental and analytical work on axial and radial shields is being conducted with the experimental part being performed at the Oak Ridge National Laboratory (ORNL) Tower Shielding Facility. Activities and technical progress for the period October through December 1972 are reported. The major topics include program definition and scheduling, experimental measurements, analytical studies, and comparisons between experimental and calculated data.

1. INTRODUCTION

The LMFBR shielding program is based on design requirements for reduced uncertainties in critical parameters of demonstration plant shielding design. In the current PA-62 program, shielding experiments and their analyses are being conducted to reduce calculational uncertainties for the following neutron shields (Figure 1-1):

- Reactor closure lower neutron shield (this is the principal bulk shield for reducing the neutron flux level above the reactor closure head)
- Radial neutron shield (this shield limits neutron fluences at the lateral core support and at the reactor vessel)

An important calculational uncertainty for these two neutron shields arises from their actual heterogeneous form as opposed to their approximated homogeneous form in calculations. Configurations simulating the actual shields have been designed and fabricated for testing at the ORNL Tower Shielding Reactor to provide accurate data on neutron transmission through heterogeneous near-core neutron shields. These measurements will also provide neutron flux inputs to either calculations or experiments, or both, for regions farther from the core.

2. SUMMARY

Delays in the test program at ORNL have resulted in rescheduling the balance of the axial and radial experiments. Completion of the PA-62 measurements is expected by May 1, 1973.

Hydrogen counter and NE-213 spectrometer results for the GE and ARD spectrum modifiers were received. Also included were some NE-213 spectrometer and Bonner ball results of measurements of the radial modifier plus B_4C rod or slab layers. The results of Hornyak button measurements comparing heterogeneous vs homogeneous transmission were received for one and two rows of large rods and homogeneous slabs.

Three UNCL-DOT-SPACETRAN calculations were completed for the radial modifier plus (a) one row of 5.25-inch homogeneous equivalent B_4C slabs, (b) three rows of 1-inch homogeneous equivalent B_4C slabs, and (c) one row of 1-inch homogeneous equivalent B_4C slabs. The calculated data were compared with experimental results and found to generally agree well for the 3-inch Bonner ball. However, calculated response values for the 6-inch and 10-inch Bonner balls are slightly higher (factor of about 1.3) than experimental results.

MORSE Monte Carlo calculations were performed for the radial modifier plus one row of 5.25-inch o.d. B_4C -filled tubes. The streaming through the aluminum triffutes between the rods was evaluated along with the effect of changing the triffute material from aluminum to sodium to void (no triffute material). Calculated results generally agree well with experimental results and show that streaming effects are small. MORSE calculated results for 6-inch and 10-inch Bonner ball response follow the same trend as DOT III calculated results and are slightly higher than experimental results.

Figure 1-1. Near-Core Upper Axial and Radial Neutron Shields

3. TECHNICAL ACCOMPLISHMENTS

3.1 PROGRAM DEFINITION AND SCHEDULING

The planning diagram (Figure 3-1) is being used to monitor progress in the program and to assure the timely completion of interfacing experimental and analytical data. In view of the delays in completing the test program at ORNL, this figure is being changed and a revised version will be issued during the third quarter of Fiscal Year '73.

Table 3-1 is an updated version of the experimental program being conducted at ORNL. This table has been modified to show completed and partially completed measurements and to indicate receipt of measurement data. This table will also undergo revision to reflect small changes in scope based on results of measurements and analysis to date in order to provide a better match to program needs.

Figure 3-2 illustrates the schedule of ORNL measurements for the PA-62 program. The Fast Flux Test Facility (FFTF) gamma-ray experiment will be concluded by mid-January 1973. The SNAP measurements were cancelled. It is expected that all PA-62 measurements will be completed by May 1, 1973, and measurement results will be reported by June 1, 1973.

Table 3-2 illustrates the planned data disposition and analysis corresponding to specific experimental configurations to be tested. The schedule for completing the General Electric Breeder Reactor Department (GE-BRD) portion of the analytical program is illustrated in Figure 3-3. Both table and figure have been modified to show completed analyses.

3.2 EXPERIMENTAL MEASUREMENTS

Additional preliminary experimental data and preliminary results of ORNL calculations were received during this quarter from ORNL. In particular, hydrogen counter and NE-213 spectrometer results for the GE and ARD spectrum modifiers were received. Also included were some NE-213 spectrometer results of Item VII, measurements of the radial modifier plus B₄C rod or slab layers. Table 3-3 gives a summary of Bonner ball and Hornyak Button radial shield (B₄C rod and slab) measurements performed to date by ORNL for GE. Tables 3-4 to 3-12 present the data of particular interest for the work done at GE-BRD during the last quarter. These data were used for comparison with GE-BRD analytical results which are discussed in Subsection 3.3 of this report.

3.3 ANALYTICAL STUDIES

The following analytical activities were accomplished during the October–December 1972 quarter:

- Preparation of additional neutron cross sections for materials needed in two- and three-dimensional calculations.
- Updating of the Tower Shielding Facility (TSF) neutron source according to the latest ORNL revision (October 4, 1972).
- Preparation of input, checkout, and execution of DOT III calculations for three B₄C homogeneous slab test assemblies. Also, generation of neutron isoflux plots for these cases.
- Preparation of input, checkout, and execution of MORSE calculations for one B₄C rod test assembly.

3.3.1 Preparation of Additional Neutron Cross Sections for Materials Needed in Two- and Three-Dimensional Calculations

In order to perform DOT and MORSE calculations, it was necessary to prepare cross sections for materials which appear in the two- and three-dimensional geometries. In particular, cross sections were needed for the plain polyethylene (CH₂) lining in the tower shielding reactor (TSR) collimator, borated polyethylene (5 wt % natural boron) filling the Type-304 stainless steel frame surrounding the 5.25-inch B₄C rod assembly, and for the concrete used in the TSR collimator and in the shield blocks used to surround the test assemblies. These cross sections were added to the GE-BRD macroscopic cross-section tape and then converted to ANISN format for use at ORNL. Table 3-13 gives a complete list of densities and compositions for materials used in the DOT and MORSE calculations. It will be noted that the compositions for Boral and Type-304 stainless steel have been adjusted slightly from the values in the second quarterly report.² These adjustments account for updated information on the materials involved.

Table 3-1
EXPERIMENTAL PROGRAM FOR GENERAL ELECTRIC
AXIAL AND RADIAL SHIELD MEASUREMENTS AT TSF*

Configuration Number And Description	Neutron Measurements ^(a)					
			Bonner Balls			
	NE-213	H ₂ Counter	Axial Traverse ^(b)		Radial Traverse ^(c)	
			All 9 Balls	3, 6, and 10 in.	All 9 Balls	3, 6, and 10 in.
I. Axial Shield						
A. Partial Modifier (18 in. SS only)	☑, Close ^(d)	☑, 12 in.	—	☑, 12 to 144 in.	—	—
B. Full Modifier (18 in. SS + 48 in. Na + 1/8-in. Boral)	☑, Close ^(d)	☑, 12 in.	☑, 12 to 144 in.	—	—	12 in.; 0 to 36 in. on each side of ☑. 144 in.; 0 to 144 in. on one side of ☑
C. Full Modifier + 24 in. Axial Shield (5-1/4 in. OD SS rods)	—	☑, 12 in.	—	☑, 12 to 144 in.	—	12 in.; 0 to 36 in. on each side of ☑. 144 in.; 0 to 144 in. on one side of ☑
D. Full Modifier + Axial Shield + 30 in. Na	—	—	—	☑, 12 to 144 in.	—	—
II. Radial Spectrum Modifier ^(f)						
A. Radial Modifier ^(e)	☑, Close ^(d) 45°, Close	☑, 12 in.	—	☑, 12 to 144 in.	—	12 in.; 0 to 36 in. on each side of ☑. 144 in.; 0 to 144 in. on one side of ☑
III. Axial Shield With Radial Spectrum Modifier						
A. Axial Shield with Radial Spectrum Modifier	☑, Close ^(d)	☑, 12 in.	—	☑, 12 in.	—	—

Experiments
Completed

Experimental
Data Received

Experiments
Partially
Completed

GEAP-13822-4

Table 3-1 Continued

Configuration Number And Description	Neutron Measurements ^(a)					
	NE-213	H ₂ Counter	Axial Traverse ^(b)		Bonner Balls	
			All 9 Balls	3, 6, and 10 in.	All 9 Balls	Radial Traverse ^(c) 3, 6, and 10 in.
IV. Radial Blanket Measurements for Westinghouse						
g { A. Radial Modifier + 5 in. Radial Blanket ^(e)	ϕ , Close ^(d) 45°, Close	ϕ , 12 in.	—	ϕ , 12 to 144 in.	—	12 in.; 0 to 36 in. on each side of ϕ . 144 in.; 0 to 144 in. on one side of ϕ
B. Radial Modifier + 10 in. Radial Blanket ^(e)	ϕ , Close ^(d) 45°, Close	ϕ , 12 in. 45°, 144 in.	—	ϕ , 12 to 144 in.	—	12 in.; 0 to 36 in. on each side of ϕ . 144 in.; 0 to 144 in. on one side of ϕ
C. Radial Modifier + 10 in. Radial Blanket + 5 in. Reflector ^(e)	ϕ , Close ^(d) 45°, Close	ϕ , 12 in.	—	ϕ , 12 to 144 in.	—	12 in.; 0 to 36 in. on each side of ϕ . 144 in.; 0 to 144 in. on one side of ϕ
V. Radial Shield—Stainless Steel versus B ₄ C Slabs						
A. IV.C. Modifier + 10 in. B ₄ C Slabs	ϕ , Close ^(d)	ϕ , 12 in.	—	ϕ , 12 to 144 in.	—	12 in.; 0 to 36 in. on each side of ϕ . 144 in.; 0 to 144 in. on one side of ϕ
B. IV.C. Modifier + 10 in. B ₄ C Slabs + Axial Shield	—	—	—	ϕ , 12 to 144 in.	—	12 in.; 0 to 36 in. on each side of ϕ . 144 in.; 0 to 60 in. on one side of ϕ
C. IV.C. Modifier + 10 in. SS + Axial Shield	—	—	—	ϕ , 12 to 144 in.	—	12 in.; 0 to 36 in. on each side of ϕ . 144 in.; 0 to 60 in. on one side of ϕ

Table 3-1 Continued

Configuration Number And Description	Neutron Measurements ^(a)					
	NE-213	H ₂ Counter	Bonner Balls			
			Axial Traverse ^(b)		Radial Traverse ^(c)	
			All 9 Balls	3, 6, and 10 in.	All 9 Balls	3, 6, and 10 in.
D. IV.C. Modifier + 10 in. SS	☉, Close ^(d)	☉, 12 in.	—	☉, 12 to 144 in.	—	12 in.; 0 to 36 in. on each side of ☉. 144 in.; 0 to 144 in. on one side of ☉.
VI. Radial Shield Measurements for Westinghouse						
A. IV.C. + 5 in. Inconel + 12 in. Na						
B. VI.A. + 5 in. SS						
C. Radial Modifier + 10 in. Radial Blanket + 2-1/2 in. Inconel						
D. Radial Modifier + 10 in. Radial Blanket + 5 in. Inconel						
E. IV.C. + 5 in. Inconel + 5 in. Stainless Steel						
VII. Radial Shield—B ₄ C Rods and Slabs						
A. Radial Modifier + 5-1/4 in. OD B ₄ C Rods						
a. 1 and 3 rows**	☉, Close ^(d)	☉, 12 in.	—	☉, 12 to 144 in.; repeat 72 to 144 in. foreground, measure background at 72 and 144 in.	—	12 in.; 0 to 36 in. on each side of ☉. 72 in.; 0 to 72 in. on one side of ☉. 144 in.; 0 to 144 in. on one side of ☉.
b. 2 rows**	—	—	—	☉, 12 to 144 in.; repeat 72 to 144 in. foreground; measure background at 72 and 144 in.	—	12 in.; 0 to 36 in. on each side of ☉. 72 in.; 0 to 72 in. on one side of ☉. 144 in.; 0 to 144 in. on one side of ☉.
B. Radial Modifier + 2 in. OD B ₄ C Rods						
a. 1 row	☉, Close ^(d)	☉, 12 in.	—	☉, 12 to 144 in.	—	12 in.; 0 to 36 in. on each side of ☉.

**Also, radial traverses were measured with Hornyak buttons 2.6 inches behind the test configurations—1 and 2 rows of rods vs 1 and 2 slabs. Experimental data have been received for the latter.

Table 3-1 Continued

Configuration Number And Description	Neutron Measurements ^(a)					
	NE-213	H ₂ Counter	Axial Traverse ^(b)		Bonner Balls	Radial Traverse ^(c)
			All 9 Balls	3, 6, and 10 in.	All 9 Balls	3, 6, and 10 in.
C. Radial Modifier + 1 in. OD B ₄ C Rods a. 4 rows	—	—	—	☒, 12 to 144 in.	—	12 in.; 0 to 36 in. on each side of ☒. 144 in.; 0 to 144 in. on one side of ☒.
D. Radial Modifier + 0.6 in. and 3.8 in. B ₄ C Slabs a. 1, 2, 3, and 4 0.6 in. slabs	—	—	—	☒, 12 to 144 in. Completed for 3 and 4 slabs only	—	Completed for 3 slabs only 12 in.; 0 to 36 in. on each side of ☒. 144 in.; 0 to 144 in. on one side of ☒.
b. 1, 2, and 3 3.8 in. slabs***	☒, Close ^(d) ****	☒, 12 in.	—	☒, 12 to 144 in. Completed for 1 slab only	—	12 in.; 0 to 36 in. on each side of ☒. 72 in.; 0 to 72 in. on one side of ☒.
E. Radial Modifier + 5-1/4 in. OD B ₄ C Rods (3 rows) a. 6 in. SS reflector ~ 4 in. behind B ₄ C b. Axial shield ~ 4 in. behind B ₄ C	} Traverse with 3 in. Bonner ball adjacent to back of B ₄ C rods to locate peaks and valleys that may exist.					

*** Also, radial traverses were measured with Hornyak buttons 2.6 inches behind the test configurations—1 and 2 rows of rods vs 1 and 2 slabs. Experimental data have been received for the latter.

**** Measured at 10 feet behind and 10 feet off center for three 3.8-inch slabs.

a. Measurements unless otherwise specified will be in the horizontal plane.

b. Axially out beam centerline from back of configuration.

c. Radially from beam centerline.

d. As close to the back of the sample as the upper limit of the gamma ray sensitivity of the scintillator will permit.

e. Gamma ray spectral measurements will be made (as part of the Westinghouse LMFBR shielding program) at one angle between 45° to 60° from centerline at a distance from the back of the slab to be determined by background considerations.

f. This radial spectrum modifier was specified by Westinghouse for use with their radial shield measurements of neutron and gamma fluxes. Its use is specified in the GE program (III, V, and VII) since it also provides a satisfactory spectrum for the GE experiments and reduces overall TSF experimental time and costs.

g. IV is a part of the AEC-funded Westinghouse LMFBR shielding base program. A description of the measurements is included here since the radial modifier + 10 in. radial blanket + 5 in. SS reflector will be used as a spectrum modifier for Part V of the GE program.

h. VI is also a part of the AEC-funded Westinghouse LMFBR shielding base program. A description of the configurations to be measured is included for general information and schedule interaction.

Table 3-2
PA-62 EXPERIMENTAL AND ANALYTICAL PROGRAM

<u>Configuration No. and Description</u>	<u>Data Disposition and Analysis*</u>	
	<u>GE-BRD</u>	<u>ORNL Program Priority</u>
I. Axial Shield		
A. Partial Modifier 18-in. SS	MORSE-100-gp MORSE-24-gp	MORSE - I
B. Full Modifier 18-in. SS + 48-in. Na + 1/8-in. Boral	1-D Trans/Diff	DOT III - I
C. Full Modifier + 24-in. Axial Shield (5-1/4-in. o.d. SS rods)	DOT/DOMINO/ MORSE	Programming Assistance - I
D. Full Modifier + Axial Shield + 30-in. Na	1-D Trans/Diff	DOT/DOMINO/MORSE + Programming Assist - II
II. Radial Spectrum Modifier (W)		
A. Radial Modifier 4-in. SS + 6-in. Na + 1-in. Boral	1-D Trans/Diff	MORSE - IV
III. Axial Shield with Radial Spectrum Modifier		
A. Radial Modifier + Axial Shield	Alternate for I-C; Omit Measurement if I-C is successful	Programming Assistance - I
IV. W Radial Blanket and SS Reflector		
D. Radial Modifier + 10-in. Blanket + 5-in. SS	No analysis	DOT III - I
V. Radial Shield - SS vs B₄C Slabs		
A. Radial Modifier + 10-in. Radial Blanket + 5-in. SS + 10-in. B ₄ C Slabs	A, D DOT III or DOT/DOMINO/ MORSE	Programming - I DOT or DOT/DOMINO/ MORSE - II
B. As above + Axial Shield		

Completed

Partially Completed

Table 3-2 (Continued)

Data Disposition and Analysis		ORNL Program Priority
Configuration No. and Description	GE-BRD	
C. As above except 10-in. SS replaces 10-in. B ₄ C slabs	B, C 1-D Trans/Diff	No Analysis
D. As above except remove axial shield		
VII. Radial Shield - B ₄ C Rods and Slabs		
A. Radial Modifier + 5-1/4-in. o.d. B ₄ C Rods		
a. 1 and 3 rows	MORSE - 1 row only	MORSE - I
b. 2 rows	Omit	Omit
B. Radial Modifier + 2-in. o.d. B ₄ C Rods	1 MORSE calculation on B or C (By pseudo-collision only)	Programming - I
a. 1 row		
C. Radial Modifier + 1-in. o.d. B ₄ C Rods		
a. 4 rows		
D. Radial Modifier + 0.6-in. and 3.8-in. B ₄ C Slabs	DOT III for 1 and 3 0.6-in. slabs; DOT III for 1 3.8-in. slab	DOT III for 3 3.8-in. slabs - I
a. 1, 2, 3, and 4 0.6-in. B ₄ C Slabs		
b. 1, 2, and 3 3.8-in. B ₄ C Slabs		
E. Radial Modifier + 5-1/4-in. o.d. B ₄ C Rods (3 rows)		
a. 6-in. SS reflector about 4 in. behind B ₄ C	Compare Experimental results to unreflected experimental results in VII A	DOT III and/or DOT/DOMINO/ MORSE - III
b. Axial shield about 4-in. behind B ₄ C		

Table 3-3
LISTING* OF BONNER BALL AND HORNYAK BUTTON
RADIAL SHIELD MEASUREMENTS
PERFORMED BY ORNL FOR GENERAL ELECTRIC

VII-A: 5-1/4 in. B₄C Rods

		0 Rows	1 Row	2 Rows	3 Rows	4 Rows	Repeat
a.1	Axial	—	8/1/72(4, 5)**		8/15/72	—	8/21/72 (3 Rows)
7	2.6 in.	—	(12)		—	—	
2	12 in.	—	8/3/72(6)	—	8/22/72	—	
3	144 in.	—	8/8/72(8)	—	8/18/72	—	
6	72 in.	8/28/72(7)	8/28/72(7)	—	8/21/72	—	
b.1	Axial	—	—	8/11/72	—	—	8/29/72 (2 Rows)
5	2.6 in.	—	—	(12)	—	—	
2	12 in.	—	—	8/10/72	—	—	
3	144 in.	—	—	8/11/72	—	—	
4	72 in.	—	—	8/29/72	—	—	

VII-C: 1-in. B₄C Rods

a.1	Axial	—	7/19/72	—	—	7/19/72
2	12 in.	—	7/25/72	—	—	7/19/72
3	144 in.	—	7/21/72	—	—	7/20/72

VII-D: 1-in. Homogeneous Slabs

a.1	Axial	—	—	—	7/27/72(9)	7/25/72
2	12 in.	—	—	—	7/28/72(10)	—
3	144 in.	—	—	—	7/28/72(11)	—

VII-D: 5 1/4 in. Homogeneous Slabs

a.1	Axial	—	8/2/72(4)	—	—	—
3	2.6 in.	—	(12)	(12)	—	—

*Measurements not listed here have not been performed to date (January 25, 1972).

**Numbers in parentheses refer to table numbers in this section where the experimental data are given; e.g., (4) means refer to Table 3-4, (4, 5) means refer to Tables 3-4 and 3-5.

Table 3-4
BONNER BALL AXIAL TRAVERSE ALONG BEAM CENTERLINE
BEHIND WESTINGHOUSE MODIFIER PLUS
ONE ROW OF 5-1/4-IN. B₄C RODS OR HOMOGENEOUS SLABS,
ITEMS A.a.1. AND D.a.1.

Position (inches, measured from back of B ₄ C slabs)	Bonner Ball Responses (cpm/1 kW)					
	3-in. Ball		6-in. Ball		10-in. Ball	
	Rods	Homogeneous	Rods	Homogeneous	Rods	Homogeneous
12	210,903	212,476	2,261,963	2,240,573	1,411,080	1,470,631
18	145,983	144,087	1,476,272	1,466,024	944,563	976,007
24	108,345	103,399	1,061,854	1,029,270	652,213	690,502
36	66,454	61,718	600,614	592,853	394,954	404,204
48	44,104	41,360	392,233	384,309	261,260	263,297
72	23,146	21,502	202,885	195,671	137,748	137,510
96	14,520	13,281	127,704	122,776	87,544	87,002
120	10,205	9,234	88,039	84,852	62,484	61,260
144	7,668	7,006	64,982	61,814	45,870	44,885
Background						
72	3,890	4,146	12,392	15,097	6,811	6,393
144	2,503	2,560	9,267	8,902	4,056	3,903

Table 3-5
BONNER BALL AXIAL TRAVERSE ALONG BEAM CENTERLINE
BEHIND WESTINGHOUSE SPECTRUM MODIFIER PLUS 1, 2,
AND 3 ROWS 5-1/4 IN. B₄C RODS,
ITEMS A.a.1. AND A.b.1

Position (inches, measured from back of B ₄ C slabs)	Bonner Ball Responses (cpm/1 kW)								
	3-in. Ball			6-in. Ball			10-in. Ball		
	1 Row	2 Rows	3 Rows	1 Row	2 Rows	3 Rows	1 Row	2 Rows	3 Rows
12	210,903	52,462	11,856	2,261,963	507,325	124,480	1,411,080	328,168	83,913
18	145,983	—	8,252	1,476,272	339,591	82,583	944,563	218,977	55,926
24	108,345	25,734	6,242	1,061,854	237,012	59,312	652,213	155,712	40,335
36	66,454	16,005	4,028	600,614	136,998	35,398	394,954	89,922	23,399
48	44,104	10,604	2,932	392,233	87,961	23,838	261,260	50,909	15,399
72	23,146	5,902	1,834	202,885	45,883	12,706	137,748	31,255	8,160
96	14,520	3,930	1,304	127,704	28,996	8,094	87,544	19,437	5,049
120	10,205	2,842	1,037	88,039	20,186	5,967	62,484	13,457	3,611
144	7,668	2,195	826	64,982	14,821	4,594	45,870	9,957	2,748
Background									
72	3,890	1,268	—	12,392	4,556	1,316	6,811	1,661	504
144	2,503	—	—	9,267	—	—	4,056	—	175

Table 3-6
 BONNER BALL RADIAL TRAVERSE AT 12 IN.
 BEHIND WESTINGHOUSE SPECTRUM MODIFIER
 PLUS 1 AND 3 ROWS OF 5-1/4 IN. B₄C RODS,
 ITEM A.a.2.

Position (inches, measured from beam centerline)	Bonner Ball Response (cpm/1 kW), ψ (r)					
	3-in. Ball		6-in. Ball		10-in. Ball	
	1 Row	3 Rows	1 Row	3 Rows	1 Row	3 Rows
36 N(a)	—	770	—	—	—	—
30	47,561	2,006	320,106	—	180,107	—
24	70,570	4,095	560,755	33,693	313,817	—
21	—	—	—	—	—	30,799
18	105,392	6,187	914,580	55,559	539,917	38,489
12	150,822	8,717	1,401,775	81,074	887,145	59,602
9	—	9,883	—	95,315	—	69,173
6	193,625	10,947	1,929,583	104,522	1,259,927	75,682
3	—	11,573	—	110,780	—	80,871
CL	212,858	11,798	2,167,601	113,509	1,417,616	82,708
CL	210,165	11,772	—	113,369	—	83,899
2 S(b)	211,967	—	—	—	—	—
3	—	11,437	—	111,397	—	80,735
4	206,703	—	—	—	—	—
6	195,399	10,779	1,968,677	102,637	1,268,371	74,737
8	185,546	—	—	—	—	—
9	—	9,713	—	89,114	—	66,476
10	172,806	—	—	—	—	—
12	156,423	8,381	1,467,999	74,741	895,641	55,096
14	139,561	—	—	—	—	—
16	124,964	—	—	—	—	—
18	111,347	5,815	944,779	48,181	554,254	34,871
20	98,084	—	—	—	—	—
21	—	—	—	—	—	27,257
22	85,863	—	—	—	—	—
23	—	—	—	—	—	22,580
24	76,168	4,041	572,117	29,416	318,488	—
26	68,027	—	—	—	—	—
28	60,764	—	—	—	—	—
30	54,046	2,618	339,745	—	183,086	—
$2\pi f\psi(r)rdr$	$2.82+8^{(c)}$	$1.54+7$	$2.42+9$	$1.08+8$	$1.45+9$	$6.82+7$

(a) North of centerline

(b) South of centerline

(c) 2.82×10^8

Table 3-7
 BONNER BALL RADIAL TRAVERSE AT 72 IN.
 BEHIND WESTINGHOUSE SPECTRUM MODIFIER
 PLUS 0, 1, 2, AND 3 ROWS 5-1/4 IN. B₄C RODS,
 ITEMS A.a.6 AND A.b.4

Position (inches, measured from beam centerline)	Bonner Ball Responses (cpm/1 kW), $\psi(r)$											
	3-in. Ball				6-in. Ball				10-in. Ball			
	0 Rows	1 Row	2 Rows	3 Rows	0 Rows	1 Row	2 Rows	3 Rows	0 Rows	1 Row	2 Rows	3 Rows
0	117,854	22,681	4,412	1,134	1,028,836	204,359	44,766	11,122	725,899	134,805	31,036	7,851
12 S(a)	112,696	21,428	4,280	1,081	938,650	191,244	42,008	10,784	625,307	122,823	28,833	7,340
18	104,758	20,202	4,039	1,046	803,099	175,928	39,765	9,945	499,661	110,942	26,971	—
24	95,445	18,620	3,796	967	683,207	153,714	35,687	9,360	390,627	92,543	23,467	6,129
30	90,494	17,039	3,447	914	623,418	140,027	33,024	8,373	342,847	82,271	21,196	—
36	81,221	15,746	3,159	807	573,339	125,734	29,231	7,627	313,790	71,997	18,668	5,003
48	65,986	12,384	2,522	655	462,896	99,507	23,304	5,988	244,960	56,514	14,288	3,830
60	53,282	9,600	2,023	518	359,660	76,852	17,736	4,617	188,198	42,539	10,958	2,845
72	41,878	7,311	1,562	404	278,225	58,912	13,038	3,434	143,589	31,951	8,018	2,154
Background												
0	—	2,621	602	164	—	9,541	2,335	656	—	4,125	536	—
72 S(a)	8,369	1,792	365	109	28,990	6,704	1,480	416	11,649	2,808	656	186
$2\pi \int \psi(r) r dr$	9.49+8(b)	1.71+8	3.46+7	8.67+6	7.10+9	1.54+9	3.53+8	9.12+7	3.99+9	9.05+8	2.33+8	6.01+7

(a) South of centerline

(b) 9.49×10^8

Table 3-8
BONNER BALL RADIAL TRAVERSE AT 144 IN.
BEHIND WESTINGHOUSE SPECTRUM MODIFIER
PLUS 1, 2, AND 3 ROWS 5-1/4 IN. B₄C RODS,
ITEMS A.a.3 and A.b.3

Position (inches, measured from beam centerline)	Bonner Ball Responses (cpm/10 kW), $\psi(r)$								
	3-in. Ball			6-in. Ball			10-in. Ball		
	1 Row	2 Rows	3 Rows	1 Row	2 Rows	3 Rows	1 Row	2 Rows	3 Rows
0	79,182	19,081	3,637	654,563	154,662	33,582	456,710	95,239	27,620
12 S ^(a)	77,085	18,844	—	648,728	139,578	32,509	426,691	91,418	26,883
24	73,597	18,486	—	599,782	132,369	31,062	373,375	84,053	25,478
36	68,467	17,385	—	486,045	120,461	28,598	293,848	73,258	23,046
48	63,206	16,384	—	475,693	109,250	26,287	261,469	65,220	20,483
72	52,843	13,890	2,560	360,767	91,163	21,007	209,706	52,747	16,890
96	43,104	11,493	—	—	70,577	16,195	158,735	41,241	13,128
108	—	—	—	251,992	—	—	—	—	—
120	35,187	9,426	—	—	56,262	12,689	121,722	31,117	9,951
144	27,521	7,634	1,290	167,451	42,504	9,498	91,779	23,386	—
Background									
0	—	6,285	1,123	—	23,803	4,438	—	10,401	2,115
72	20,709	5,247	882	75,289	19,336	3,436	31,397	8,396	1,567
144	14,611	3,792	593	50,561	13,026	2,399	20,434	5,400	1,090
$2\pi \int \psi(r) r dr$	1.63+9 ^(b)	4.48+8	—	1.50+10	3.67+9	9.00+8	9.59+9	2.30+9	6.35+8

(a) South of centerline

(b) 1.63×10^9

Table 3-9
BONNER BALL AXIAL TRAVERSE ALONG BEAM CENTERLINE
BEHIND WESTINGHOUSE MODIFIER
PLUS THREE 1-IN. HOMOGENEOUS B₄C SLABS,
ITEM D.a.1.

Position (inches, measured from back of B ₄ C slabs)	Bonner Ball Responses (cpm/1 kW)		
	3-in. Ball	6-in. Ball	10-in. Ball
12	438,369	4,368,350	2,580,780
18	296,897	2,916,310	1,706,420
24	216,514	2,069,050	1,237,480
48	84,608	766,660	473,130
72	43,897	400,080	253,550
96	27,138	247,750	156,210
120	19,117	173,130	114,090
144	14,117	125,510	84,500
Background			
72	5,215	1,840	7,240
144	4,077	1,529	6,300

Table 3-10
BONNER BALL RADIAL TRAVERSE AT 12-IN.
BEHIND WESTINGHOUSE SPECTRUM MODIFIER
PLUS THREE 1-IN. HOMOGENEOUS B₄C SLABS,
ITEM D.a.2.

Position (inches, measured from beam centerline)	Bonner Ball Responses (cpm/1 kW), $\psi(r)$		
	3-in. Ball	6-in. Ball	10-in. Ball
28 N ^(a)	122,769	785,330	418,360
24	159,316	1,119,720	611,630
12	333,651	2,857,640	1,704,460
6	421,138	3,853,770	2,403,630
℄	433,933	4,336,200	2,682,890
6	402,581	3,848,760	2,346,440
12	315,236	2,828,010	1,646,370
24	156,579	1,113,820	601,370
28	120,056	818,740	415,150
$2\pi \int \psi(r) r dr$	5.88+8 ^(b)	4.60+9	2.63+9

(a) North of centerline

(b) 5.88×10^8

Table 3-11
BONNER BALL RADIAL TRAVERSE AT 144-IN.
BEHIND WESTINGHOUSE SPECTRUM MODIFIER
PLUS THREE 1-IN. HOMOGENEOUS B₄C SLABS,
ITEM D.a.3

Position (inches, measured from beam centerline)	Bonner Ball Responses (cpm/1 kW), $\psi(r)$		
	3-in. Ball 3 Slabs	6-in. Ball 3 Slabs	10-in. Ball 3 Slabs
℄	14,548	128,977	86,174
12 S ^(a)	14,011	119,978	79,010
24	13,052	106,133	66,965
36	12,056	89,947	52,326
48	11,156	82,614	45,040
72	9,369	66,965	35,900
96	7,728	52,762	27,634
120	6,151	41,055	20,840
144	4,833	31,250	15,675
Background			
72	3,421	13,312	5,304
144	2,423	8,904	3,343
$2\pi \int \psi(r) r dr$	3.07+8 ^(b)	2.82+9	1.63+9

(a) South of centerline

(b) 3.07×10^8

Table 3-12
HORNYAK BUTTON RADIAL TRAVERSES AT 2.6 IN.
BEHIND THE WESTINGHOUSE SPECTRUM MODIFIER
PLUS ONE AND TWO ROWS OF 5-1/4-IN. B₄C RODS
OR HOMOGENEOUS SLABS

Position (inches, measured from beam centerline)	Hornyak Button Responses (cpm/25 kW), $\psi(r)$				
	One Row		Two Rows		
	Rods	Homogeneous	Rods	Homogeneous	
0	96,222	106,057	24,362	25,535	
0.5 S ^(a)	96,280	—	24,091	—	
1	98,188	106,628	23,665	—	
1.5	100,163	—	22,895	—	
2	102,538	104,067	22,586	24,843	
2.5	102,224	—	21,745	—	
3	100,658	100,196	21,060	—	
3.5	97,762	—	20,831	—	
4	95,695	94,992	20,856	23,416	
4.5	90,352	—	20,362	—	
5	85,551	92,241	20,459	—	
5.5	81,208	—	19,785	—	
6	77,974	86,231	19,540	21,340	
6.5	75,043	—	—	—	
7	74,216	80,605	17,510	—	
8	71,363	73,670	15,467	18,042	
9	65,685	66,514	13,785	—	
10	55,605	55,730	12,595	14,330	
11	44,370	45,852	11,345	—	
12	36,118	38,438	9,770	10,648	
13	—	32,379	8,141	—	
14	—	26,346	6,719	7,470	
15	—	22,359	5,615	—	
16	—	18,351	4,973	5,317	
17	—	—	4,124	—	
18	—	—	3,483	3,660	
19	—	—	2,700	—	
20	—	—	2,338	2,442	
22	—	—	—	1,660	
24	—	—	—	1,153	
$2\pi \int \psi(r) r dr$	$3.03+7^{(b)}$	$3.15+7$	$1.10+7$	$1.10+7$	$1.31+7$

(a) South of centerline
(b) 3.03×10^7

Table 3-13
DENSITIES AND COMPOSITIONS OF MATERIALS USED
IN DOT AND MORSE CALCULATIONS

Material	Density (gm/cc)	Atom Density
Sodium	0.945	Na = 2.4766(-2)atoms/barn-cm
Aluminum	2.702	Al = 6.0366(-2)atoms/barn-cm
B ₄ C	2.463	B-10 = 2.0902(-2)atoms/barn-cm C(a) = 1.1318(-1)atoms/barn-cm
Boral(b)	2.3	B-10 = 6.9765(-3)atoms/barn-cm C(a) = 3.6908(-2)atoms/barn-cm Al = 3.3370(-2)atoms/barn-cm
Type-304 SS(b)	7.88	C = 1.8578(-4)atoms/barn-cm Si(c) = 1.1405(-3)atoms/barn-cm Cr = 1.6719(-2)atoms/barn-cm Mn = 7.7777(-4)atoms/barn-cm Fe(d) = 6.0238(-2)atoms/barn-cm Ni = 6.9869(-3)atoms/barn-cm Cu = 1.9427(-4)atoms/barn-cm Mo = 1.4846(-4)atoms/barn-cm
Plain Polyethylene	0.900	H = 7.7292(-2)atoms/barn-cm C = 3.8646(-2)atoms/barn-cm
Borated Polyethylene	0.940	H = 7.6682(-2)atoms/barn-cm C(a) = 4.0441(-2)atoms/barn-cm B-10 = 5.1836(-4)atoms/barn-cm
Concrete	2.400	Si(e) = 4.3500(-3)atoms/barn-cm Ca = 9.7700(-3)atoms/barn-cm O = 4.4470(-2)atoms/barn-cm C = 9.9600(-3)atoms/barn-cm H = 6.4200(-3)atoms/barn-cm Mg = 2.2000(-3)atoms/barn-cm Al = 4.5000(-4)atoms/barn-cm K = 1.1000(-4)atoms/barn-cm Fe = 1.1000(-4)atoms/barn-cm

(a) Boron-11 is included in this density.

(b) Modified slightly from composition given in Reference 1, page 3-37.

(c) Sulphur and phosphorus are included in this density.

(d) Cobalt is included in this density.

(e) Sulphur is included in this density.

EXPERIMENTAL PROGRAM FOR 1972 AND 1973 (REVISED JANUARY 25, 1973)

	1972							1973					
	J	J	A	S	O	N	D	J	F	M	A	M	J
I. GE AXIAL SHIELD MEASUREMENTS	■	■								■			
II. RADIAL SPECTRUM* MODIFIER PLUS GAMMA MEASUREMENTS (W)		■	■					■					
III. GE AXIAL SHIELD WITH RADIAL SPECTRUM MODIFIER												■	
IV. W RADIAL BLANKET & STAINLESS STEEL REFLECTOR									■	■			
V. GE RADIAL SHIELD (B ₄ C SLABS vs STAINLESS STEEL										■	■		
VI. W RADIAL SHIELD												■	■
VII. GE RADIAL SHIELD (B ₄ C-FILLED TUBES AND SLABS) WITH RADIAL SPECTRUM MODIFIER		■	■								■		
FFTF GAMMA-RAY EXPERIMENT				■	■	■	■	■	■	■			
SNAP PROGRAM													

*THE SCHEDULE FOR THE WESTINGHOUSE ARD BASE PROGRAM EXPERIMENTS ARE SHOWN SINCE THEIR EXPERIMENTS ARE ALSO SCHEDULED FOR COMPLETION DURING FY-73 - HENCE, ARE INTERSPERSED WITH THE GE-BRD BASE PROGRAM EXPERIMENTS. FURTHER, PART V GE EXPERIMENTS USE THE PART IV-D ASSEMBLY AS A RADIAL SPECTRUM MODIFIER.

Figure 3-2. Schedule of ORNL Measurements for PA-62 LMFBR Shielding Experiments

C COMPLETION OF ANALYSIS
 --- COMPARISON & EVALUATION
 — 1D CALCULATIONS
 == 2D CALCULATIONS
 === 3D CALCULATIONS
 ■ COUPLED 2D + 3D CALCULATIONS

	J	A	S	O	N	D	J	F	M	A	M	J
I. AXIAL SHIELD												
A. PARTIAL AXIAL MODIFIER = 18 in. STAINLESS STEEL												
B. AXIAL MODIFIER = 18 in. STAINLESS STEEL + 48 in. Na + 1/8 in. BORAL												
C. AXIAL MODIFIER + AXIAL SHIELD												
D. AXIAL MODIFIER + AXIAL SHIELD + 30 in. Na												
II. RADIAL MODIFIER												
A. 4 in. STAINLESS STEEL + 6 in. Na + 1 in. BORAL												
III. RADIAL MODIFIER + AXIAL SHIELD												
A. 4 in. STAINLESS STEEL + 6 in. Na + 1 in. BORAL + AXIAL SHIELD												
V. RADIAL SHIELD - STAINLESS STEEL vs B₄C SLABS												
A. W ASSEMBLY** + 10 in. B ₄ C SLAB												
B. AS ABOVE + AXIAL SHIELD												
C. AS ABOVE EXCEPT 10 in. STAINLESS STEEL REPLACES 10 in. B ₄ C SLAB												
D. W ASSEMBLY** + 10 in. STAINLESS STEEL SLAB												
VII. RADIAL MODIFIER + B₄C SLABS OR RODS												
A a. 1 ROW 5-1/4 in. RODS												
A a. 3 ROWS 5-1/4 in. RODS												
A b. 2 ROWS 5-1/4 in. RODS												
C a. 1 ROW 1 in. RODS												
C a. 4 ROWS 1 in. RODS												
D a. 1 ROW 0.6 in. SLABS												
D a. 2 ROWS 0.6 in. SLABS												
D a. 3 ROWS 0.6 in. SLABS												
D a. 4 ROWS OF 0.6 in. SLABS												
D b. 1 ROW 3.8 in. SLABS												
D b. 2 ROWS 3.8 in. SLABS												
D b. 3 ROWS 3.8 in. SLABS												
E a. 3 ROWS 5-1/4 in. RODS + 6 in. STAINLESS STEEL SLAB												
E b. 3 ROWS 5-1/4 in. RODS + AXIAL SHIELD												

*ORNL, WITHIN FY-73 FUNDING LIMITATIONS, PLANS TO ANALYZE A NUMBER OF THE CONFIGURATIONS TESTED.

**W ASSEMBLY = 4 in. STAINLESS STEEL + 6 in. Na + 1 in. BORAL + 10 in. BLANKET + 5 in. REFLECTOR.

Figure 3-3. Schedule for Completing the GE-BRD Portion* of the PA-62 Analytical Program

The densities and composition of materials used in these calculations were determined from vendors' data, chemical and spectrographic analysis done at General Electric Nuclear Energy Division, manufacturing procedures, and data provided by ORNL. It should be noted that the B_4C density of 2.463 gm/cm^3 is a theoretical (maximum) density based on mixing three different mesh sizes of B_4C particles. For purposes of these calculations the actual density resulting from the compacting of each separate homogeneous slab configuration was used. These values turned out to be approximately 70%. For the MORSE calculations involving a single row of 5.25-inch diameter B_4C -filled tubes, an average B_4C density of 1.6833 gm/cc (68.36% of theoretical) was used.

3.3.2 Updating of the TSF Neutron Source Data

The TSR-II neutron source is represented in these calculations by collapsing 100-group ORNL data to 24 groups as discussed in the second quarterly report.² During the past quarter the ORNL data for the TSR-II bare beam was revised for neutron energy groups below an energy of 13.7 eV. GE-BRD groups 22 through 24 were revised accordingly from the values given in the second quarterly report² and the new 24-group source spectrum is shown in Table 3-14. This new spectrum was used for all DOT and MORSE calculations discussed in this report.

Table 3-14
TSR-II 24-GROUP SOURCE SPECTRUM
(Revised October 4, 1972)

Group Number	Energy Band	Lethargy Increment (ΔU)	Percent of Total Flux	Neutron Flux* ($n/\text{cm}^2 \cdot \text{min} \cdot \text{W}$)
1	10.0-16.5 MeV	0.5	0.12	3.1800(+2)
2	6.07-10.0 MeV	0.5	1.91	5.1480(+3)
3	3.68-6.07 MeV	0.5	6.93	1.8730(+4)
4	2.23-3.68 MeV	0.5	11.38	2.0740(+4)
5	1.35-2.23 MeV	0.5	9.30	2.5135(+4)
6	0.821-1.35 MeV	0.5	4.57	1.2355(+4)
7	498-821 KeV	0.5	3.62	9.7800(+3)
8	302-498 KeV	0.5	2.15	5.8150(+3)
9	183-302 KeV	0.5	1.68	4.5500(+3)
10	111-183 KeV	0.5	1.50	4.0540(+3)
11	67.4-111 KeV	0.5	1.36	3.6600(+3)
12	40.9-67.4 KeV	0.5	1.25	3.3800(+3)
13	24.8-40.9 KeV	0.5	1.15	3.1200(+3)
14	15.0-24.8 KeV	0.5	1.08	2.9300(+3)
15	9.12-15.0 KeV	0.5	1.00	2.7100(+3)
16	5.53-9.12 KeV	0.5	0.95	2.5700(+3)
17	3.35-5.53 KeV	0.5	0.90	2.4200(+3)
18	2.03-3.35 KeV	0.5	0.86	2.3300(+3)
19	1.01-2.03 KeV	0.7	1.14	3.0730(+3)
20	0.249-1.01 KeV	1.4	2.05	5.5380(+3)
21	55.6-249 eV	1.5	2.02	5.4450(+3)
22	12.4-55.6 eV	1.5	2.00	5.4160(+3)
23	0.625-12.4 eV	3.0	4.87	1.3148(+4)
24	Thermal	∞	36.22	9.7864(+4)
			Total 100.00	Total 2.7023(+5)

*As collapsed from 100-group structure given in Reference 2, and normalized to a power level of 1 watt. The values are given for a point on the centerline at the end of the collimator.

3.3.3 DOT III Calculations for Three B₄C Homogeneous Slab Test Assemblies

Three large UNCL-DOT-SPACETRAN calculations were performed by GE at ORNL during the quarter. These calculations determined the neutron attenuation through and Bonner ball responses behind (1) the radial modifier plus one 5.25-inch B₄C slab unit, (2) the radial modifier plus three 1-inch B₄C slab units, and (3) the radial modifier plus one 1-inch B₄C slab unit.* Figures 3-4 and 3-5 illustrate the experimental configuration used by ORNL for the radial modifier plus one 5.25-inch slab and Figure 3-6 illustrates the case of the radial modifier plus three 1-inch slabs. The three-dimensional experimental configuration was approximated by two-dimensional R-Z geometry in the calculations. Figures 3-7 and 3-8 are schematic diagrams of the material and zone maps used for the UNCL and DOT III calculations. Tables 3-15, 3-16, and 3-17 provide the details of the two-dimensional mesh used for each of the three configurations.

Table 3-15
MESH DESCRIPTION AND ZONE DIMENSIONS FOR DOT CALCULATIONS
OF THE RADIAL MODIFIER PLUS ONE "5.25-INCH" B₄C SLAB
(i.e., EQUIVALENT TO ONE ROW OF 5.25-INCH O.D. B₄C-FILLED TUBES)

Zone ^(a)	Number of Radial Mesh Intervals	Number of Axial Mesh Intervals	R _O , Radial Origin of Zone (cm)	Z _O , Axial Origin of Zone (cm)	ΔR, Zone Radial Width (cm)	ΔZ, Zone Axial Length (cm)
1	43	2	0.0	0.0	109.0	1.0
2	10	105	85.982	1.0	23.018	63.68
3	23	8	21.907	41.82	64.075	22.86
4	2	8	19.367	41.82	2.54	22.86
5	8	8	0.0	41.82	19.367	22.86
6	1	5	0.0	31.58	2.421	10.24
7	1	2	0.0	30.95	2.421	0.63
8	1	5	0.0	15.71	2.421	15.24
9	1	2	0.0	15.08	2.421	0.63
10	1	10	0.0	12.95	2.421	2.13
11	1	5	0.0	12.54	2.421	0.41
12	32	5	2.421	31.58	83.561	10.24
13	32	2	2.421	30.95	83.561	0.63
14	32	5	2.421	15.71	83.561	15.24
15	32	2	2.421	15.08	83.561	0.63
16	32	10	2.421	12.95	83.561	2.13
17	32	5	2.421	12.54	83.561	0.41
18	1	3	0.0	12.42	2.421	0.12
19	1	6	0.0	11.95	2.421	0.47
20	1	49	0.0	2.42	2.421	9.53
21	1	4	0.0	1.95	2.421	0.47
22	1	6	0.0	1.0	2.421	0.95
23	32	3	2.421	12.42	83.561	0.12
24	32	6	2.421	11.95	83.561	0.47
25	32	49	2.421	2.42	83.561	9.53
26	32	4	2.421	1.95	83.561	0.47
27	32	6	2.421	1.0	83.561	0.95

(a) Refer to Figures 3-6 and 3-7 for schematic diagrams of the zones and materials for this calculation.

* Each "1-inch" B₄C slab unit has an actual B₄C thickness of 0.6 inch. This gives it the same mass of B₄C as a single row of 1-inch o.d. B₄C-filled tubes. The "5.25-inch" B₄C slab unit has an actual B₄C thickness of 3.755 inches which gives it the same mass of B₄C as a single row of 5.25-inch o.d. B₄C-filled tubes.

Table 3-16
MESH DESCRIPTION AND ZONE DIMENSIONS FOR DOT CALCULATIONS OF THE
RADIAL MODIFIER PLUS THREE "1-INCH" B₄C SLABS
(i.e., EQUIVALENT TO THREE ROWS OF 1-INCH O.D. B₄C-FILLED TUBES)

Zone*	Number of Radial Mesh Intervals	Number of Axial Mesh Intervals	R _O , Radial Origin of Zone (cm)	Z _O , Axial Origin of Zone (cm)	ΔR, Zone Radial Width (cm)	ΔZ, Zone Axial Length (cm)
1	43	1	0.0	0.0	109.0	1.0
2	10	106	85.982	1.0	23.018	58.74
3	23	8	21.907	36.88	64.075	22.86
4	2	8	19.367	36.88	2.54	22.86
5	8	8	0.0	36.88	19.367	22.86
6	1	5	0.0	26.64	2.421	10.24
7	1	2	0.0	26.01	2.421	0.63
8	1	5	0.0	10.79	2.421	15.24
9	1	2	0.0	10.14	2.421	0.63
10	1	10	0.0	8.01	2.421	2.13
11	1	5	0.0	7.66	2.421	0.41
12	32	5	2.421	26.64	83.561	10.24
13	32	2	2.421	26.01	83.561	0.63
14	32	5	2.421	10.77	83.561	15.24
15	32	2	2.421	10.14	83.561	0.63
16	32	10	2.421	8.01	83.561	2.13
17	32	5	2.421	7.6	83.561	0.41
18	1	3	0.0	7.36	2.421	0.24
19	1	16	0.0	5.84	2.421	1.52
20	1	2	0.0	5.6	2.421	0.24
21	1	2	0.0	5.4	2.421	0.2
22	32	3	2.421	7.36	83.561	0.24
23	32	16	2.421	5.84	83.561	1.52
24	32	2	2.421	5.6	83.561	0.24
25	32	2	2.421	5.4	83.561	0.2
26	1	3	0.0	5.16	2.421	0.24
27	1	16	0.0	3.04	2.421	1.52
28	1	2	0.0	3.4	2.421	0.24
29	1	2	0.0	3.2	2.421	0.2
30	32	3	2.421	5.16	83.561	0.24
31	32	16	2.421	3.64	83.561	1.52
32	32	2	2.421	3.4	83.561	0.24
33	32	2	2.421	3.2	83.561	0.2
34	1	3	0.0	2.98	2.421	0.24
35	1	16	0.0	1.44	2.421	1.52
36	1	2	0.0	1.2	2.421	0.24
37	1	2	0.0	1.0	2.421	0.2
38	32	3	2.421	2.98	83.561	0.24
39	32	16	2.421	1.44	83.561	1.52
40	32	2	2.421	1.2	83.561	0.24
41	32	2	2.421	1.0	83.561	0.2

* Refer to Figures 3-7 and 3-8 for schematic diagrams of the zones and materials for this calculation.

Table 3-17
MESH DESCRIPTION AND ZONE DIMENSIONS FOR DOT CALCULATIONS OF THE
RADIAL MODIFIER PLUS ONE "1-INCH" B₄C SLAB
(i.e., EQUIVALENT TO ONE ROW OF 1-INCH O.D. B₄C-FILLED TUBES)

Zone*	Number of Radial Mesh Intervals	Number of Axial Mesh Intervals	R _O , Radial Origin of Zone (cm)	Z _O , Axial Origin of Zone (cm)	ΔR, Zone Radial Width (cm)	ΔZ, Zone Axial Length (cm)
1	43	47	0.0	0.0	109.0	1.0
2	10	60	85.982	1.0	23.018	54.34
3	23	8	21.907	32.48	64.075	22.86
4	2	8	19.367	32.48	2.54	22.86
5	8	8	0.0	32.48	19.367	22.86
6	1	5	0.0	22.24	2.421	10.24
7	1	2	0.0	21.61	2.421	0.63
8	1	5	0.0	6.37	2.421	15.24
9	1	2	0.0	5.74	2.421	0.63
10	1	10	0.0	3.61	2.421	2.13
11	1	5	0.0	3.20	2.421	0.41
12	32	5	2.421	22.24	83.561	10.24
13	32	2	2.421	21.61	83.561	0.63
14	32	5	2.421	6.37	83.561	15.24
15	32	2	2.421	5.74	83.561	0.63
16	32	10	2.421	3.61	83.561	2.13
17	32	5	2.421	3.20	83.561	0.41
18	1	3	0.0	2.96	2.421	0.24
19	1	16	0.0	1.44	2.421	1.52
20	1	2	0.0	1.2	2.421	0.24
21	1	2	0.0	1.0	2.421	0.2
22	32	3	2.421	2.96	83.561	0.24
23	32	16	2.421	1.44	83.561	1.52
24	32	2	2.421	1.2	83.561	0.24
25	32	2	2.421	1.0	83.561	0.2

* Refer to Figures 3-7 and 3-8 for schematic diagrams of the zones and materials for this calculation.

SLABS:

STAINLESS STEEL 5 ft x 5 ft (2.012 in. + 2.021 in.)

Na 5 ft x 5 ft

BORAL 5 ft x 5 ft

B₄C 50 in. W x 52 in. H (ONE 5-1/4 in. B₄C HOMOGENEOUS SLAB, G1-S5-3)

Figure 3-4. Top View of Experimental Configuration for Radial Modifier Plus One 5.25-Inch B₄C Slab Unit

Figure 3-5. Side View of Experimental Configuration for Radial Modifier Plus One 5.25-Inch B₄C Slab Unit

SLABS:

STAINLESS STEEL 5 ft x 5 ft (2.012 + 2.021 in.)

Na 5 ft x 5 ft

BORAL 5 ft x 5 ft

B₄C 50 in. W x 52 in. H (THREE 1-in. B₄C HOMOGENEOUS SLABS, G2-SI-1, G2-SI-2, G2-SI-4)

Figure 3-6. Top View of Experimental Configuration for Radial Modifier Plus Three 1-Inch B₄C Slab Units

MATERIAL MAP

Figure 3-7. Schematic Diagram of Materials for Three DOT Calculations of the Radial Modifier Plus Three Different B₄C Slab Configurations

Figure 3-8. Schematic Diagram of Zones Used in Three DOT Calculations of the Radial Modifier Plus Three Different B₄C Slab Configurations

The calculations used the GE-BRD 24-group neutron cross section library with P_3 scattering matrices, and used a special 100-angle quadrature set developed at ORNL for TSR shielding calculations. The mesh size used for all three R-Z problems was 43 radial (R) intervals and 107 axial (Z) intervals. In each case, UNCL was used to generate a first collision source which was then input to DOT for the transport calculation. An output scalar flux tape generated by DOT was used in later separate runs by SPACETRAN for calculating total flux and Bonner ball responses (for 3-, 6-, and 10-inch diameter balls) at 30 detector locations behind each shield configuration. Table 3-18 gives a list of the detector locations used for all three configurations. The axial coordinate, Z, is the distance from the back of the slab ($Z=0.0$) to the detector and is input to SPACETRAN as a negative quantity.* Input to the program UNCL requires that the neutron beam be directed in the negative Z direction and that the origin of the coordinate system be located on the down beam side of the shield. Figures 3-9 through 3-23 show five isoflux plots for each of the three configurations. The first plot in each set gives total flux contours. The remaining four plots are few-group isoflux contours for each of four neutron energy groups used to summarize the 24-group calculational results. The energy range for Groups 1, 2, 3, and 4 are 0.821 to 16.5 MeV, 5.53 keV to 0.821 MeV, 0.625 eV to 5.53 keV, and 0.0 to 0.625 eV, respectively.

Table 3-18
DETECTOR COORDINATES FOR SPACETRAN CALCULATIONS

	Detector Number	Axial Coordinate, Z (in.)	Radial Coordinate, R (in.)
Axial Traverse	1	-12	0.0
	2	-18	0.0
	3	-24	0.0
	4	-36	0.0
	5	-48	0.0
	6	-72	0.0
	7	-96	0.0
	8	-120	0.0
	9	-144	0.0
Radial Traverse	10	-12	6
	11	-12	12
	12	-12	24
	13	-12	30
Radial Traverse	14	-72	12
	15	-72	18
	16	-72	24
	17	-72	30
	18	-72	36
	19	-72	48
	20	-72	60
	21	-72	72
Radial Traverse	22	-144	12
	23	-144	24
	24	-144	36
	25	-144	48
	26	-144	72
	27	-144	92
	28	-144	120
	29	-144	144
45 Degrees	30	-120	120

* Actually the back of the slab was at $Z=1.0$ cm for convenience in setting up the three problems such that all problems had the same total number of mesh intervals. The 1-cm void region was used to accommodate differences in the axial mesh, and has been neglected in making comparisons with experimental Bonner ball results.

Figure 3-9. Total Neutron Isoflux Plot from a DOT III Calculation for the Radial Modifier Plus One B₄C Slab (Equivalent to One Row of 5.25-Inch o.d. B₄C-Filled Tubes)

Figure 3-10. High-Energy (16.5 to 0.821 MeV) Neutron Isoflux Plot from a DOT III Calculation for the Radial Modifier Plus One B₄C Slab (Equivalent to One Row of 5.25-Inch o.d. B₄C-Filled Tubes)

Figure 3-11. Intermediate-Energy (0.821 MeV to 5.53 keV) Neutron Isoflux Plot from a DOT III Calculation for the Radial Modifier Plus One B₄C Slab (Equivalent to One Row of 5.25-Inch o.d. B₄C-Filled Tubes)

Figure 3-12. Epithermal-Energy (5.53 keV to 0.625 eV) Neutron Isoflux Plot from a DOT III Calculation for the Radial Modifier Plus One B₄C Slab (Equivalent to One Row of 5.25-Inch o.d. B₄C-Filled Tubes)

Figure 3-13. Thermal-Energy (0.625 to 0.0 eV) Neutron Isoflux Plot from a DOT III Calculation for the Radial Modifier Plus One B₄C Slab (Equivalent to One Row of 5.25-Inch o.d. B₄C-Filled Tubes)

Figure 3-14. Total Neutron Isoflux Plot from a DOT III Calculation for the Radial Modifier Plus Three B₄C Slabs (Equivalent to Three Rows of 1-Inch o.d. B₄C-Filled Tubes)

Figure 3-15. High-Energy (16.5 to 0.821 MeV) Neutron Isoflux Plot from a DOT III Calculation for the Radial Modifier Plus Three B₄C Slabs (Equivalent to Three Rows of 1-Inch o.d. B₄C-Filled Tubes)

Figure 3-16. Intermediate Energy (0.821 MeV to 5.53 keV) Neutron Isoflux Plot from a DOT III Calculation for the Radial Modifier Plus Three B₄C Slabs (Equivalent to Three Rows of 1-Inch o.d. B₄C-Filled Tubes)

Figure 3-17. Epithermal-Energy (5.53 keV to 0.625 eV) Neutron Isoflux Plot from a DOT III Calculation for the Radial Modifier Plus Three B₄C Slabs (Equivalent to Three Rows of 1-Inch o.d. B₄C-Filled Tubes)

Figure 3-18. Thermal-Energy (0.625 to 0.0 eV) Neutron Isoflux Plot from a DOT III Calculation for the Radial Modifier Plus Three B₄C Slabs (Equivalent to Three Rows of 1-Inch o.d. B₄C-Filled Tubes)

Figure 3-19. Total Neutron Isoflux Plot from a DOT III Calculation for the Radial Modifier Plus One B₄C Slab (Equivalent to One Row of 1-Inch o.d. B₄C-Filled Tubes)

Figure 3-20. High-Energy (16.5 to 0.821 MeV) Neutron Isoflux Plot from a DOT III Calculation for the Radial Modifier Plus One B₄C Slab (Equivalent to One Row of 1-Inch o.d. B₄C-Filled Tubes)

Figure 3-21. Intermediate-Energy (0.821 MeV to 5.53 keV) Neutron Isoflux from a DOT III Calculation for the Radial Modifier Plus One B₄C Slab (Equivalent to One Row of 1-Inch o.d. B₄C-Filled Tubes)

Figure 3-22. Epithermal-Energy (5.53 keV to 0.625 eV) Neutron Isoflux Plot from a DOT III Calculation for the Radial Modifier Plus One B₄C Slab (Equivalent to One Row of 1-Inch o.d. B₄C-Filled Tubes)

Figure 3-23. Thermal-Energy (0.625 to 0.0 eV) Neutron Isoflux Plot from a DOT III Calculation for the Radial Modifier Plus One B₄C Slab (Equivalent to One Row of 1-Inch o.d. B₄C-Filled Tubes)

Tables 3-19 and 3-20 show a comparison of the DOT III-SPACETRAN calculated and experimental Bonner ball results for axial traverses behind the 5.25-inch homogeneous slab array and the three 1-inch homogeneous slab array. Table 3-21 gives only the calculated DOT III-SPACETRAN results for the one 1-inch homogeneous slab array since the experimental measurements have not yet been made for this case. The data corresponding to Tables 3-19 and 3-20 have been plotted and the graphical comparisons between experimental and calculated results are shown in Figures 3-24 and 3-25. In plotting the data the calculated Bonner ball responses have been displaced axially away from the neutron source (down beam) by an amount equal to $0.7 \times$ Bonner ball radius. This is done to account for the fact that the center of response is not located at the geometric center of a Bonner ball. Agreement between calculation and experiment is excellent for the 3-inch Bonner ball. For the 6- and 10-inch diameter balls, the agreement is reasonably good but calculated values are higher than experiment—increasingly so as the distance between detector and slab decreases. The reason for this behavior is unknown at present but further analysis is in process.

Table 3-19
COMPARISON OF MEASURED VERSUS DOT CALCULATED DATA FOR
BONNER BALL AXIAL TRAVERSE ALONG BEAM
CENTERLINE BEHIND RADIAL MODIFIER PLUS
ONE 5.25-INCH B₄C SLAB

Position (inches, measured from back of B ₄ C slabs)	Bonner Ball Responses ^(a) (cpm/W)					
	3-in. Ball		6-in. Ball		10-in. Ball	
	Experiment	Calculated	Experiment	Calculated	Experiment	Calculated
12	2.1248+2 ^(b)	2.0437+2	2.2406+3	2.6717+3	1.4706+3	1.7237+3
18	1.4409+2	1.3441+2	1.4660+3	1.7212+3	9.7601+2	1.1161+3
24	1.0340+2	9.2850+1	1.0293+3	1.1870+3	6.9050+2	7.7212+2
36	6.1718+1	5.2904+1	5.9285+2	6.5905+2	4.0420+2	4.2764+2
48	4.1360+1	3.3379+1	3.8431+2	4.0856+2	2.6330+2	2.6424+2
72	2.1502+1	1.6678+1	1.9567+2	1.9772+2	1.3751+2	1.2758+2
96	1.3281+1	9.7818+0	1.2278+2	1.1463+2	8.7002+1	7.3695+1
120	9.234 +0	6.4967+0	8.4852+1	7.4891+1	6.1260+1	4.8238+1
144	7.006 +0	4.5773+0	6.1814+1	5.2626+1	4.4885+1	3.3953+1

**Measured
Background**

72	0.4146+1	0.1510+2	0.0639+2
144	0.2503+1	0.8902+1	0.3903+1

Comparison of 3 Axial Positions with Background Subtracted

12	2.1248+2	2.0437+2	2.2406+3	2.6717+3	1.4706+3	1.7237+3
72	1.7356+1	1.6678+1	1.8057+2	1.9772+2	1.3112+2	1.2758+2
144	4.5040+0	4.5773+0	5.2912+1	5.2626+1	4.0982+1	3.3953+1

(a) Experimental data from Tables 3-4, 3-5

(b) 2.1248×10^2

Table 3-20
**COMPARISON OF MEASURED VERSUS DOT CALCULATED DATA FOR
 BONNER BALL AXIAL TRAVERSE ALONG BEAM
 CENTERLINE BEHIND RADIAL MODIFIER PLUS
 THREE 1-INCH B₄C SLABS**

Position (inches, measured from back of B ₄ C slabs)	Bonner Ball Responses ^(a) (cpm/W)					
	3-in. Ball		6-in. Ball		10-in. Ball	
	Experiment	Calculated	Experiment	Calculated	Experiment	Calculated
12	4.3837+2 ^(b)	4.4737+2	4.3684+3	5.6442+3	2.5808+3	3.5146+3
18	2.9690+2	2.9391+2	2.9163+3	3.6688+3	1.7064+3	2.3000+3
24	2.1651+2	2.0545+2	2.0691+3	2.5395+3	1.2375+3	1.5945+3
48	8.4608+1	7.3655+1	7.6666+2	8.7253+2	4.7313+2	5.4061+2
72	4.3897+1	3.6567+1	4.0008+2	4.2272+2	2.5355+2	2.6077+2
96	2.7138+1	2.1472+1	2.4775+2	2.4534+2	1.5621+2	1.5062+2
120	1.9117+1	1.4164+1	1.7313+2	1.6023+2	1.1409+2	9.8530+1
144	1.4117+1	9.9707+0	1.2551+2	1.1266+2	8.4500+1	6.9406+1
Background						
72	5.2150+0		1.840 +0		7.240 +0	
144	4.0770+0		1.529 +0		6.300 +0	
Comparison for 3 Axial Positions with background subtracted						
12	4.3837+2	4.4737+2	4.3684+3	5.6442+3	2.5808+3	3.5146+3
72	3.8682+1	3.6567+1	3.9824+2	4.2272+2	2.4631+2	2.6077+2
144	1.0040+1	9.9707+0	1.2398+2	1.1266+2	7.8200+1	6.9406+1

(a) Experimental data from Table 3-9

(b) 4.3837×10^2

Table 3-21
COMPARISON OF MEASURED VERSUS DOT CALCULATED DATA FOR
BONNER BALL AXIAL TRAVERSE ALONG BEAM
CENTERLINE BEHIND RADIAL MODIFIER PLUS
ONE 1-INCH B₄C SLAB

Position (inches, measured from back of B ₄ C slabs)	Bonner Ball Responses ^(a) (cpm/W)					
	3-in. Ball		6-in. Ball		10-in. Ball	
	Experiment	Calculated	Experiment	Calculated	Experiment	Calculated
12	*	7.2140+2 ^(b)	*	9.0017+3	*	5.7232+3
18	*	4.7628+2	*	5.9266+3	*	3.8299+3
24	*	3.3315+2	*	4.0954+3	*	2.6438+3
36	*	1.8816+2	*	2.2390+3	*	1.4221+3
48	*	1.1846+2	*	1.3847+3	*	8.7335+2
72	*	5.8492+1	*	6.6977+2	*	4.2026+2
96	*	3.4305+1	*	3.8827+2	*	2.4227+2
120	*	2.2533+1	*	2.5350+2	*	1.5843+2
144	*	1.5858+1	*	1.7844+2	*	1.1179+2

(a) Experiment not yet performed

(b) 7.2140×10^2

Figure 3-24. Measured and DOT III Calculated Bonner Ball Response for Axial Traverse Behind One 5.25-Inch Homogeneous B_4C Slab

Figure 3-25. Measured and DOT III Calculated Bonner Ball Response for Axial Traverse Behind Three 1-Inch Homogeneous B_4C Slabs

Tables 3-22 and 3-23 show a comparison of the DOT III-SPACETRAN calculated and experimental Bonner ball results for radial traverses at 12 inches and 144 inches behind the three 1-inch homogeneous slab array. The data corresponding to Tables 3-22 and 3-23 have been plotted and the graphical comparisons between experimental and calculated results are shown in Figures 3-26 and 3-27. In plotting these data the center of response was assumed to coincide with the geometric center for all Bonner balls. This means that the calculated data points should actually be plotted slightly higher than shown since the radial traverse distance from the back of the slab is defined as the distance between the back of the slab and the geometric center of a Bonner ball. Inspection of Figures 3-26 and 3-27 shows that the agreement between calculation and experiment is reasonably good for the 3-inch diameter ball but that calculated results for the 6- and 10-inch diameter balls are higher than experiment at points off the neutron beam centerline.

Figure 3-28 shows a comparison of DOT III-SPACETRAN calculated and NE-213 spectrometer results for the neutron spectrum at a detector point located 10 feet off centerline and 10 feet back of the three 1-inch homogeneous B₄C slabs. The NE-213 data correspond to neutron energies greater than about 1 MeV (GE-BRD energy groups 1 to 6). The calculated value for the integral over this energy range appears to be higher than the measured value by a factor of ~1.8. This result tends to agree with the differences between calculated and measured Bonner ball responses (Table 3-23 and Figure 3-27).

Table 3-22
COMPARISON OF MEASURED VERSUS DOT CALCULATED DATA FOR
BONNER BALL RADIAL TRAVERSE AT 12 INCHES BEHIND
RADIAL SPECTRUM MODIFIER PLUS THREE 1-INCH B₄C SLABS

Position (inches, measured from beam centerline)	Bonner Ball Responses ^(a) (cpm/W)					
	3-in. Ball		6-in. Ball		10-in. Ball	
	Experiment	Calculated	Experiment	Calculated	Experiment	Calculated
30N ^(b)		7.3747+1 ^(c)		6.9512+2		3.4655+2
28	1.2277+2		7.8533+2		4.1836+2	
24	1.5932+2	1.2065+2	1.1197+3	1.2214+3	6.1163+2	6.2132+2
12	3.3365+2	3.0134+2	2.8576+3	3.4781+3	1.7045+3	1.9801+3
6	4.2114+2	4.0063+2	3.8538+3	4.7834+3	2.4036+3	2.8006+3
C	4.3393+2	4.4737+2	4.3362+3	5.6442+3	2.6829+3	3.5146+3
6	4.0258+2	4.0063+2	3.8488+3	4.7834+3	2.3464+3	2.8006+3
12	3.1524+2	3.0134+2	2.8280+3	3.4781+3	1.6464+3	1.9801+3
24	1.5658+2	1.2065+2	1.1138+3	1.2214+3	6.0137+2	6.2132+2
28	1.2006+2		8.1874+2		4.1515+2	
30S ^(d)		7.3747+1		6.9512+2		3.4655+2

(a) Experimental data from Table 3-10

(b) North of centerline

(c) 7.3747×10^1

(d) South of centerline

Note: Experimental data not yet available on background count rates for this shield configuration.

Table 3-23
COMPARISON OF MEASURED VERSUS DOT CALCULATED DATA FOR
BONNER BALL RADIAL TRAVERSE AT 144 INCHES BEHIND
RADIAL SPECTRUM MODIFIER PLUS THREE 1-INCH B₄C SLABS

Position (inches, measured from beam centerline)	Bonner Ball Responses ^(a) (cpm/W)					
	3-in. Ball		6-in. Ball		10-in. Ball	
	Experiment	Calculated	Experiment	Calculated	Experiment	Calculated
0	1.4548+1 ^(b)	9.9709+0	1.2898+2	1.1266+2	8.6174+1	6.9406+1
12	1.4011+1	9.7387+0	1.1998+2	1.0888+2	7.9010+1	6.6315+1
24	1.3052+1	9.3497+0	1.0613+2	1.0447+2	6.6965+1	6.3401+1
36	1.2056+1	8.8047+0	8.9947+1	9.7995+1	5.2326+1	5.9163+1
48	1.1156+1	8.0782+0	8.2614+1	8.8936+1	4.5040+1	5.3123+1
72	9.3690+0	6.5128+0	6.6965+1	6.8600+1	3.5900+1	3.8844+1
96	7.7280+0	5.2020+0	5.2762+1	5.4637+1	2.7634+1	3.0837+1
120	6.1510+0	3.7923+0	4.1055+1	3.7940+1	2.0840+1	2.0517+1
144S ^(c)	4.8330+0	2.8640+0	3.1250+1	2.7860+1	1.5675+1	1.4575+1
Background						
0	4.077 +0		1.529 +1		6.300 +0	
72	3.421 +0		1.3312+1		5.304 +0	
144	2.423 +0		8.094 +0		3.343 +0	
Comparison for two radial positions with background subtracted						
0	1.0471+1	9.9709+0	1.1309+2	1.1200+2	7.9874+1	0.9408+1
72	5.9480+0	6.5128+0	5.3653+1	6.8600+1	3.0598+1	3.8844+1
144	2.4100+0	2.8640+0	2.2346+1	2.7860+1	1.2332+1	1.4575+1

(a) Experimental data from Table 3-11

(b) 1.4548×10^1

(c) South of centerline

Figure 3-26. Measured and DOT III Calculated Bonner Ball Response for Radial Traverse at 12 Inches Behind Three 1-Inch B_4C Homogeneous Slabs

Figure 3-27. Measured and DOT III Calculated Bonner Ball Response for Radial Traverse at 144 Inches Behind Three 1-Inch B_4C Homogeneous Slabs

Figure 3-28. Comparison of NE-213 Measured and DOT-SPACETRAN Calculated Spectra Behind Three 1-Inch B_4C Slabs at a Distance of 10 Feet and 10 Feet Off Centerline

3.3.4 MORSE Calculations for One Row of 5.25-Inch B₄C Rods

Three MORSE calculations were performed by GE at ORNL during the quarter. These calculations determined the neutron attenuation through and Bonner ball responses behind (1) the radial modifier plus one row of 5.25-inch diameter B₄C-filled tubes with aluminum triflutes between tubes (corresponding to test assembly No. G3-T5-3*), (2) the same shield configuration except with sodium triflutes between the rods, and (3) the same shield configuration except with void triflutes, i.e., no material in the triflute spaces. Figures 3-29 and 3-30 illustrate the experimental configuration used at ORNL for the radial modifier plus one row of 5.25-inch B₄C-filled tubes. The three-dimensional experimental configuration was approximated by using the combinatorial geometry version of MORSE with 41 geometrical bodies used in the description. An examination of previous Monte Carlo calculations, done by ORNL for the radial modifier alone, showed that neutrons scattered in the concrete surrounding the modifier did not contribute significantly to the fluxes measured in the region of space sampled by detectors behind the modifier. Consequently, in order to simplify the geometry and reduce particle tracking time, the concrete was neglected in the three-dimensional combinatorial geometry model. The effects of air attenuation were also neglected. The geometry and material input was checked out with the auxiliary program, PICTURE, prior to performing the Monte Carlo calculations. Figures 3-31 and 3-32 show the output of PICTURE from one of several runs that were made to examine a cross section view of the geometry as provided by the intersection of horizontal and vertical planes (containing the neutron beam axis) with the radial modifier slabs and the B₄C rod assembly.

The Monte Carlo calculations used the same neutron cross section library that the DOT calculations of Subsection 3.3.3 used with one exception. That is, GE-BRD 24-group P₃ scattering matrices were used for all materials and in addition, ORNL "point" total cross sections were used but only for Type-304 stainless steel and for neutron energies greater than 10 keV. The "point" total cross sections were included in the calculations through an option in MORSE which allows use of an 06R "point" total cross section tape in addition to multigroup cross sections. The "point" total cross sections were used in sampling collision sites and in next-flight estimation; they were not used in calculating the uncollided flux since this component is a very small part of the total flux. Variance reduction techniques used in these Monte Carlo calculations consisted of path stretching (with no energy or region dependence), and Russian roulette. Figure 3-33 displays the energy group and biasing parameter input values. The path stretching parameter, XNU, was assigned a value of 0.5 for all regions and for particles of all energies. Particles were ignored when their energies fell below 0.625 eV. Russian roulette was invoked for all regions for particles whose weight fell below 1.0×10^{-3} and a weight of 1.0×10^{-2} was assigned to surviving particles. Track length per unit volume and collision density fluence estimation routines were used in the calculations. These estimators provided data on neutron fluxes and spectra internal to the shield array which can later be compared with one- and two-dimensional calculations. The Monte Carlo computer runs each consisted of approximately 20 batches of particles with 100 particles per batch (~2000 histories) and 25 detectors representing 13 detector locations. Table 3-24 gives a list of the detector types and locations used for all three Monte Carlo calculations discussed in this section. Detectors 1 through 9 provide comparisons with experimental data for an axial traverse. Detectors 10 through 18 were located so as to evaluate the worst case streaming effect, i.e., these detectors are on a horizontal line passing through the "virtual" point source and the center of the first off-axis inter-rod gap. Detectors 19 through 22 plus 24 and 25 provide comparisons with experimental data for radial traverses taken perpendicularly to the beam axis at 12, 72, and 144 inches back of the rods. Detector 23 (at 10 X 10 feet or 45 degrees) provided comparisons with NE-213 spectrometer measurements made at this location.

Table 3-25 shows a comparison of the MORSE calculated and experimental Bonner ball results for an axial traverse behind the 5.25-inch diameter B₄C-filled tube array. The data corresponding to Table 3-25 have been plotted and the graphical comparison between experimental and calculated results are shown in Figure 3-34. In plotting the data the calculated Bonner ball responses have been displaced axially away from the neutron source (down beam) by an amount equal to 0.7 X Bonner ball radius (as was done also for the DOT calculations discussed in Subsection 3.3.3). Agreement between calculation and experiment is good for the 3-inch Bonner ball. For the 6-inch, and 10-inch diameter balls, the agreement follows the same general trend as the DOT calculation for the equivalent homogeneous slab case. Calculated values are higher than experiment—increasingly so as the distance between detector and slab decreases. (See Figure 3-24.) The reason for this behavior is unknown at present.

* See Reference 2, Tables 3-14, 3-15, pp 3-32, 3-33, for detailed information on this shield unit.

Table 3-24
DETECTOR COORDINATES FOR 24-GROUP MORSE CALCULATIONS
(RADIAL MODIFIER PLUS ONE ROW OF
5.25-INCH DIAMETER B₄C-FILLED TUBES)

Detector Number	Detector Type	Axial Distance from Back of Rods (in.)	Radial Distance from Beam Centerline (in.)
1	Uncollided flux	12	0
2	Collided flux	12	0
3	Total flux	12	0
4	Uncollided flux	72	0
5	Collided flux	72	0
6	Total flux	72	0
7	Uncollided flux	144	0
8	Collided flux	144	0
9	Total flux	144	0
10	Uncollided flux	12	3.146
11	Collided flux	12	3.146
12	Total flux	12	3.146
13	Uncollided flux	72	5.29
14	Collided flux	72	5.29
15	Total flux	72	5.29
16	Uncollided flux	144	7.86
17	Collided flux	144	7.86
18	Total flux	144	7.86
19	Total flux	12	15.15
20	Total flux	12	24
21	Total flux	72	36
22	Total flux	72	72
23	Total flux	120	120
24	Total flux	144	72
25	Total flux	144	144

Table 3-25
COMPARISON OF MEASURED VERSUS MORSE CALCULATED DATA FOR
BONNER BALL AXIAL TRAVERSE ALONG BEAM CENTERLINE BEHIND
RADIAL MODIFIER PLUS ONE ROW OF 5.25-INCH O.D. B₄C-FILLED TUBES

Position (inches, measured from back of B ₄ C rod-slabs)	Bonner Ball Responses ^(a) (cpm/W)					
	3-in. Ball		6-in. Ball		10-in. Ball	
	Experiment	Calculated	Experiment	Calculated	Experiment	Calculated
12	2.1090+2 ^(b)	2.674+2	2.2620+3	3.241+3	1.4111+3	2.055+3
18	1.4598+2		1.4763+3		9.4456+2	
24	1.0835+2		1.0619+3		6.5221+2	
36	6.6454+1		6.0061+2		3.9495+2	
48	4.4104+1		3.9223+2		2.6126+2	
72	2.3146+1	2.013+1	2.0289+2	2.404+2	1.3775+2	1.515+2
96	1.4520+1		1.2770+2		8.7544+1	
120	1.0205+1		8.8039+1		6.2484+1	
144	7.668 +0	5.732+0	6.4982+1	7.038+1	4.5870+1	4.584+1
Measured Background						
72	3.890 +0		1.2392+1		6.811 +0	
144	2.503 +0		9.267 +0		4.056 +0	
Comparison for 3 axial positions with background subtracted						
12	2.1090+2	2.674+2	2.2620+3	3.241+3	1.4111+1	2.055+3
72	1.9256+1	2.013+1	1.9050+2	2.404+2	1.3094+2	1.515+2
144	5.165 +0	5.732+0	5.5715+1	7.038+1	4.1814+1	4.584+1

(a) Experimental data from Tables 3-4, 3-5

(b) 2.1090×10^2

SLABS:

STAINLESS STEEL 5 ft x 5 ft (2.012 in + 2.021 in.)

Na 5 ft x 5 ft

BORAL 5 ft x 5 ft

B₄C 50 in. W x 52 in. H (5-1/4 in. DIA B₄C ROD-SLAB, G3-T5-3)

Figure 3-29. Schematic Diagram of Test Configuration for Radial Modifier Plus One Row of 5.25-Inch B₄C-Filled Tubes

Figure 3-30. Schematic Diagram of Test Configuration and Radial Traverse Behind a Typical B₄C-Filled Tube Shield

Figure 3-31. Program PICTURE Output for Horizontal Half-Plane Intersection with Morse Combinatorial Geometry Model for Radial Modifier Plus One Row of 5.25-Inch Diameter B₄C-Filled Tubes

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GROUP PARAMETERS, GROUP NUMBERS GREATER THAN 24 CORRESPOND TO SECONDARY PARTICLES

GROUP	UPPER EDGE (EV)	VELOCITY (CM/SEC)
1	1.4900E 07	4.8799E 09
2	1.0000E 07	3.9203E 09
3	6.0700E 06	3.0536E 09
4	3.6800E 06	2.3774E 09
5	2.2300E 06	1.8503E 09
6	1.3500E 06	1.4409E 09
7	8.2100E 05	1.1231E 09
8	4.9800E 05	8.7459E 08
9	3.0200E 05	6.8105E 08
10	1.8300E 05	5.3025E 08
11	1.1100E 05	4.1305E 08
12	6.7400E 04	3.2193E 08
13	4.0900E 04	2.5056E 08
14	2.4800E 04	1.9510E 08
15	1.5000E 04	1.5198E 08
16	9.1200E 03	1.1437E 08
17	5.5300E 03	9.2154E 07
18	3.3500E 03	7.1730E 07
19	2.0300E 03	5.3219E 07
20	1.0100E 03	3.4599E 07
21	2.4900E 02	1.7058E 07
22	5.5000E 01	8.0542E 06
23	1.2400E 01	3.5294E 06
24	6.2500E-01	2.2000E 05

INITIAL RANDOM NUMBER = 93C605195A5D

NSPLT= 0 NKILL= 1 NPAST= 1 NOLEAK= 0 IERIAS= 0 MXREG= 40 MAXGO= 24

WEIGHT STANDARDS FOR SPLITTING AND RUSSIAN ROULETTE AND PATHLENGTH STRETCHING PARAMETERS

NGP1	NDG	NGP2	NRG1	NRG2	NRG3	WT1H1	WTLOW1	WTAVE1	XN11
1	1	24	1	1	40	0.0	1.0000E-03	1.0000E-02	0.5000E 00

NSOUR= 0 MFISTP= 0 NKCALC= 0 NORMF= 0

Figure 3-33. Biasing Parameters for 24-Group MORSE Calculation for the Radial Modifier Plus One Row of 5.25-Inch Diameter B₄C-Filled Tubes

Figure 3-34. Measured vs MORSE Calculated Bonner Ball Response Behind One Row of 5.25-Inch Diameter B_4C -Filled Tubes

Tables 3-26, 3-27, and 3-28 show a comparison of MORSE calculated and experimental Bonner ball results for radial traverses at 12, 72, and 144 inches behind the one-row rod array. The data corresponding to Tables 3-26, 3-27, and 3-28 have been plotted and the graphical comparisons between experimental and calculated results are shown in Figures 3-35, 3-36, and 3-37. In plotting these data, the center of response was assumed to coincide with the geometric center for all Bonner balls. This means that the calculated data points should actually be plotted slightly higher than shown since the radial traverse distance from the back of the rods is defined as the distance between the plane tangent to the back of the rods and the geometric center of a Bonner ball. Inspection of Figures 3-35, 3-36, and 3-37 shows that the agreement between calculation and experiment is reasonably good for the 3-inch diameter ball but that calculated results are generally higher than experiment by factors in the range 1.0 to 1.9.

Figure 3-38 shows a comparison of MORSE calculated and NE-213 spectrometer results for the neutron spectrum at a detector point located 10 feet off centerline and 10 feet back of the 5.25-inch o.d. B_4C rod array. The NE-213 data correspond to neutron energies greater than about 1 MeV (GE-BRD energy Groups 1 to 6). The MORSE calculated value for the integral over this energy range appears to be higher than the measured value by a factor of ~ 1.7 . This result tends to agree with the difference between calculated and measured Bonner ball responses (Table 3-28 and Figure 3-37).

One of the main purposes of these calculations was to determine the amount of neutron streaming through the triffute regions between the B_4C rods. This information can then be used to evaluate the effectiveness of a rod-type core radial shield. In performing this analysis, there are some differences between experimental, Monte Carlo model, and actual core radial rod-type shields which should be considered. The triffutes used in the experiment were made of aluminum for convenience of construction and because aluminum has neutron total flux attenuation properties similar to sodium which is the material which would be present in the core radial shield. Also, the aluminum triffutes used in the experiment were equally concave on all three of their longitudinal surfaces and therefore constituted a volume fraction of 0.093 of the rod array rather than a volume fraction of 0.2146 which was actually used in the Monte Carlo calculations. In order to determine the effect on neutron attenuation introduced by these differences, the Monte Carlo calculations were done for the three cases already mentioned, i.e., (1) with aluminum triffutes, (2) with sodium triffutes, and (3) with void triffutes. Figures 3-39, 3-40, and 3-41 show the results of these calculations for detector locations representative of radial traverses at 12, 72, and 144 inches behind the rod array. Inspection of these figures reveals that a small but noticeable increase in streaming occurs when the aluminum triffutes are replaced with voids. The calculations therefore predict experimental results that are intermediate between these two cases. Figure 3-42 shows a comparison of the Monte Carlo calculated neutron energy spectra for these three cases at a detector located 12 inches behind the rod-slab and off-axis by a distance such that it receives maximum exposure to neutrons streaming between the center and first off-axis B_4C rods. The effect of the 3 keV sodium resonance shows up as a deeper valley at this energy for the case with sodium triffutes. Figures 3-39, 3-40, and 3-41 also show DOT calculated results for the corresponding homogeneous slab configuration (one 5.25-inch equivalent homogeneous B_4C slab). These comparisons of heterogeneous vs homogeneous shield neutron transmission show that there is a relatively minor increase in transmitted flux in going from a homogeneous slab to the heterogeneous rod-type shield. This calculational result confirms the experimental results obtained from the measurements made at ORNL (see Figures 3-43 to 3-46). Figures 3-43 and 3-44 show the rod-slab vs homogeneous slab comparison for 3- and 6-inch Bonner ball axial traverse measurements. Figures 3-45 and 3-46 show similar comparisons for Hornyak button radial traverse measurements made at 2.6 inches behind one and two rows of rod-slabs and homogeneous slabs. Some evidence of maxima and minima is noted in the Hornyak button results although the peaking due to streaming of high-energy neutrons is obviously not a large effect even for a single row of rods.

Table 3-26
COMPARISON OF MEASURED VERSUS MORSE CALCULATED DATA
FOR BONNER BALL RADIAL TRAVERSE AT 12 INCHES BEHIND
RADIAL SPECTRUM MODIFIER PLUS ONE ROW OF 5.25-INCH O.D. B₄C-FILLED TUBES

Position (inches, measured from beam centerline)	Bonner Ball Responses ^(a) (cpm/W)					
	3-in. Ball		6-in. Ball		10-in. Ball	
	Experiment	Calculated	Experiment	Calculated	Experiment	Calculated
30N ^(b)	47.561		320.106		180.107	
24	70.570	80.31	560.755	773.5	313.817	362.0
18	105.392		914.580		539.917	
15.15		148.8		1,581		831.2
12	150.822		1401.775		889.145	
6	193.625		1,929.583		1,259.927	
3.14		253.4		3,084		1,924
3	—		—			
C	212.858	267.4	2,167.601	3,241	1,417.616	2,055
C	210.165	267.4	—	3,241	—	2,055
2S ^(c)	211.967		—		—	
3.146		253.4		3,084		1,924
4	206.703		—		—	
6	195.399		1,968.677		1,268.371	
8	185.546		—		—	
10	172.806		—		—	
12	156.423		1,467.999		895.641	
14	139.561		—		—	
15.15		148.8		1,581		831.2
16	124.964		—		—	
18	111.347		944.779		554.254	
20	98.084		—		—	
22	85.863		—		—	
24	76.168	80.31	572.117	773.5	318.488	362.0
26	68.027		—		—	
28	60.764		—		—	
30	54.046		339.745		183.086	

(a) Experimental data from Table 3-6

(b) North of centerline

(c) South of centerline

Note: Experimental data not yet available on background count rates for these measurements.

Table 3-27
COMPARISON OF MEASURED VERSUS MORSE CALCULATED DATA
FOR BONNER BALL RADIAL TRAVERSE AT 72 INCHES BEHIND
RADIAL SPECTRUM MODIFIER PLUS
ONE ROW OF 5.25-INCH O.D. B₄C-FILLED TUBES

Position (inches, measured from beam centerline)	Bonner Ball Responses ^(a) (cpm/W)					
	3-in. Ball		6-in. Ball		10-in. Ball	
	Experiment	Calculated	Experiment	Calculated	Experiment	Calculated
0	22.681	20.13	204.359	240.4	134.805	151.5
5.285		20.33		242.5		152.2
12S(b)	21.428		191.244		122.823	
15.15						
18	20.202		175.928		110.942	
24	18.620		153.714		92.543	
30	17.039		140.027		82.271	
36	15.746	15.01	125.734	165.0	71.997	90.76
48	12.384		99.507		56.514	
60	9.600		76.852		42.539	
72	7.311	8.612	58.912	88.89	31.951	43.11
Background						
0	2.621		9.541		4.125	
72S(b)	1.792		6.704		2.808	

(a) Experimental data from Table 3-7

(b) South of centerline

Table 3-28
COMPARISON OF MEASURED VERSUS MORSE CALCULATED DATA FOR
BONNER BALL RADIAL TRAVERSE AT 144 INCHES BEHIND
RADIAL SPECTRUM MODIFIER PLUS ONE ROW OF 5.25-INCH O.D. B₄C-FILLED TUBES

Position (inches, measured from beam centerline)	Bonner Ball Responses ^(a) (cpm/W)					
	3-in. Ball		6-in. Ball		10-in. Ball	
	Experiment	Calculated	Experiment	Calculated	Experiment	Calculated
℄	7.9182	5.732	65.4563	70.38	45.6710	45.84
7.85		5.828		71.03		45.96
12S(b)	7.7085		64.8728		42.6691	
24	7.3597		59.9782		37.3375	
36	6.8468		48.6045		29.3848	
48	6.3206		47.5693		26.1469	
72	5.2843	4.149	36.0767	45.13	20.9706	24.35
96	4.3104		—		15.8735	
108			25.1992			
120	3.5187				12.1722	
144	2.7521	2.177	16.7451	22.28	9.1779	10.71
Background						
℄	—		—		—	
72	2.0709		7.5289		3.1397	
144	1.4611		5.0561		2.0434	

(a) Experimental data from Table 3-8

(b) South of centerline

Figure 3-35: Measured and MORSE Calculated Bonner Ball Response for Radial Traverse at 12 Inches Behind One Row of 5.25-Inch o.d. B_4C -Filled Tubes

Figure 3-36. Measured and MORSE Calculated Bonner Ball Response for Radial Traverse at 72 Inches Behind One Row of 5.25-Inch o.d. B_4C -Filled Tubes

Figure 3-37. Measured and MORSE Calculated Bonner Ball Response for Radial Traverse at 144 Inches Behind One Row of 5.25-Inch o.d. B_4C -Filled Tubes

Figure 3-38. Comparison of NE-213 Measured and MORSE Calculated Spectra Behind One Row of 5.25-Inch Diameter B_4C Rods at a Distance of 10 Feet and 10 Feet Off Centerline

Figure 3-39. Comparison of MORSE Calculated Bonner Ball Response for Radial Traverse at 12 Inches Behind 5.25-Inch o.d. Rod-Slab with Aluminum Triflutes and DOT Calculated Bonner Ball Response at 12 Inches Behind 5.25-Inch Homogeneous B_4C Slab

Figure 3-40. Comparison of MORSE Calculated Bonner Ball Response for Radial Traverse at 12 Inches Behind 5.25-Inch o.d. Rod-Slab with Sodium Triflutes and DOT Calculated Bonner Ball Response at 12 Inches Behind 5.25-Inch Homogeneous B_4C Slab

Figure 3-41. Comparison of MORSE Calculated Bonner Ball Response for Radial Traverse at 12 Inches Behind 5.25-Inch o.d. Rod-Slab with Void Triflutes and DOT Calculated Bonner Ball Response at 12 Inches Behind 5.25-Inch Homogeneous B_4C Slab

Figure 3-42. Comparison of MORSE Calculated Neutron Energy Spectra for Al, Na, and Void Triflutes at 3.146 Inches Off Axis, 12 Inches Behind One 5.25-Inch o.d. Rod-Slab

Figure 3-43. Measured 3-Inch Bonner Ball Response for Axial Traverses Behind One 5.25-Inch Rod-Slab or Homogeneous Slab

Figure 3-44. Measured 6-Inch Bonner Ball Response for Axial Traverses Behind One 5.25-Inch Rod-Slab or Homogeneous Slab

Figure 3-45. Measured Hornyak Button Response for Radial Traverse at 2.6 Inches Behind One 5.25-Inch Rod-Slab or Homogeneous Slab

Figure 3-46. Measured Hornyak Button Response for Radial Traverse at 2.6 Inches Behind Two 5.25-Inch Rod-Slabs or Homogeneous Slabs

4. ADMINISTRATIVE

4.1 TRIPS

W. H. Harless to ORNL, November 6 to 21, 1972.

4.2 VISITS

J. E. Stewart, RDT, Core Design Branch, on October 5-6, 1972.

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