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OPERATION HENRE

RADIATION OUTPUT DESCRIPTION FROM
THE $T(d,n)^4\text{He}$ REACTION IN A LARGE
TARGET (1000 cm^2) — OPERATION HENRE

Z. G. Burson

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RADIATION OUTPUT DESCRIPTION FROM THE $T(d,n)^4\text{He}$ REACTION IN A LARGE TARGET (1000 cm^2)—OPERATION HENRE

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fly

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ABSTRACT

Eleven major programs, including about 25 individual projects, obtained successful measurements during Operation HENRE (High Energy Neutron Reactions Experiment). To make maximum use of these data and to allow rigorous comparison with calculations, a thorough description of the radiation output from the targets was required.

The target substrate was made of 2.54-cm thick copper, 40 cm in diameter and weighing 20,850 g (46 lb). A depression 1.83 cm deep in the center of this plate provided a 37.5-cm diameter flat area for the deposition of a 1000-cm² ErT₂ film. The thick rim of the plate provided a means for easy mounting to the accelerator tube. A deuterium beam of 400 ma at 150 kv produced 10¹³ neutrons/sec over 4 π .

Calculations of the energy and angular distribution of neutrons emerging from the targets show that in the direction of 0⁰ (straight down), 80 percent of the neutrons were in the 13- to 15-MeV region, 5 percent were in the 5- to 13-MeV region, and 15 percent were in the 0- to 5-MeV region. At 88°, the percentages were 67, 22.5, and 10.5, respectively. For the total 4 π output, the percentages were 80, 6.5, and 13.6, respectively. The calculated angular distribution of the 13- to 15-MeV component compares well with activation foil data.

Another set of activation foil data, taken at 0⁰ utilizing 14 different reactions, was studied in detail. Forty-seven different trial spectra were chosen to evaluate the sensitivity of these foils to spectral changes. The spectrum giving the best fit was nearly the same as that predicted from calculations. The foil data showed a strong sensitivity to the fraction of "14 MeV" neutrons present, but were nearly insensitive to the shape of the spectrum below the "14 MeV" peak.

The results of this study are useful and applicable to all measurements taken during Operation HENRE.

CONTENTS

ACKNOWLEDGMENTS.....	4
ABSTRACT.....	5
CHAPTER 1 INTRODUCTION.....	11
CHAPTER 2 SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS.....	12
CHAPTER 3 SOURCE DESCRIPTION.....	18
CHAPTER 4 EXPERIMENTAL DATA	24
4.1 General.....	24
4.2 NDL Data.....	25
4.3 Stanford University Data.....	28
4.4 EG&G Data.....	30
4.5 ORNL Data.....	37
4.6 Other Data.....	38
CHAPTER 5 SIMPLIFIED CALCULATIONS.....	41
5.1 Introduction.....	41
5.2 Target Geometry.....	41
5.3 Cross-Section Determinations.....	41
5.4 Uncollided Beam Calculations.....	43
5.5 Elastic Scatter Contributions.....	45
5.6 (n,2n) Contribution.....	49
5.7 Inelastic Scatter and Other Contributions.....	51
5.8 Summary and Discussion.....	53
CHAPTER 6 EVALUATION AND ANALYSIS.....	59
6.1 (D-D) Contribution.....	59

6.2	Effective Energy of 13- to 15-MeV Component at 0°	59
6.3	Energy Spectrum at 0° (Above 0.50 MeV)	61
6.4	Directional Neutron Output	73
6.5	Energy Spectrum (Above 0.5 MeV) at $\sim 90^\circ$	73
6.6	Gamma Ray Output	77
6.7	Total 4π Output	79
6.8	Error Estimates	81

ILLUSTRATIONS

CHAPTER 2 SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

2.1	HENRE Source Angular Distributions	14
-----	--	----

CHAPTER 3 SOURCE DESCRIPTION

3.1	Cross Section Values for the $T(d,n)^4\text{He}$ and the $D(d,n)^3\text{He}$ Reactions	19
3.2	A Schematic View of the HENRE Neutron Generator	20
3.3	HENRE Neutron Generator at the 54-ft Position	20
3.4	HENRE Target Details	21
3.5	HENRE Target Assembly	22
3.6	Finish Cut on Cooling Channels for a HENRE Target	23
3.7	Finished Target Blank	23

CHAPTER 4 EXPERIMENTAL DATA

4.1	Activation Foils Placed on 1-1/2 Meter Arcs	26
4.2	Experimental Setup for the Intercalibration Run	26
4.3	EG&G Neutron Spectrometer Setup for a 30° Measurement	34
4.4	EG&G Neutron Spectrum Measurements	35
4.5	HENRE Target Self-Shielding	36
4.6	Approximate Neutron Fluence Across Bottom of Target Plate and Bottom of Corona Dome for a 4-Hour Run for an Average Target (Target 52, September 18, 1968)	38
4.7	Neutron Production in the HENRE Targets	39

ILLUSTRATIONS (Continued)

CHAPTER 5 SIMPLIFIED CALCULATIONS

5.1	Simplified Target Configuration.....	42
5.2	Calculated Directional Neutron Output from the HENRE Targets.....	47
5.3	Differential Elastic Scattering Cross Section.....	48
5.4	Proton or Neutron Energies from Elastic Scattering (Ref. 3).....	49
5.5	Energy Distribution of Neutrons from the (n,2n) Reaction in Natural Copper.....	51
5.6	Computed Energy Distribution of Neutrons Emitted by ^{63}Cu Bombarded by 14 MeV Neutrons. Both inelastic and (n,2n) processes are included.....	52
5.7	Estimated Energy Distribution of Neutrons Emitted by Natural Copper Bombarded by 14.75 MeV Neutrons. Both inelastic and (n,2n) processes are included.....	52
5.8	Calculated Directional Neutron Output from the HENRE Target.....	55
5.9	Calculated Neutron Energy Spectrum at 0°	56
5.10	Calculated Neutron Energy Spectrum at 88°	57
5.11	Calculated Neutron Energy Spectrum for Total 4π Output.....	58

CHAPTER 6 EVALUATION AND ANALYSIS

6.1	(D-D) Neutron Buildup on a Small Erbium-Coated (4.7 mg/cm^2) Copper Target, 150 kv.....	60
6.2	Neutron Energy at 0° versus Deuteron Energy Resulting from the $\text{T(d,n)}^4\text{He}$ Reaction in a Thin Titanium Target.....	60
6.3	Energy Dependence of Cross Section Ratios.....	62
6.4	Effective Neutron Energy Inferred by NDL Data by the Saturated Activity Ratio Method.....	63
6.5	Trial Energy Spectra at 0°	64
6.6	Trial Energy Spectra at 0°	65
6.7	Trial Energy Spectra at 0°	66
6.8	Trial Energy Spectra at 0°	67
6.9	Relative Neutron Fluence of Several Activation Foils at 0° as a Function of the "14 MeV" Fraction of Various Trial Spectra.....	70
6.10	Standard Deviations as a Function of "14 MeV" Fraction for All Trial Spectra.....	72
6.11	13-15 MeV Fluence vs. Polar Angle.....	75

TABLES

CHAPTER 2 SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

2.1	HENRE Neutron Source Spectrum at 0°	13
2.2	HENRE Source Spectrum.....	15
2.3	Correction Factors for Obtaining 4π Neutron Output Within a Specific Energy Interval.....	16

CHAPTER 4 EXPERIMENTAL DATA

4.1	Neutron Fluence as Derived from Sulfur Pellets Placed 3 Meters Below the Target on HENRE Run 68-29 1 November 1968.....	25
4.2	Activity in DPM/GM (Raw Data) of NDL Foils for HENRE Intercalibration Run.....	26
4.3	NDL Estimated Neutron Fluences at 1.5 Meters for HENRE Run 68-29, 1 November 1968.....	28
4.4	Decay-Corrected Activities in Foils 1 Meter from the Target, HENRE Run No. 40, 7/10/67.....	29
4.5	Activities in Samples Irradiated at 1 Meter HENRE Run No. 17, 11/11/66.....	30
4.6	Saturated Activities of EG&G Sulfur Pellets on 1-1/2 Meter Arc for HENRE Intercalibration Run.....	31
4.7	EG&G-Activation Foil Data Versus Angle.....	32
4.8	Results for EG&G TLD's on 1-1/2 Meter Arc for HENRE Intercalibration Run	33

CHAPTER 5 SIMPLIFIED CALCULATIONS

5.1	Macroscopic Cross-Section Determinations for 14.06 MeV Neutrons.....	43
5.2	Cross Sections, Neutron Energy, and Relative Intensity As a Function of Angle for the D-T Reaction.....	44
5.3	Summary of Neutron Output Calculations for HENRE Neutron Source. Results given in fraction of original Neutron Production at 0° , no shield.....	46
5.4	Summary of Neutron Output Calculations for the HENRE Neutron Source. Results given in relative values of original neutron production at 0° , no shield. (A value of 0.06 is assigned to the 5 - 13 MeV region for all angles.).....	54

CHAPTER 6 EVALUATION AND ANALYSIS

6.1	Activation Foil Evaluation for Effective Energy of 13-15 MeV Neutron Component at 0°	62
-----	--	----

TABLES (Continued)

6.2	Fluence Rate Determinations as a Function of Input Spectra for 14 Foil Activation Results from Table 4.4.....	68
6.3	Average Fluence Rates and Standard Deviations for the Tr. Spectra.....	71
6.4	13-15 MeV Fluence as Derived from NDL Foil Data.....	74
6.5	Neutron Fluences Above 0.5 MeV as Determined from Selected Foil Data and Assumed Spectra.....	76
6.6	Estimated Gamma Exposure as Derived from TLD Data at 1-1/2 Meters on the Intercalibration Run, November 1, 1968.....	78
6.7	Corrections to Be Applied to Quam's and Haywood's Sulfur Data to Obtain an Average Fluence.....	80

Chapter 1

INTRODUCTION

Operation HENRE (High Energy Neutron Reactions Experiment) was conceived¹ as a follow-on to Operation BREN² (Bare Reactor Experiment in Nevada). Its 14-MeV neutron source enabled researchers to study neutron and secondary gamma ray transport through the air, in/at the ground, and in various shielding configurations.³ The nearly monoenergetic purity of the source provided opportunities for experimental verifications of basic calculational techniques.

Eleven major programs, including about 25 individual projects, obtained successful measurements during the HENRE Operation.⁴ To make maximum use of these data and to allow rigorous comparison with calculations, a thorough description of the radiation output from the targets was required.

Several measurements by many different groups were made at many locations at, and near, the targets to describe the output. Unfortunately, these data were not as definitive as desirable. Nevertheless, these data are assembled here to summarize what is known about the target output. Some simplified calculations are also included. It is hoped that the resultant description will be thorough enough for many useful comparisons to be made, and that it will provide meaningful information for the various programs to meet their objectives.

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Chapter 2

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

The targets used for the $T(d,n)^4\text{He}$ reaction during Operation HENRE were thick and heavy. Consequently, the neutron output was neither isotropic or monoenergetic. The best estimate of the radiation output description was obtained by comparing activation foil data with results from simplified calculations.

The target substrate was made of 2.5-cm thick copper, 40 cm in diameter and weighing 20,850 g (46 lb). A depression 1.83 cm deep in the center of this plate provided a 37.5-cm diameter flat area for deposition of a 1000-cm² ErT_2 film. The thick rim of the plate provided a means for easy mounting to the accelerator tube. The shielding provided by this copper plate and outer ring perturbed both the energy and angular distribution of neutrons emerging from the source system.

Point kernel calculations were made of the uncollided neutron fluence versus polar angle emerging from the targets. In addition, estimated contributions from elastic and inelastic scatter events and $(n,2n)$ reactions were made. Major assumptions were:

1. The elastic scattered neutrons were greater than 13 MeV in energy and continued essentially in the same direction.
2. All neutrons from the $(n, 2n)$ reactions were generated isotropically.
3. Emerging neutrons from inelastic scattering were isotropic.

Two sets of activation foil data were examined to determine the effective energy at 0° of the "14-MeV" component. An energy of $14.75 \text{ MeV} \pm 200 \text{ keV}$ is recommended.

Another set of activation foil data, taken at 0° , utilizing 14 different reactions, was examined in detail to determine the neutron energy spectrum at 0° . Forty-seven different trial spectra were chosen to evaluate the sensitivity of these foils to spectral changes. The spectrum giving the best fit was nearly the same as that calculated when the $(D-D)$ component is included. The foil data showed a strong sensitivity to the fraction of "14 MeV" neutrons present, but were nearly insensitive to the shape of the spectrum below the "14 MeV" peak.

For the neutron spectrum at 0° , it is recommended that spectrum D in Fig. 6.7 be used for all source heights and all runs for Operation HENRE. This spectrum is tabulated in Table 2.1. A value was assigned to the energy interval,

TABLE 2.1. HENRE NEUTRON SOURCE SPECTRUM AT 0°.

Energy Interval (MeV)	Percentage of Total Fluence (%)	Energy Interval (MeV)	Percentage of Total Fluence (%)
0.1 - 0.5	1.08	7.5 - 8.0	0.44
0.5 - 1.0	1.14	8.0 - 8.5	0.38
1.0 - 1.5	1.60	8.5 - 9.0	0.31
1.5 - 2.0	1.36	9.0 - 9.5	0.28
2.0 - 2.5	1.30	9.5 -10.0	0.23
2.5 - 3.0	2.67	10.0 -10.5	0.18
3.0 - 3.5	1.50	10.5 -11.0	0.15
3.5 - 4.0	1.52	11.0 -11.5	0.11
4.0 - 4.5	1.40	11.5 -12.0	0.08
4.5 - 5.0	1.10	12.0 -12.5	0.05
5.0 - 5.5	0.80	12.5 -13.0	0.03
5.5 - 6.0	0.76	13.0 -13.5	0
6.0 - 6.5	0.67	13.5 -14.0	0
6.5 - 7.0	0.58	14.0 - 14.5	0
7.0 - 7.5	0.51	14.5 - 15.0	79.8

0.1-0.5 MeV, to complete the spectrum even though no effort was made to evaluate this component.

Activation foil data at 1-1/2 m at several polar angles confirm the calculated directional output of the "14-MeV" component. Table 2.2 and Fig. 2.1 present the neutron angular distributions for several energy intervals. These energy intervals were chosen to correspond to Straker's calculations of neutron and gamma dose distributions in air.¹

Note that the values given in Table 2.2 and Fig. 2.1 are percentages of the total output (from 0.111 to 15 MeV) at 0°. Furthermore, the values pertain to number of neutrons, not neutrons/MeV. The angle, 0°, refers to the direction of the deuterium beam which was normal to the target plate. The angles are polar angles. The results assume that for any polar angle, the neutrons emerging were constant over azimuthal directions.

These results are the best estimate of the neutron output description. High confidence is placed in the 12.2- to 15-MeV component. The directional shapes at other energies are less certain. The difficulty was in the assumptions of the angular distributions of neutrons from the inelastic and (n,2n) events.

Rough estimates were made of the gamma ray component emerging from the source system. The following values are recommended:

Gamma Ray Energy
(MeV)

Exposure Level at 1 Meter
(R/source neutron)

~ 0.150

5.3×10^{-16}

~ 2.75

5.3×10^{-16}

~ 6.0

6.6×10^{-16}

The total 4π neutron output (0.111 to 15 MeV) for the HENRE source is 19.3 percent less than it would be if it were isotropic. Furthermore, of those that escape, only 80 percent are in the 12.2- to 15-MeV region. Of those in the 12.2- to 15-MeV region, the 4π output is 20.7 percent less than if these were isotropic.

Fig. 2.1—HENRE source angular distributions.

TABLE 2.2. HENRE SOURCE SPECTRUM.

Cos θ	Polar Angle (θ , deg)	Relative Number of Neutrons Within Designated Energy Interval							
		12.2- 15.0 MeV	10.0- 12.2 MeV	8.18- 10.0 MeV	6.36- 8.18 MeV	4.06- 6.36 MeV	2.35- 4.06 MeV	1.108- 2.35 MeV	0.111- 1.108 MeV
1.00	0	79.8	0.60	1.00	1.80	4.40	6.00	3.90	3.00
0.985	10	79.8	0.60	1.00	1.80	4.40	6.00	3.90	3.00
0.940	20	79.3	0.60	1.00	1.80	4.40	5.74	3.86	2.96
0.866	30	78.4	0.60	1.00	1.80	4.37	5.35	3.80	2.90
0.766	40	77.1	0.60	1.00	1.80	4.34	5.10	3.75	2.87
0.643	50	74.7	0.60	1.00	1.80	4.25	4.73	3.61	2.76
0.500	60	71.2	0.60	1.00	1.80	4.10	4.35	3.38	2.59
0.342	70	65.4	0.60	1.00	1.80	3.92	3.91	3.11	2.38
0.174	80	47.9	0.60	1.00	1.80	3.57	3.13	2.55	1.95
0.087	85	28.4	0.60	1.00	1.80	3.03	2.09	1.70	1.30
0.035	88	15.4	0.60	1.00	1.80	2.35	0.79	0.64	0.49
0	90	32.1	0.60	1.00	1.80	2.37	0.82	0.67	0.51
-0.035	92	38.3	0.60	1.00	1.80	2.37	0.82	0.67	0.51
-0.096	95	68.9	0.60	1.00	1.80	3.12	2.26	1.84	1.41
-0.174	100	73.7	0.60	1.00	1.80	3.42	2.85	2.32	1.78
-0.259	105	61.9	0.60	1.00	1.80	3.66	3.30	2.69	2.06
-0.342	110	71.4	0.60	1.00	1.80	3.97	3.89	3.17	2.43
-0.500	120	75.6	0.60	1.00	1.80	4.13	4.20	3.43	2.62
-0.643	130	74.3	0.60	1.00	1.80	4.25	4.43	3.61	2.76
-0.766	140	72.7	0.60	1.00	1.80	4.32	4.57	3.73	2.85
-0.866	150	67.4	0.59	1.00	1.72	2.61	2.76	2.25	1.72
-0.906	155	30.5	0.27	0.47	0.83	0.85	0.90	0.74	0.56
-0.940	160	17.8	0.16	0.28	0.48	0.29	0.31	0.25	0.19
-0.966	165	11.1	0.10	0.17	0.30	0.15	0.17	0.14	0.10
-0.985	170	8.2	0	0.12	0.22	0	0	0	0
-1.00	180	0	0	0	0	0	0	0	0

TABLE 2.3. CORRECTION FACTORS* FOR OBTAINING 4π NEUTRON
OUTPUT WITHIN A SPECIFIC ENERGY INTERVAL.

Energy Interval (MeV)	Phase I	Phase II
0.5-15	1.021	0.904
13-15	0.807	0.716
12-13	0	0
11-12	0.0021	0.0019
10-11	0.0038	0.0033
9-10	0.0058	0.0051
8-9	0.0082	0.0072
7-8	0.0111	0.0094
6-7	0.0144	0.0127
5-6	0.0185	0.0163
4-5	0.0251	0.0224
3-4	0.0307	0.0269
2-3	0.0363	0.0321
1-2	0.0301	0.0263
0.5-1	0.0281	0.0249

*Correction factors to be applied to previously given 4π neutron output for Operation HENRE.

It is recommended that the spectrum in Fig. 5.11, plus an appropriate component for the (D-D) reaction, be used for the neutron spectrum of the total 4π output. To obtain the corrected neutron output for all runs in Phases I and II of Operation HENRE, the values in Table 2.3 are recommended. These values include a 1 percent (D-D) component.

Uncertainties in the absolute magnitude of the 4π neutron output were estimated. The combined errors resulted in an uncertainty of about ± 17 percent for the total 4π neutron output. The uncertainty of the 4π output of the 12.2- to 15-MeV component is a little better than this, about ± 15 percent.

In addition to the above recommendations, the following conclusions and general recommendations are given:

1. Through calculations of the neutron transport and interactions through the copper plate would be useful, providing that detailed energy and angular distributions of the neutrons resulting from the inelastic and $(n,2n)$ processes were included.
2. Activation foil data cannot be used to obtain a neutron spectrum to any degree of certainty unless cross sections and specific activities are precisely known. Otherwise, only the general shape of the spectrum can be inferred.
3. If another accelerator is designed or built for a field program similar to Operation HENRE, it is recommended that the target be designed to provide minimum perturbation of the neutrons. It is further recommended that calculations be made and thorough measurements be taken to describe the radiation output before a field program is begun.

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Chapter 3

SOURCE DESCRIPTION

Producing 14-MeV neutrons by deuteron bombardment in a tritium target is a widely used technique. The $T(d,n)^4He$ reaction cross-section peaks at a deuteron energy of 110 keV (see Fig. 3.1).¹

The accelerator for Operation HENRE was designed to produce a 4-hr average of 10^{13} n/sec over 4π ; a yield higher by more than an order of magnitude than any other accelerator then in existence.² Major component parameters chosen for the accelerator were: (1) A copper target of 1000 cm² coated with erbium containing 1800 curies of tritium; (2) a duoplasmatron ion source capable of up to 500 milliamperes of beam current of deuterium; and (3) a power supply of 150 kv. A schematic of the accelerator and a general view of it mounted on the BREN tower at the U.S. Atomic Energy Commission Nevada Test Site are shown in Figs. 3.2 and 3.3. A thorough description of the accelerator and a discussion of its performance is found in Ref. 3.

The basic copper backing for the target contained 117 cooling slots, 0.086 cm wide and varying from 0.206 to 0.300 cm deep. The copper plate was 0.635 cm thick and the depression was 37.5 cm in diameter in order to accommodate an active area of erbium tritide of 1000 cm² (35 cm in diameter). Surrounding the disk, the copper backing contained a thick copper "ring" and "ears" to provide easy mounting onto the accelerating column. It also contained headers, 180° apart, for the cooling channels, and quick disconnect fittings for the coolant.

A copper target blank weighted 20,850 g (46 lb). In addition, it contained 276 g of water when filled.

Drawings of the target are shown in Figs. 3.4 and 3.5. The cooling channels before a 0.32-cm thick target cover was welded onto it are shown in Fig. 3.6. A photograph of a finished, blank target is shown in Fig. 3.7.

In tritiated a target, the copper blank first received a thick coating of erbium (4 mg/cm²). It was then transferred to a tritiated oven and brought to 450°C, and simply "soaked" in tritium. About 1800 curies was taken up by the erbium in the form of Er^3H . The compound actually formed was $ErT_{1.75}$ (best estimate).

For operations on the BREN tower, a corona dome was placed around the target (see Figs. 3.2 and 3.3). It was 1/16 inch thick and spun from aluminum.

The composition of the deuterium beam from the duoplasmatron ion source was estimated to consist of at least 75 percent atomic ions.⁴

Fig. 3.1—Cross-section values for the $T(d,n)^4\text{He}$ and the $D(d,n)^3\text{He}$ reactions.

Fig. 3.2—Schematic view of the HENRE neutron generator.

Fig. 3.3—HENRE neutron generator at the 54-ft position.

Fig. 3.4—HENRE target details.

Fig. 3.5—HENRE target assembly.

NOT TO SCALE

Fig. 3.6—Finish cut on cooling channels for a HENRE target.

Fig. 3.7—Finished target blank.

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3. J. E. Jobst, *Description and Operational Performance of an Intense 14-MeV Neutron Generator*, USAEC Report CEX-65.06 (to be published).
4. O. B. Morgan, Oak Ridge National Laboratory, private communication, April, 1970.

Chapter 4

EXPERIMENTAL DATA

4.1 GENERAL

Many different groups and projects obtained experimental data at or near the targets to support their own objectives. Most of these unpublished data have been reviewed and examined. A few sets of data are given in this chapter. No single organization was responsible for documenting a detailed description of the neutron output.

The Technical Director, through ORNL and/or EG&G, was responsible, however, for determining the total 4π output, and time-dependent output, for each run.

An estimate of the neutron fluence above 3 MeV was determined for each experimental run and for each target at a point 3 m below the tritiated target surface. Sulfur pellets, using standard counting techniques, were the primary detectors.

During Phase I, Haywood (ORNL) determined the fluences at the Nevada Test Site by using counting equipment calibrated at ORNL. The fluences were later confirmed by repeating the activation analysis at ORNL. During Phase II, Quam (EG&G) determined the fluences at the Santa Barbara Laboratory. The activity of the pellets was counted at least twice, separated by at least two weeks.

Sulfur cross-sections of 210 mb and 206 mb were used, respectively, by Quam and Haywood. At the beginning of Phase II, many sulfur pellets were counted by both Quam and Haywood. The differences are discussed in Chapter 6. The total neutron output into a sphere of 4π steradians was estimated from this sulfur fluence at 3 m. These values were then issued to each program and each project for each run. The actual 4π neutron output is the subject of this report.

On November 1, 1968, four organizations placed sulfur pellets 3 m below the target for comparison purposes. Each organization assumed a different cross section for the $^{32}\text{S}(n,p)^{32}\text{P}$ reaction. These ranged from 206 mb to 248 mb. After normalizing their results to a common cross section of 210 mb, the agreement was satisfactory, lending confidence in interlaboratory counting techniques. These data¹⁻⁴ are shown in Table 4.1. The fluences given assume all neutrons at that point are at an energy of about 14.75 MeV. (Actually, all of the neutrons are not at this energy.) The influence of the spectrum on these measurements will be discussed in Chapter 6.

To obtain the relative time-dependent neutron output, a fission counter was placed in the hoist car, about 1-1/2 m above the target. The

fission counts were recorded on a strip chart recorder, and issued to each program upon request.

TABLE 4.1. NEUTRON FLUENCE AS DERIVED FROM SULFUR PELLETS PLACED 3 METERS BELOW THE TARGET ON HENRE RUN 68-29 1 NOVEMBER 1968.

Agency	Fluence (n/cm ²)	Cross Section Used	Fluence When σ Normalized to 210 mb	
		σ (mb)	Fluence (n/cm ²)	Deviation From Avg
EG&G (Santa Barbara)	6.50×10^{10}	210	6.50×10^{10}	-1.4%
ORNL - Program 1	7.16×10^{10}	206	7.04×10^{10}	+6.8%
NDL - Program 5	5.7×10^{10}	225	6.11×10^{10}	-7.3%
NRDL - Program 3	5.7×10^{10}	248	6.73×10^{10}	+2.1%
		Avg	6.59×10^{10}	$\pm 5.9\%*$

*Standard Deviation

4.2 NDL DATA

On Run 68-29, November 1, 1968, the target was positioned at a height of 8.2 m (27 ft) for an intercalibration run. Two arcs, made of plywood and 1-1/2 m in radius, were placed on two great circles in a plane perpendicular to the target plane where the center of the circles coincided with the center of the target. One arc contained sulfur, magnesium, aluminum, and zirconium foils, placed by the U.S. Army Nuclear Defense Lab (NDL) in support of Program 9. The arc was in the direction of the Program 9 experimental setup, about 37° (azimuthal angle) from the normal to the face of the tower.

A photograph showing these arcs in place is shown in Fig. 4.1. The arc to the left contains the NDL foils, the one in the center contains EG&G foils (Section 4.4). The plywood was about 4 cm wide and about 4 cm thick. Another photo is shown in Fig. 4.2. It should be noted that at, and near, the working platform there exists a conglomerate of steel railings, girders, and pipes, and some wood slabs that undoubtedly perturbed the neutron spectrum at that point. The mass of steel above that point (see Fig. 3.3) was much less. It should also be noted that the arcs intersected the platform at about 150° (0° being straight down). The NDL foils were counted by Kilminster (NDL) and the raw data⁵ given in Table 4.2. The lowest activity of each foil set appears at 88°, corresponding to the direction of maximum thickness of copper in the target for neutron penetration.

The $^{32}\text{S}(n,p)^{32}\text{P}$, $^{27}\text{Al}(n,\alpha)^{24}\text{Na}$, $^{24}\text{Mg}(n,p)^{24}\text{Na}$, and $^{90}\text{Zr}(n,2n)^{89}\text{Zr}$ reactions have thresholds at energies of about 2, 4, 6, and 12 MeV, respectively. Approximate fluences were obtained from the activation foil data by assigning a trial spectrum and processing the data through an unfolding code. The results^{3,6} are given in Table 4.3. It was first postulated that these fluence values

Fig. 4.1—Activation foils placed on $1\frac{1}{2}$ meter arcs.

Fig. 4.2—Experimental setup for the intercalibration run.

TABLE 4.2. ACTIVITY IN DPM/GM (RAW DATA) OF NDL FOILS FOR HENRE INTERCALIBRATION RUN.

Angle (deg)	$^{32}\text{S}(\text{n}, \text{p})^{32}\text{P}$	$^{24}\text{Mg}(\text{n}, \text{p})^{24}\text{Na}$	$^{27}\text{Al}(\text{n}, \alpha)^{24}\text{Na}$	$^{90}\text{Zr}(\text{n}, 2\text{n})^{89}\text{Zr}$
0	3.41 E4*	7.42 E5	4.16 E5	1.68 E5
5	3.30 E4	7.46 E5	3.97 E5	1.70 E5
10	3.30 E4	7.25 E5	4.04 E5	1.73 E5
15	3.51 E4	7.42 E5	4.04 E5	1.73 E5
20	3.28 E4	7.33 E5	4.18 E5	1.62 E5
25	3.36 E4	7.00 E5	4.11 E5	1.62 E5
30	3.30 E4	7.21 E5	4.04 E5	1.66 E5
35	3.31 E4	7.42 E5	3.97 E5	1.62 E5
40	3.37 E4	7.58 E5	4.02 E5	1.58 E5
45	3.30 E4	7.62 E5	4.04 E5	1.57 E5
50	3.23 E4	7.25 E5	4.11 E5	1.56 E5
55	3.26 E4	7.54 E5	4.04 E5	1.47 E5
60	3.32 E4	7.46 E5	3.97 E5	1.47 E5
62.5	3.29 E4	7.46 E5	3.90 E5	1.39 E5
65	3.26 E4	7.42 E5	3.83 E5	1.38 E5

TABLE 4.2 (Continued)

Angle (deg)	$^{32}\text{S}(n,p)^{32}\text{P}$	$^{24}\text{Mg}(n,p)^{24}\text{Na}$	$^{27}\text{Al}(n,\alpha)^{24}\text{Na}$	$^{90}\text{Zr}(n,2n)^{89}\text{Zr}$
67.5	3.30 E4	7.21 E5	3.72 E5	1.34 E5
70	3.14 E4	6.79 E5	3.72 E5	1.23 E5
72.5	3.02 E4	7.00 E5	3.53 E5	1.23 E5
75	2.92 E4	6.28 E5	3.40 E5	1.06 E5
77.5	2.61 E4	5.82 E5	3.14 E5	1.08 E5
80	2.48 E4	5.20 E5	2.91 E5	9.05 E4
82	2.27 E4	4.48 E5	2.42 E5	6.85 E4
83	2.00 E4	4.16 E5	2.23 E5	6.85 E4
84	1.78 E4	3.52 E5	1.95 E5	5.84 E4
85	1.57 E4	2.99 E5	1.65 E5	4.69 E4
86	1.32 E4	2.34 E5	1.30 E5	3.69 E4
87	1.11 E4	1.94 E5	1.02 E5	2.85 E4
88	9.47 E3	1.52 E5	8.43 E4	2.14 E4
89	1.05 E4	1.80 E5	9.98 E4	2.81 E4
90	1.19 E4	2.27 E5	1.14 E5	3.43 E4
91	1.41 E4	2.73 E5	1.49 E5	4.39 E4
92	1.60 E4	2.84 E5	1.64 E5	4.91 E4
93	1.74 E4	3.30 E5	1.82 E5	5.40 E4
94	2.01 E4	4.23 E5	2.36 E5	6.60 E4
95	2.33 E4	4.90 E5	2.66 E5	7.60 E4
96	2.61 E4	5.24 E5	3.00 E5	8.71 E4
97	2.98 E4	6.37 E5	3.30 E5	9.67 E4
98	3.11 E4	6.45 E5	3.58 E5	1.04 E5
100	3.10 E4	6.58 E5	3.72 E5	8.98 E4
102.5	3.07 E4	6.20 E5	3.44 E5	1.00 E5
105	3.19 E4	6.20 E5	3.44 E5	9.81 E4
107.5	3.23 E4	6.37 E5	3.58 E5	1.02 E5
110	3.32 E4	6.74 E5	3.58 E5	1.00 E5
112.5	3.45 E4	6.91 E5	3.90 E5	1.02 E5
115	3.45 E4	7.04 E5	3.79 E5	1.04 E5
120	3.57 E4	7.21 E5	3.97 E5	1.05 E5
125	3.74 E4	8.00 E5	3.90 E5	1.02 E5
130	3.79 E4	7.71 E5	3.14 E5	9.40 E4

*Note: Read 3.41 E4 as 3.41×10^4

TABLE 4.3. NDL ESTIMATED NEUTRON FLUENCES AT 1.5 METERS
FOR HENRE RUN 68-29, 1 NOVEMBER 1968.

Angle (deg)	Fluence (n/cm ²)	Angle (deg)	Fluence (n/cm ²)	Angle (deg)	Fluence (n/cm ²)
0	2.1 E11*	72.5	1.8 E11	95	1.2 E11
5	2.1 E11	75	1.6 E11	96	1.4 E11
10	2.1 E11	77.5	1.6 E11	97	1.6 E11
15	2.1 E11	80	1.4 E11	98	1.7 E11
20	2.1 E11	82	1.1 E11	100	1.6 E11
25	2.0 E11	83	1.1 E11	102.5	1.6 E11
30	2.1 E11	84	9.2 E10*	105	1.6 E11
35	2.1 E11	85	7.7 E10	107.5	1.6 E11
40	2.1 E11	86	6.1 E10	110	1.7 E11
45	2.1 E11	87	4.8 E10	112.5	1.7 E11
50	2.0 E11	88	3.7 E10	115	1.7 E11
55	2.0 E11	89	4.6 E10	120	1.8 E11
60	2.0 E11	90	5.6 E10	125	1.8 E11
62.5	2.0 E11	91	7.1 E10	130	1.6 E11
65	2.0 E11	92	7.7 E10		
67.5	1.9 E11	93	8.6 E10		
70	1.8 E11	94	1.1 E10		

*Read 2.1 E11 as 2.1×10^{11} . Read 9.2 E10 as 9.2×10^{10} .

represented the total fluence above 3 MeV. Later evaluation and analysis indicated that they represented only the 13-15 MeV component.

The NDL raw data in Table 4.2 were relied upon heavily for determining the directional contribution of the 13- to 15-MeV component (see Chapter 6).

4.3 STANFORD UNIVERSITY DATA

On July 10, 1967, Barrall of Stanford University placed 15 different foil materials 1 m below (0°) the HENRE target as a part of the US Air Force Program 7. The cross sections of 24 reactions at 14.6 MeV were evaluated. A thorough description of this experiment can be found in Ref. 7.

Again, the target was placed 8.2 m above the ground. Care was taken to minimize materials in the immediate vicinity of the foils. However, it can be seen from Fig. 4.2 that much steel remained.

The results of this run are tabulated in Table 4.4. It became obvious from these data that the number of lower energy neutrons present (0.5 to 5 MeV) was not negligible. The saturation activity of these foils was relied upon heavily for determination of the neutron spectrum at 0°.

TABLE 4.4. DECAY-CORRECTED ACTIVITIES IN FOILS 1 METER FROM THE TARGET, (7) HENRE RUN NO. 40, 7/10/67.

Reaction	Average measured activity (DPM/gram)	Activity at saturation (DPS/nucleus)*	Activity at saturation caused only by D, T neutrons (DPS/nucleus)*
$^{19}\text{F}(n, 2n)^{18}\text{F}$	783000	1.16	1.16
$^{23}\text{Na}(n, \gamma)^{24}\text{Na}$	3406	0.415	(0.364)**
$^{23}\text{Na}(n, 2n)^{22}\text{Na}$	68.4	1.23	1.23
$^{24}\text{Mg}(n, p)^{24}\text{Na}$	294131	4.82	4.82
$^{27}\text{Al}(n, \alpha)^{24}\text{Na}$	209635	3.00	3.00
$^{34}\text{S}(n, \alpha)^{31}\text{Si}$	42900	3.42	2.86
$^{32}\text{S}(n, p)^{32}\text{P}$	14400	5.76	4.46
$^{35}\text{Cl}(n, \alpha)^{32}\text{P}$	4818	2.68	2.68
$^{55}\text{Mn}(n, \gamma)^{56}\text{Mn}$	62599	0.356	(0.186)
$^{55}\text{Mn}(n, 2n)^{54}\text{Mn}$	1364	19.5	19.5
$^{54}\text{Fe}(n, p)^{54}\text{Mn}$	37.6	9.38	8.61
$^{56}\text{Fe}(n, p)^{56}\text{Mn}$	446494	2.81	2.81
$^{59}\text{Co}(n, \gamma)^{60}\text{Co}$	13.2	1.24	(0.55)
$^{59}\text{Co}(n, 2n)^{58}\text{Co}$	5427	18.9	18.9
$^{58}\text{Ni}(n, np)+(n, d)^{57}\text{Co}$	941	18.2	18.2
$^{58}\text{Ni}(n, p)^{58}\text{Co}$	1838	9.388	8.48
$^{58}\text{Ni}(n, 2n)^{57}\text{Ni}$	7634	0.8293	0.8293
$^{65}\text{Cu}(n, 2n)^{64}\text{Cu}$	238500	22.3	22.3
$^{63}\text{Cu}(n, \alpha)^{60}\text{Co}$	8.37	1.23	1.23
$^{64}\text{Zn}(n, p)^{64}\text{Cu}$	62921	3.83	3.66
$^{90}\text{Zr}(n, 2n)^{89}\text{Zr}$	40385	19.7	19.7
$^{115}\text{In}(n, 2n)^{114\text{m}}\text{In}$	6641	33.0	33.0
$^{115}\text{In}(n, n')^{115\text{m}}\text{In}$	169290	3.44	1.66
$^{127}\text{I}(n, 2n)^{126}\text{I}$	30914	41.6	41.6
$^{197}\text{Au}(n, 2n)^{196\text{g}}\text{Au}$	50800	51.4	51.4
$^{197}\text{Au}(n, \gamma)^{198}\text{Au}$	82020	36.3	(16.6)
$^{232}\text{Th}(n, f)\text{Tracks}$	1957000***	12.6	11.1
$^{232}\text{Th}(n, f) [^{99}\text{Mo}]$	2510000	16.1	14.2
$^{235}\text{U}(n, f) [^{99}\text{Mo}]$	10970000***	71.34	(63.88)
$^{238}\text{U}(n, f)\text{Tracks}$	5555000***	36.6	30.8
$^{238}\text{U}(n, f) [^{99}\text{Mo}]$	5230000***	34.4	28.9

* = Multiply values in this column by 10^{-18}

** = Values in parenthesis show effect of additional low energy neutrons.

*** = Fissions/min-gram

TABLE 4.5. ACTIVITIES IN SAMPLES IRRADIATED AT 1
METER⁽⁷⁾ HENRE RUN NO. 17, 11/11/66.

Angle	Reaction	Decay Corrected Activity (DPM/gram)	Activity at Saturation (DPS/nucleus)	Flux Density* (n/cm ² -sec)
0	⁵⁸ Ni(n,p) ⁵⁸ Co	16858	27.4 E-18**	77.8 E6
	⁵⁸ Ni(n,2n) ⁵⁷ Ni	48.3	1.79 E-18	55.4 E6
	³² S(n,p) ³² P	136300	17.3 E-18	75.4 E6
	³² S(n,α) ³¹ Si	278500	9.48 E-18	68.3 E6
45	⁵⁸ Ni(n,p) ⁵⁸ Co	17302	27.9 E-18	79.1 E6
	⁵⁸ Ni(n,2n) ⁵⁷ Ni	48645	1.81 E-18	55.9 E6
	³² S(n,p) ³² P	139500	17.7 E-18	77.2 E6
90	⁵⁸ Ni(n,p) ⁵⁸ Co	6710	10.90 E-18	31.0 E6
	⁵⁸ Ni(n,2n) ⁵⁷ Ni	9496	0.353 E-18	10.9 E6
	³² S(n,p) ³² P	51200	6.49 E-18	28.3 E6

* Calculated by assuming all activity caused by 14.5 neutrons, and by using the following values for cross section:

⁵⁸Ni(n,p)⁵⁸Co ----- 0.352 Barns
⁵⁸Ni(n,2n)⁵⁷Ni ----- 0.0308 Barns
³²S(n,p)³²P ----- 0.2292 Barns
³²S(n,α)³¹Si ----- 0.1346 Barns

**Read 27.4 E-18 as 27.4 x 10⁻¹⁸.

Also, as a part of the Program 7 experiment, 95 sulfur pellets were placed on a 1-m arc around the target in an effort to determine the polar angular distribution of source neutrons. In addition, nickel foils were placed at 0°, 45°, and 90°. The sulfur results showed a nearly constant fluence from about -70° to +70°, with a sharp dip in the horizontal direction. The data at 0°, 45°, and 90° are tabulated in Table 4.5. The information in Tables 4.4 and 4.5 was taken directly from Ref. 7 with the authors' permission.

4.4 EG&G DATA

For the intercalibration run on November 1, 1968, several sulfur pellets were placed on the 1-1/2 m arc (see Fig. 4.1). The activities were counted by Quam of the EG&G Santa Barbara Laboratories.¹ The raw data are tabulated in Table 4.6, assuming a run time of 175.86 minutes.

In addition to the above, several other activation foils (nickel, sulfur, and zirconium) were placed at specific angles on both arcs. The individual reactions utilized were: ⁵⁸Ni(n,p)⁵⁸Co; ³²S(n,p)³²P; ⁵⁸Ni(n,2n)⁵⁷Ni; and ⁹⁰Zr(n,2n)⁸⁹Zr.

TABLE 4.6. SATURATED ACTIVITIES OF EG&G SULFUR PELLETS ON
1-1/2 METER ARC FOR HENRE INTERCALIBRATION RUN.

Angle (deg)	Saturated Activity (DPS/nucleus)*	Angle (deg)	Saturated Activity (DPS/nucleus)*
0	4.86	82	3.37
5	4.95	84	2.87
10	3.57	85	2.49
15	4.53	86	2.11
20	4.81	90	1.69
25	4.38	95	3.19
30	4.92	99	4.43
35	4.72	102.5	4.31
40	4.66	105	4.59
45	4.86	107.5	4.40
55	4.77	110	4.80
60	4.57	112.5	4.98
62.5	4.60	115	5.04
65	4.72	117.5	4.98
67.5	4.57	120	4.92
70	4.59	125	5.26
72.5	4.45	130	5.33
75	4.11	135	5.24
77.5	3.93	140	5.00
80	3.79	145	3.93
81	3.47	150	5.59

*Multiply values in this column by 10^{-18} .

Effective cross sections for the reactions¹ were chosen on the basis of proton recoil telescope spectra (discussed later) at 0° and 90°. A summary of these fluence results is given in Table 4.7. The last column of the table shows the ratio between "14 MeV" neutrons and all others above 3 MeV. The data suggest that there are relatively few neutrons between 3 and 13.5 MeV at 0° but about equal numbers at 90°.

To aid in estimating the gamma radiation present near the source, some TLD's (EG&G Model TL-12) were placed on the 1-1/2 m arc.⁸ These results are tabulated in Table 4.8.

TABLE 4.7. EG&G-ACTIVATION FOIL DATA VERSUS ANGLE.

Angle (deg)	$E_{th} = 3.0 \text{ MeV}^*$ (fluence) (n/cm ²)	$E_{th} = 13.5 \text{ MeV}^*$ (fluence) (n/cm ²)	$\frac{\Phi_{3 \rightarrow \Phi_{13.5}}^*}{\Phi_{13.5}}$
0	2.04 E11**	1.72 E11	0.19
30	2.09 E11	1.70 E11	0.23
60	2.18 E11	1.65 E11	0.32
81	1.60 E11	0.95 E11	0.68
85	1.08 E11	0.58 E11	0.86
90	0.89 E11	0.48 E11	0.86
95	1.59 E11	0.80 E11	0.99
99	2.12 E11	1.16 E11	0.83
117.5	2.50 E11	1.08 E11	1.32

* Where E_{th} = Threshold energy and $\Phi_3 = n/cm^2$ for $E > 3 \text{ MeV}$.

**Read 2.04 E11 as 2.04×10^{11} .

Several attempts to measure the neutron spectrum directly near the targets were made by Lucas and Quam of EG&G Santa Barbara¹ during the second phase of Operation HENRE.

The spectrometer used was one of their own design, consisting of two planar wire electrode proportional counters and a silicon detector. These three were operated in triple coincidence similar to other neutron telescope designs. The counting gas was 9 cm argon, 1 cm Co₂. An alpha source mounted within the counter was used for routine calibration. Polyethylene radiators of various thicknesses were used for different parts of the spectrum and were also mounted within the counter. Readout of the coincidence-gated pulses from the silicon detector was performed with a 400-channel analyzer.

A typical run consisted of 30 min of exposure with a polyethylene radiator (or a series of radiators) and 60 min of exposure with no radiator to determine a background. The two runs were normalized to one another via the fission counter.

Data reduction was done on a small computer and consisted of corrections for nonstandard gain, analyzer nonlinearity, nonzero intercept, background, and the overall counter efficiency.

The measurements were made at 0°, 30°, and 90°. The detector placement (arrow) for a 30° measurement is shown in Fig. 4.3. Data at 30° and 90° were taken when the target was placed at 8.2 m. Data at 0° were taken when the target was located at 16.5 m above the ground.

The data are shown in Fig. 4.4. Contrary to expectations, the data show relatively fewer neutrons between 2 and 13 MeV at 90° than at 0° and 30°. The reason for this is not known. Perhaps the influence of scatter from steel

TABLE 4.8. RESULTS FOR EG&G TLD'S ON 1-1/2 METER ARC
FOR HENRE INTERCALIBRATION RUN.

Angle (deg)	TLD Response* (R)	Angle (deg)	TLD Response* (R)
0	423	85	191
5	302	86	146
10	314	88	143
15	376	90	174
20	270	92	178
25	359	94	207
30	385	96	234
35	305	98	352
40	364	99	252
45	368	100	272
50	344	102.5	241
55	321	105	266
60	334	107.5	258
62.5	300	110	302
65	363	112.5	323
67.5	338	115	258
70	378	120	207
75	292	125	391
77.5	318	130	310
80	285	135	390
81	195	140	371
82	206	145	258
84	253		

*Uncorrected for neutron response.

near the detector was greater than anticipated. All measurements were made at approximately 9 m from the target. Difficulties were encountered in separating out the data from background. Therefore, the results are not expected to be very reliable. Nevertheless, the general shapes of the curves are indicative of the neutron spectrum.

Many programs were concerned with measuring the radiation levels as a function of distance from the neutron source. These measurements were influ-

Fig. 4.3—EG&G neutron spectrometer setup for a 30° measurement.

RELATIVE FLUENCE IN 1 MeV ENERGY INTERVAL

Fig. 4.4—EG&G neutron spectrum measurements.

Fig. 4.5—HENRE target self-shielding.

enced by the nonisotropic output of the targets, particularly for measurements near the source. Measurements by EG&G were made to determine the influence of the horizontal "shadow" on the dose distributions as a function of distance. These are shown as curves B, C, and D in Fig. 4.5, along with NDL data (from Table 4.3) as Curve A.

Tissue-equivalent ion chambers, TLD's, and Hurst proportional counters were used.⁹ Curve B represents dose measurements at a distance of 26 m (86 ft) when the source was 8.2 m high; curve C, at 61 m (200 ft) distance and source height of 16.5 m; and curve D at 244 m (800 ft) distance and source height of 91 m.

In each case, curves B, C, and D, the left data point represents a location 1 m above the ground. The ground undoubtedly influenced the dose distributions. Nevertheless, the data indicate a "washing out" of the depression as the distance increases.

During runs 68-8 and 68-11 on September 11 and 18, 1968, foil measurements were made across the bottom of the target plate and across the bottom of the corona dome. Aluminum, sulfur, and copper were used. The accelerator was operated conservatively at about 145 kv with a beam current of 200 to 212 ma.

The fluence data are shown in Fig. 4.6. All data have been normalized and adjusted to the 68-11 run. This was a nominal 4-hour run for an average target. Activation cross sections were chosen assuming all neutrons were at an energy of 14.75 MeV.

The data show that the deuterium beam was on the order of 30 cm (12 in.) in diameter for these two runs. The bottom of the corona dome was located 2.54 cm below the bottom of the target plate (3.17 cm from the source of neutrons). Note that the fluence was higher on the corona dome than on the target at points away from the center. This is expected, due to the shielding geometry provided by the flat copper plate.

The maximum fluence attainable was about 8.5×10^{13} n/cm² over 10 cm diameter area in the center of the target backing. At this point, the fluence rate began at about 2.5×10^{10} n/cm² per second at the beginning of a 4-hour run and reduced to about 2×10^9 n/cm² per second at the end. A fluence of between 1 and 3.7×10^{13} n/cm² was attainable over a 41 cm diameter area on the bottom of the corona dome.

Neutron production in the target as a function of radius from the center is shown in Fig. 4.7. A ring source of 1 cm width was chosen. The data were derived from the target plate data in Fig. 4.6. As expected, most of the neutrons are produced in a circular band 5 to 12 cm from center.

4.5 ORNL DATA

During Phase II, Haywood (ORNL) placed several activation and fission foils near the targets to measure the directional neutron output. The target was placed 16.5 m above the ground. A thin-wall steel tube was formed into an arc (180°) with a radius of 3 m and placed in a vertical plane in a direction straight out from the center of the tower. Aluminum, copper, gold, and sulfur foils were placed every few degrees on the arc. In addition, ²³⁸U, ²³⁹Pu, and ²³⁷Np fission foils in proximity to lexan detectors, inside cadmium and boron covers, were placed on the arc.

After irradiation, the foils and lexan detectors were taken to ORNL for analysis. The results¹⁰ of the activation foils showed nearly the same angular distribution as those of NDL and others. The results of the fission foils, however, were inconsistent among themselves. Their fission product counts seemed to show dips at 30° and 150° with no dip at 90°. Furthermore, the calculated fluences did not agree with each other. After many attempts to resolve the inconsistencies, a conclusion was reached that fission foils of uncertain quality were used. Consequently, with regret, these ORNL results were not used in this analysis.

Fig. 4.6—Approximate neutron fluence across bottom of target plate and bottom of corona dome for a 4-hour run for an average target (target 52, September 18, 1968).

4.6 OTHER DATA

Many other sets of data were taken during Operation HENRE which substantiate the assumed shape of the neutron spectrum emerging from the source. Some will be mentioned in this section.

W. W. Webster of LRL placed some activation foils 546 cm below the target for a run when the accelerator was 343 m above the ground.¹¹ He estimated only 6 percent of the neutrons at that point were below "14 MeV".

Fig. 4.7—Neutron production in the HENRE targets.

Several foils were placed on the corona dome by NDL for one of the accelerator runs.³ However, because of the uncertainty of exact positioning, the results were not used in the analysis of this report.

Several measurements were made at an intercalibration point 1 m above the ground, 8.2 m from the tower when the target was placed 8.2 m above the ground. Measurements by Barrall,⁷ Sanna,¹² and Jeter¹³ all show similar results. There is a strong 14-MeV component with many neutrons below 6 MeV. The ground strongly influenced the spectrum at this point.

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Chapter 5

SIMPLIFIED CALCULATIONS

5.1 INTRODUCTION

Point Kernal calculations were made of the uncollided neutron fluence versus polar angle emerging from the HENRE targets. In addition, estimated contributions from elastic and inelastic scatter events and (n,2n) reactions were made. The purpose of these calculations was to estimate the number of emerging neutrons that were below 13 MeV in energy and to estimate their energy spread. Many broad assumptions and "ball-park" estimates were made. Nevertheless, the results of these calculations provided good evidence of what the neutron output probably was and provided a basis for analysis of the foil activation results in Chapter 6.

The neutrons from the (D-D) reaction are not considered in this chapter. They are treated in Chapter 6 in relation to the experimental data.

5.2 TARGET GEOMETRY

The copper plate, outer ring, lucite insulator, steel clamp rings, and steel drift tube were compartmentalized for convenience in the calculations. The simplified target configurations are shown in Fig. 5.1

The copper target weighed 20,850 g. The inner disk weighed 5,640 g, leaving 15,210 g in the outer ring. The target contained 276 g of water. However, since the water was spread over a large area, it was considered negligible in the calculations. The copper was assumed to be composed of 69.09% ^{63}Cu and 30.91% ^{65}Cu .

Lucite was considered to be methyl methacrylate ($\text{CH}_2:\text{C}(\text{CH}_3)-\text{COOCH}_3$).

The steel was considered to be 304 stainless, consisting of 20% chromium, 10% nickel, and 70% iron.

5.3 CROSS-SECTION DETERMINATIONS

The macroscopic cross-sections, for total reactions, were determined for each material by the following equation:

$$\Sigma_{\tau} = \frac{N_o \rho}{A} \left(F_1 \sigma_{\tau_1} + F_2 \sigma_{\tau_2} \dots \right) \quad (1)$$

Fig. 5.1—Simplified target configuration.

where

Σ_{τ} = the macroscopic cross section for the material

N_0 = Avogadro's number = 6.02×10^{23}

ρ = density in g/cm^3

A = molecular weight

F_1 = fractional abundance (atomic) of an element
in the material

$\sigma_{\tau 1}$ = total microscopic cross section of the element
in cm^2

Table 5.1 contains the appropriate ingredients for determination of the total macroscopic cross sections¹ for copper, lucite, and steel for 14.06 MeV neutrons (as an example).

TABLE 5.1. MACROSCOPIC CROSS-SECTION DETERMINATIONS
FOR 14.06 MeV NEUTRONS.

Material	ρ (gm/cm ³)	A	Element	F	σ_{τ} (cm ²)	Σ_{τ} (cm ⁻¹)
Copper	8.95	63.54	⁶³ Cu	1.00	2.925 E-24*	0.2477
Lucite	1.18	100.11	¹ H	0.533	0.700 E-24	0.00714
			⁶ C	0.333	1.30 E-24	
			⁸ O	0.134	1.50 E-24	
Steel	7.75	55	⁵⁴ Cr	0.2	2.46 E-24	0.218
			⁵⁸ Ni	0.1	2.69 E-24	
			⁵⁶ Fe	0.7	2.58 E-24	

*Read 2.925 E-24 as 2.925×10^{-24} .

Cross sections vary with neutron energy. Furthermore, the neutrons from the (D-T) reaction vary in energy and intensity with angle. This information is given in Table 5.2. The neutron energies are not exact because of uncertainty of the accelerating voltage. Nevertheless, one set of values (Seagrave)² are taken for consistency. The cross sections are certainly not accurate to four significant figures. However, to denote small changes with angle, four figures were used in the calculations.

5.4 UNCOLLIDED BEAM CALCULATIONS

For simplicity, all neutrons were assumed to be generated at a point in the center of the target. It was convenient to normalize all calculations to an unperturbed fluence, I_0 , at a point directly below the source (0°), assuming no shield or scattering material. The uncollided fluence at an angle θ (the same distance from the source) (I_θ) can be written

$$I_\theta/I_0 = ce^{-\Sigma_{\tau} t} \quad (2)$$

where c is the relative intensity at an angle θ of the (D-T) reaction (Table 5.2, Column 2) and t is the slant penetration through the shielding material.

Equation 2 was used to calculate the uncollided fluence at angles from $\theta = 0^\circ$ to 88° . Values of t (in cm) through the copper disk were computed to be $t = 0.635/\cos \theta$. For 90° and 92° , a thickness of 5.13 cm of copper was used.

TABLE 5.2. CROSS SECTIONS, NEUTRON ENERGY, AND RELATIVE INTENSITY AS A FUNCTION OF ANGLE FOR THE D-T REACTION.

Angle (deg)	Relative Intensity (C)	Neutron* Energy [E(MeV)]	Macroscopic Cross-Sections $\Sigma\tau$			
			Copper (Cm ⁻¹)	Lucite (Cm ⁻¹)	Steel (Cm ⁻¹)	Aluminum (Cm ⁻¹)
0	1.000	14.74	0.2405			
10	1.000	14.73	0.2405			
20	0.997	14.71	0.2408			
30	0.992	14.66	0.2412			
40	0.985	14.58	0.2412			
50	0.977	14.50	0.2420			
60	0.968	14.40	0.2435			
70	0.960	14.29	0.2450			
80	0.950	14.17	0.2467			
85	0.946	14.12	0.2471			
88	0.942	14.08	0.2471			
90	0.940	14.06	0.2477			
92	0.938	14.04	0.2511			
95	0.935	14.01		0.00714	0.218	
100	0.930	13.96		0.00714	0.219	
105	0.925	13.91			0.220	
110	0.920	13.85			0.220	
120	0.910	13.75			0.221	
130	0.897	13.66			0.222	
140	0.887	13.58			0.223	
150	0.880	13.51			0.223	
155	0.876	13.49	0.26		0.23	0.1045
160	0.873	13.46	0.26		0.23	0.1045
165	0.871	13.45	0.26		0.23	0.1045
170	0.870	13.44	0.26		0.23	0.1045

*Seagrave (Ref. 2)

For angles of 95.5° and 100°, attenuation through both the steel wall and the lucite ring was considered. At an angle of 105°, the steel ring intersected the neutron beam. For angles 110° through 140°, only the steel wall of the target bucket intersected the beam. In all cases, the effect of the corona dome was assumed to be negligible.

For angles above 140°, attenuation through the accelerator components was considered. Gross estimates were made of the weight distribution of aluminum, copper, and steel at various levels of the accelerator. At an angle of 172°, the neutron beam intersected the edge of the power supply. At these angles (172° to 180°), it was assumed that no uncollided neutrons emerged.

The results of the uncollided beam calculations are listed in Column 2 of Table 5.3, and shown graphically in Fig. 5.2. Note that even at 0° the 0.635-cm copper plate reduces the neutrons by 14 percent. The sharp dip at 88° is a result of attenuation through 24 cm of copper. The ledge, hump, and dip at 91°, 95°, and 105°, respectively, show the attenuation through the copper, lucite, and steel rings, respectively.

Actually, the source is in the form of a disk with radius about 16 cm, rather than a point source. Consideration of this geometric effect tends to smear out anomalies. The error bars on the data at 95°, 100°, and 110° takes this into account. They represent attenuation values from a source at two points located 10 cm off center. A good bit of judgment was exercised in drawing the curve through the points.

The area under the uncollided curve in Fig. 5.2 was integrated over 4π . The integrated result was 0.6357. That is, the uncollided number of neutrons escaping from the HENRE source system is 63.57 percent of the 4π output of a point, isotropic source in a vacuum.

The actual 4π neutron production from the D-T reaction is 94 percent of an isotropic source. Therefore, the total uncollided 4π output from the HENRE source system is 67.6 percent of the neutrons produced.

5.5 ELASTIC SCATTER CONTRIBUTIONS

The cross sections for the various neutron reactions in copper at 14.74 MeV (as an example) can be summarized as follows:

<u>Reactions</u>	<u>Cross Section (Barns)</u>	<u>Percent of Total Reactions</u>
Total	2.85	100
Elastic Scatter	1.37	48
n,2n	0.70	24.5
Inelastic Scatter	0.60	21.8
Other Reactions	0.18	5.7

Of all reactions in copper, 48 percent are a result of elastic scatter events. For steel, 47 percent are due to elastic scatter. Therefore, it was assumed that 48 percent of all reactions that took place in the material surrounding the target were due to elastic scattering.

When an elastic scattering event occurs with a copper atom, the neutron tends to continue in the same direction, as can be seen in Fig. 5.3.

TABLE 5.3. SUMMARY OF NEUTRON OUTPUT CALCULATIONS FOR
HENRE NEUTRON SOURCE. RESULTS GIVEN IN FRACTION
OF ORIGINAL NEUTRON PRODUCTION AT 0°, NO SHIELD.

Angle (deg)	Uncollided	Elastic Scatter	(n,2n)
0	0.859	0.065	0.154
10	0.858	0.065	0.154
20	0.848	0.069	0.152
30	0.830	0.073	0.150
40	0.808	0.081	0.148
50	0.770	0.091	0.142
60	0.710	0.111	0.134
70	0.609	0.145	0.124
80	0.387	0.195	0.104
85	0.157	0.173	0.072
88	0.00258	0.023	0.028
90	0.264	0.200	0.024
92	0.258	0.204	0.024
95.5	0.859	0.037	0.068
100	0.853	0.037	0.104
105	0.578	0.140	0.090
110	0.855	0.030	0.124
120	0.839	0.035	0.134
130	0.818	0.039	0.142
140	0.794	0.045	0.148
150	0.657	0.120	0.086
155	0.188	0.164	0.030
160	0.081	0.125	0.010
165	0.041	0.087	0.006
170	0.025	0.070	0
172	0.001	0.011	0
180	0	0	0

Fig. 5.2—Calculated directional neutron output from the HENRE targets.

As an example, 83 percent of the events result in scatters less than 30° , 61 percent less than 20° , and 20 percent less than 10° . Furthermore, the neutron loses very little energy during the scatter, as can be seen in Fig. 5.4. In fact, if a neutron of original energy of 14.8 MeV undergoes 10 consecutive elastic scatters at 30° , its resulting energy will still be above 14 MeV. It requires 4 consecutive scatters at 90° to reduce the neutron energy to 13 MeV. Therefore, for simplicity in the calculations, it was assumed that neutrons undergoing elastic scattering continued in the same direction with no loss in energy. It was further assumed that all these events occurred at half the thickness penetrated by the uncollided beam. The equation for the determination of the number of elastic scattered neutrons emerging at an angle reduces to:

$$N_e = 0.48 R (1 - U) \left\{ 1 + 0.48(1 - R) R + R^2 [0.48 (1 - R)]^2 \right\} \quad (3)$$

Fig. 5.3—Differential elastic scattering cross section.

if 3 scatters are considered, where N_e is the number of elastic scattered neutrons emerging, R is the new attenuation of the beam, and U is the uncollided fraction emerging.

For example, at 70° the thickness penetrated by the uncollided beam was 1.858 cm of copper. Of the original neutrons traveling in that direction, 17.5 percent have been removed by elastic scatter in that thickness. We assume that these occurred at 0.929 cm, and that the scattered neutrons continue in the same direction. They must penetrate another 0.929 cm to escape the copper. In this distance, 20 percent of them were removed from the beam. However, 48 percent of those removed were due to elastic scatter, which we assign as remaining in the beam. So, if we consider only 2 scatters, the result is that 15.1 percent of the original neutrons traveling in that direction escape as

Fig. 5.4—Proton or neutron energies from elastic scattering.³

elastic scattered neutrons [$R = 0.800$ and $U = 0.635$]. Normalizing to the original neutron production at 0° , 14.5 percent emerge as elastic scattered neutrons. The contribution of neutrons from elastic scatter at other angles was calculated in the same manner. The results are listed in Table 5.3 in column 3 and shown graphically in Fig. 5.2.

The data show peaks and valleys between 80° and 110° , forced by the assumptions of a point source and scattered neutrons continuing in the same direction. Small angle scattering will diffuse the neutrons, thus removing the anomalies. Actually, the data could have error bars $\pm 20^\circ$ wide. A smooth curve was drawn through the points, arbitrarily, by the author as an estimate, considering these assumptions.

5.6 (n,2n) CONTRIBUTION

The cross section for the ^{63}Cu (n,2n) ^{62}Cu reaction was taken from BNL 325¹ to be about 0.56 barns, and for the ^{65}Cu (n,2n) ^{64}Cu reaction, 0.99 barns at 14.75 MeV. The weighted average cross section for natural copper then is 0.70 barns with about an equal number of reactions taking place in the two isotopes.

The neutrons resulting from the (n,2n) reaction are assumed to be isotropic. No information was found in the literature about the directionality

of this reaction. The energy distribution of these neutrons was also difficult to find in the literature. However, most of the literature suggested that the energy of the first neutron would follow a Maxwellian distribution according to evaporation theory. The correct equation and corresponding constants for the copper (n,2n) reaction could not be found. However, one was assumed from information in Ref. 4. The equation assumed was:

$$E' e^{-E'/T} \quad \text{where } T = (\bar{E}/a)^{1/2} \quad (4)$$

where

E' = the energy of the first neutron

T = the nuclear temperature

$\bar{E}$ = $E - E$ threshold

a = ~ 7.9

When $E = 14.75$ MeV, $\bar{E} = 4.19$ MeV, and 4.99 MeV for the ^{63}Cu (n,2n) ^{62}Cu and the ^{65}Cu (n,2n) ^{64}Cu reactions, respectively. It would follow that the energy of the second neutron would simply be $\bar{E} - E'$.

The energy distributions were calculated and are presented in Fig. 5.5. The curve marked "Total" is simply a summation of the other four curves, since about equal number of neutrons result from reactions in the two isotopes in natural copper. This is probably not the true energy distribution, but it was used for our approximations. The energy distribution of the first neutron must go to 0 at $\bar{E}$, which means its peak will occur at an energy less than $\bar{E}/2$. This would tend to produce an energy distribution having two peaks for the combination of the two neutrons.

The (n,2n) reaction in natural copper will account for 24.5 percent of all reactions in copper. Since most of the reactions took place in the copper surrounding the HENRE source, it was assumed that the total number of neutrons produced by the (n,2n) reaction was 15.8 percent of the 14-MeV neutrons produced, integrated over 4π , i.e., $0.158 = \{2 \times 0.245 \times (1.00 - 0.676)\}$.

The copper disk and copper ring present a solid angle of 7.11 steradians to the source of 14-MeV neutrons; the disk presenting 6.20 and the ring 0.91. The mass of copper in the disk was 5,640 g, and in the ring, 15,210 g. If we multiply the solid angle by the mass and normalize the sum of the two results to 1.00, we estimate that of the total (n,2n) neutrons produced, 74 percent are produced in the disk and 26 percent are produced in the outer ring.

The source of (n,2n) neutrons was, therefore, assumed to exist at two points: (1) 74 percent of them at the center of the copper disk, and (2) 26 percent of them at the center of the copper ring. For those generated in the disk, their attenuation was treated in the same manner as those in the uncollided component with values of t equal to half those in Equation (2) from $\theta = 0^\circ$ through 88° . At 90° and 92° , $t = 23.88$ cm; at 95.5° , $t = 4.00$ cm, etc. For those generated in the outer ring, $t = 1.24/\cos \theta$ for $\theta = 0^\circ$ through $64^\circ 15'$ and from $115^\circ 45'$ through 180° , and $t = 2.565/\cos (90 - \theta)$ for $\theta = 64^\circ 15'$ to $115^\circ 45'$. In all cases, a one dimensional geometry was taken with a microscopic cross section of 3.20 barns for a 2.5-MeV neutron. The contributions from those generated in the disk and outer ring were added, and the results given in Table 5.3 as fractions of the original 14-MeV neutron production at 0° . The results are also plotted in Fig. 5.2. Note that the data are plotted one decade lower than their actual values to avoid confusion on the graph.

Fig. 5.5—Energy distribution of neutrons from the (n,2n) reaction in natural copper.

5.7 INELASTIC SCATTER AND OTHER CONTRIBUTIONS

Other reactions in natural copper that result in emission of neutrons of degraded energy are: (n,n), (n,np), (n,n α) and inelastic scattering. The largest contributor of these, inelastic scattering, occurs when a neutron enters a nucleus, depositing only part of its energy. A neutron is emitted by the nucleus which experimentally is the same as the captured particle,⁵ but its energy is reduced. The energy loss is found in the nucleus which has been excited to a definite energy level. The nucleus then usually loses this energy by the emission of a gamma ray or beta particle.

The cross section for inelastic scattering and other neutron contributors for ^{63}Cu is estimated to be 0.75 barns and that for ^{65}Cu , 0.46 barns

at about 14 MeV. The exact energy distribution of these neutrons could not be found in a simple survey of the literature. However, Feld⁶ has presented an energy distribution for the combination of (n,2n) and inelastic processes (Fig. 5.6). The two peaks from the (n,2n) reaction can be seen at 1 and 3 MeV. All neutrons above 4 MeV must be due to the inelastic processes. Using this information, an energy distribution for natural copper was constructed for both (n,2n) and inelastic processes (Fig. 5.7).

Fig. 5.6—Computed energy distribution of neutrons emitted by ^{63}Cu bombarded by 14-MeV neutrons. Both inelastic and (n,2n) processes are included.⁶

Fig. 5.7—Estimated energy distribution of neutrons emitted by natural copper bombarded by 14.75-MeV neutrons. Both inelastic and (n,2n) processes are included.

The direction of the emitted neutrons from the inelastic process is expected to be isotropic for lower energies⁴ (0-4 MeV) and becoming increasingly peaked in the forward direction as the energy increases. For those peaked in the forward direction, the angular output from the HENRE target would follow a curve similar to those from the elastic scatter process (Fig. 5.2). For those generated isotropically, their angular output should follow those from the (n,2n) reaction. A combination of the two would produce a nearly isotropic angular output. That is, equal number of neutrons from the inelastic process emerge from the HENRE target in all directions. We shall adopt this assumption.

The inelastic scatter process will account for about 21.8 percent of all reactions in copper. This means that the number of neutrons involved in the inelastic process will be 7.1 percent of the total 14-MeV neutrons produced, integrated over 4π . A few of these will be absorbed in the copper before emerging from the target. We shall assume that 6.0 percent of the total output of a point, isotropic source in a vacuum, will emerge as inelastic scattered neutrons.

5.8 SUMMARY AND DISCUSSION

The uncollided and elastic scattered contributions were added to obtain the neutrons within the energy range 13 to 15 MeV. The neutrons from the (n,2n) reactions were placed in the energy range from 0 to 5 MeV. Values from the smoothed curves in Fig. 5.2 were used. These results are tabulated in Table 5.4 and plotted in Fig. 5.8. The plot is as a function of $\cos \theta$ to give the reader a concept of the relative contribution vs. polar angle in a 4π geometry.

The data presented in Fig. 5.8 were integrated over 4π with the following fractional results: total = 91.8 percent, 13- to 15-MeV region = 73.3 percent, 5- to 13-MeV region = 6.0 percent, and 0- to 5-MeV region = 12.5 percent. These are percentages of the total output of a point, isotropic source in a vacuum.

For the practical case, of the total number of neutrons escaping from the HENRE machine, 79.8 percent are expected to be in the 13- to 15-MeV energy region, 6.5 percent in the 5- to 13- MeV region, and 13.6 percent in the 0- to 5-MeV region.

In the direction below the target (0°), 14.7 percent are in the 0- to 5-MeV region, 5.2 percent in the 5- to 13-MeV region, and 80.1 percent are between 13- and 15-MeV. Selecting a few angles of interest, the following results illustrate how the spectrum changes with angle:

Angle	Percent of Total Fluence		
	0-5 MeV	5-13 MeV	13-15 MeV
0°	14.7	5.2	80.1
30	14.6	5.3	80.1
60	14.3	5.8	78.9
85	16.1	13.0	70.9
88	10.5	22.5	67.0
120	13.8	5.6	80.6
150	10.6	5.4	84.0

Using the above values and the spectrum in Fig. 5.7, an energy spectrum was constructed for the fluence at 0° , 88° , and for the total 4π output. These results are shown graphically in Figs. 5.9, 5.10, and 5.11.

TABLE 5.4. SUMMARY OF NEUTRON OUTPUT CALCULATIONS FOR THE HENRE NEUTRON SOURCE. RESULTS GIVEN IN RELATIVE VALUES OF ORIGINAL NEUTRON PRODUCTION AT 0° , NO SHIELD. (A VALUE OF 0.06 IS ASSIGNED TO THE 5 - 13 MeV REGION FOR ALL ANGLES.)

Angle (Deg)	13 - 15 MeV	0-5 MeV	Total
0	0.924	0.154	1.138
10	0.923	0.154	1.137
20	0.917	0.152	1.129
30	0.904	0.150	1.114
40	0.889	0.148	1.087
50	0.861	0.142	1.063
60	0.821	0.134	1.015
70	0.754	0.124	0.938
80	0.552	0.104	0.716
85	0.327	0.072	0.459
88	0.178	0.028	0.206
90	0.370	0.024	0.454
92	0.442	0.024	0.526
95.5	0.795	0.068	0.923
100	0.850	0.087	0.997
105	0.714	0.104	0.878
110	0.824	0.124	1.008
120	0.872	0.134	1.066
130	0.857	0.142	1.059
140	0.839	0.148	1.047
150	0.777	0.086	0.920
155	0.352	0.030	0.409
160	0.205	0.010	0.231
165	0.128	0.006	0.140
170	0.095	0	0.095
172	0.012	0	0.012
180	0	0	0

Fig. 5.8—Calculated directional neutron output from the HENRE target.

It should be noted from Table 5.4 that the total number of neutrons emerging at 0° is greater than the original production in this direction. This is because of: (1) the multiplication of neutrons from the $(n,2n)$ reaction (2 for 1), (2) the assumption that these are generated isotropically, and (3) some neutrons are scattered back to 0° from inelastic interactions.

It has been mentioned that 91.8 percent would emerge as compared with a point, isotropic source in a vacuum. However, if one measured the total

Fig. 5.9—Calculated neutron energy spectrum at 0°.

fluence, I , at a distance of R cms below the real target (0°), the total 4π neutron output can be calculated:

$$\text{total output } (4\pi) = 4\pi R^2 I \left(\frac{0.918}{1.138} \right) = 4\pi R^2 I \times 0.807$$

This indicates that about 20 percent fewer neutrons escape the HENRE source than would under the assumption of an isotropic source. Further, of these that escape, only 80 percent are in the 13- to 15- MeV region.

Fig. 5.10—Calculated neutron energy spectrum at 88°.

The above values will be further modified by the consideration of the (D-D) neutrons. The (D-D) contribution, of course, varied with each target and during each run. This is considered in the next chapter.

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Fig. 5.11—Calculated neutron energy spectrum for total 4π output.

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Chapter 6

EVALUATION AND ANALYSIS

6.1 (D-D) CONTRIBUTION

In an earlier experiment, Haywood (ORNL) determined the (D-D) neutron buildup on a small erbium-coated copper target bombarded by deuterium at a voltage of 150 kv. The neutron output reached equilibrium after about 2 hrs of operation (Fig. 6.1). The 4π output determined was 2.7×10^8 n/sec per ma of beam current. The HENRE machine was operated between 200 and 400 ma. Direct extrapolation results in a 4π output of (D-D) neutrons between about 5.4×10^{10} n/sec and 1.1×10^{11} n/sec after 2 hours or so of running time.

The 14-MeV neutron output for HENRE varied from 4×10^{13} n/sec at the beginning of a good target to about 8×10^{11} n/sec at the end of a poor target. The (D-D) neutrons, then, contributed from near 0 percent to as much as 14 percent of the neutron output.

The (D-D) contribution is further discussed later in this chapter in relation to experimental data.

6.2 EFFECTIVE ENERGY OF 13- to 15-MeV COMPONENT AT 0°

The accelerator was run at a voltage of between 132 and 156 kv for all runs. At this deuteron energy, Seagrave² indicates the effective energy at 0° should be 14.74 MeV for thick targets of zirconium or titanium. An erbium target is expected to be the same. There will be a spread in neutron energy because of the slowing down of deuterons in the occluder before a reaction takes place. Also, small angle scatter of the deuterons may cause a further reduction in effective neutron energy. Barrall³ suggests the neutrons may be spread over a 400- to 500-kev energy interval at 0° .

The resultant neutron energy at 0° for different deuteron energies for a thin target² is shown in Fig. 6.2. One can see that as a deuteron slows down the resultant energy of the neutron from the reaction decreases. Most of the reactions probably take place at deuteron energies between 50 kev and 150 kev because of the high cross section in this region (see Fig. 3.1). This would result in a neutron energy spread between 14.53 and 14.93 with an average around 14.75, corresponding to a deuteron energy of 100 kev where the maximum cross section occurs.

If a deuteron has been scattered 15° in slowing down to 100 kev, the neutron energy (in the same direction as the original beam, 0°) would be 14.67 rather than 14.75 MeV. However, most of the deuterons were slowed down as charged particles, thereby tending to go in the same direction.

Fig. 6.1—(D-D) Neutron buildup on a small erbium-coated (4.7 mg/cm^2) copper target, 150 kv.

Fig. 6.2—Neutron energy at 0° vs. deuteron energy resulting from the $T(d,n)^4\text{He}$ reaction in a thin titanium target.

The physical size of the target (18 cm in radius) and the "blowup" of the beam influenced the neutron energy slightly at a point near the target. The beam was accelerated at a point 76 cm above the target. An angle of 14 degrees is estimated between the direction of the deuteron beam intersecting the target at 10 cm off center and the direction of the resulting neutron arriving at a point 1-1/2 m below the target. Again, this results in only a 10-kev change in neutron energy because of the small angle.

In the practical case, the energy spectrum of the 13- to 15-MeV component will be further modified by elastic scattering in the target material (see Chapter 5).

As was mentioned earlier, a nonnegligible portion of the deuteron beam was molecular (D_2^+) in nature, each atom having only 75-kev energy. This resulted in a few neutrons being produced having energies below 14.65 MeV.

Both the Stanford University and NDL data were examined to determine the effective energy at 0° of the 13- to 15-MeV neutron component. Seven reactions from Table 4.4 were chosen on the basis that the neutrons present below 13 MeV would have a minimum influence on their activations.

The spectrum in Fig. 5.9 was assumed and neutron fluences calculated for three different "14 MeV" energies: (1) 14.75, (2) 14.67, and (3) 14.60. The results, given in Table 6.1, show a slight preference for an effective energy of 14.67 MeV.

The NDL data at 0° to 60° for magnesium, aluminum, and zirconium foils from Table 4.2 were evaluated. The cross section for the $^{90}\text{Zr}(n,2n)^{89}\text{Zr}$ reaction increases rapidly between 13 and 15 MeV. The cross section for both the $^{27}\text{Al}(n,\alpha)^{24}\text{Na}$ and the $^{24}\text{Mg}(n,p)^{24}\text{Na}$ reactions decrease in this energy region. Barrall³ suggests that if the cross sections are accurately known, effective neutron energies can be inferred by examining the saturation activity ratios from these foils. Since all three reactions have cross-section thresholds above 6 MeV, the resulting activations will be primarily sensitive to the uncollided and elastic scattered neutrons. The influence of the neutrons present between 6 and 13 MeV will be small (2 to 4 percent, assuming the spectrum in Fig. 5.9), but not negligible.

Cross section ratios are shown in Fig. 6.3 for the three reactions. The saturated activities for the foils for only "14 MeV" neutrons were calculated assuming the spectrum in Fig. 5.9. From these, saturated activity ratios were determined and the resulting effective neutron energy obtained from Fig. 6.3. The results, plotted in Fig. 6.4, show a preference for an effective neutron energy of about 14.75 MeV at 0° . The data follow the Seagrave⁴ curve quite well. It should be noted here that the $^{24}\text{Mg}(n,p)^{24}\text{Na}$ cross sections were taken from Barrall⁴ rather than BNL-325.⁵ The difference is significant.

6.3 ENERGY SPECTRUM AT 0° (ABOVE 0.50 MeV)

The experimental data by Barrall, tabulated in Table 4.4, were chosen to help determine the neutron energy spectrum at 0° . Fourteen different reactions were chosen on the basis of: (1) activation thresholds were at 0.5 MeV or above, and (2) a complete set of cross sections were available in the literature. There may have been many neutrons present of energy below 0.5 MeV. However, because of the resonances of many reactions in the thermal neutron region [$^{197}\text{Au}(n,\gamma)^{198}\text{Au}$ and $^{235}\text{U}(n,f)(^{99}\text{Mo})$ for instance], the analysis of these reactions would be difficult.

TABLE 6.1. ACTIVATION FOIL EVALUATION FOR EFFECTIVE
ENERGY OF 13 - 15 MeV NEUTRON COMPONENT
AT 0°.

Reaction	14.75 MeV	14.67 MeV	14.60 MeV
	Fluence (n/cm ² - sec)	Fluence (n/cm ² - sec)	Fluence (n/cm ² - sec)
²⁴ Mg(n, p) ²⁴ Na ⁺	31.6 E6*	30.9 E6	30.7 E6
²⁷ Al (n, α) ²⁴ Na ⁺⁺	31.2 E6	30.6 E6	30.3 E6
⁵⁵ Mn (n, 2n) ⁵⁴ Mn ⁺⁺	25.3 E6	25.5 E6	25.7 E6
⁵⁸ Ni (n, 2n) ⁵⁷ Ni ⁺	29.6 E6	30.5 E6	31.4 E6
⁶⁵ Cu (n, 2n) ⁶⁴ Cu ⁺⁺	27.9 E6	28.2 E6	28.3 E6
⁹⁰ Zr (n, 2n) ⁸⁹ Zr ⁺⁺	30.0 E6	30.6 E6	31.1 E6
¹⁹⁷ Au (n, 2n) ¹⁹⁶ Au ⁺⁺	29.4 E6	29.3 E6	29.1 E6
Avg	29.3 E6	29.5 E6	29.5 E6
Standard Deviation	7.90%	6.65%	6.83%

*Read 31.6 E6 as 31.6 x 10⁶

⁺Cross Sections from Ref. 4 (AFWL - TR - 65 - 34)

⁺⁺Cross Sections from Ref. 5 (BNL 325)

Fig. 6.3—Energy dependence of cross-section ratios.

Fig. 6.4—Effective neutron energy inferred by NDL data by the saturated activity ratio method.

Forty-seven different trial spectra were chosen to evaluate the sensitivity of these foils to spectral changes. Some of the trial spectra are shown in Figs. 6.5, 6.6, 6.7, and 6.8. The spectrum designated A (from Fig. 5.9) is repeated in each set of spectra for a reference. Since the results of the calculations for neutrons below 13-MeV were uncertain, many trial spectra containing different shapes and quantitative values were chosen. Those presented in Fig. 6.8 represent the best estimate from the calculations.

Trial spectra D through J (Fig. 6.8) consider some realistic neutron contributions from the (D-D) reaction. Neutrons from this reaction are not isotropic, they are peaked in the forward direction. The foils were exposed at 0° for Run No. 40 which produced an average of about 3.8×10^{12} n/sec (4π). If we assume the 4π (D-D) neutrons produced about 1×10^{11} n/sec, they would contribute about 2.5 percent of the total 4π neutrons. However, because of their forward predominance, they will contribute about 4 percent of the total fluence at 0° . Spectra No. D, E, F, G, H, I, and J in Fig. 6.8 represent (D-D) contributions of 1.3, 1.6, 2.1, 2.6, 3.6, 4.6, and 6.4 percent of the total fluence at 0° , respectively.

For each of the 14 reactions, cross-section values for each 500-kev energy interval between 0.5 MeV to 15 MeV were designated. Both BNL-325⁵ and AFWL-TR-65-34⁴ were used, the choice for each reaction being arbitrary by the author.

Fig. 6.5—Trial energy spectra at 0° .

For each of the 658 cases (47 spectra and 14 reactions), an effective cross section was determined. A small program routine for a Hewlett-Packard Electronic Calculator (9100A) was used in the analysis. From the effective cross sections and the activity at saturation of each of the foils listed in Table 4.4, a neutron fluence (above 0.5 MeV) was calculated for each of the 658 cases. These are tabulated in Table 6.2. For trial spectrum No. 3, AA, A, B, and C, the subscripts of 14.75, 14.67, and 14.60 refer to the effective energy at "14 MeV" as 14.75, 14.67, or 14.60 MeV. All other spectra assumed an energy of 14.67 MeV. For trial spectrum No. 4, 5, W, and X, the subscripts of 70, 75, and 80 refer to the cross section in mb of the $^{115}\text{In}(n,n')^{115}\text{In}$ reaction at "14 MeV". In spectra A, B, and C, the value was 75 mb; in all other

Fig. 6.6—Trial energy spectra at 0° .

spectra 70 mb was assumed. These small variations were introduced to evaluate the effect of small changes in neutron energy or cross-section values to the overall result.

The resulting fluence rates from Table 6.2 were plotted for four groups of spectra, similar in shape. These plots are shown in Fig. 6.9. It can be seen that reaction No. 11 ($^{115}\text{In}(n,n')^{115}\text{In}$) will strongly influence the choice of trial spectrum producing the best fit. The cross section for this reaction is above 200 mb from 1.5 to 10 MeV, but only about 75 mb at 14 MeV. Unfortunately, the cross sections for this reaction are probably the least known of the 14 reactions studied. This suggests that caution must be taken

Fig. 6.7—Trial energy spectra at 0° .

in drawing conclusions from the data. It is also noted in Fig. 6.9 that the spectrum producing the best fit will correspond closely to trial spectrum 2 to 5, 10, or W to Y.

For each of the 47 trial spectra, an average fluence rate and standard deviations for each set of foils was determined. These are listed in Table 6.3 and plotted in Fig. 6.10 as a function of the "14 MeV" fluence fraction. The results show a strong sensitivity to the effective energy at 14 MeV and to a choice of a cross-section value for the indium reaction for each trial spectrum evaluated. However, no consistent trend for these two effects is obvious.

Fig. 6.8—Trial energy spectra at 0° .

The lowest standard deviations (± 8.71 percent) occur for trial spectrum 3(14.67) and 4(80). The next lowest was trial spectrum H with a standard deviation of ± 8.78 percent. This spectrum represents a (D-D) contribution of 3.6 percent (at 0°) and is the one predicted from the calculations. It should be noted that activation counting techniques produce standard deviations on the order of ± 5 percent for different foils. When one adds the uncertainties due to cross-section values, the low standard deviation of ± 8.7 percent is surprisingly good.

A similar analysis was made by Barrall.⁶ The 31 reactions in Table 4.4 were calculated using the Spectrum Analysis by Neutron Detectors II (SAND II) computer code. His results also showed about a 3-percent (D-D) component. However, he found very few neutrons immediately above or below the 2.5-MeV peak.

TABLE 6.2. FLUENCE RATE* DETERMINATIONS AS A FUNCTION OF INPUT SPECTRA FOR
14 FOIL ACTIVATION RESULTS FROM TABLE 4.4.

Reaction	$^{24}\text{Mg} (n, p)^{24}\text{Na}$	$^{27}\text{Al} (n, \alpha)^{24}\text{Na}$	$^{32}\text{S} (n, p)^{32}\text{P}$	$^{55}\text{Mn} (n, 2n)^{54}\text{Mn}$	$^{54}\text{Fe} (n, p)^{54}\text{Mn}$	$^{56}\text{Fe} (n, p)^{56}\text{Mn}$	$^{59}\text{Ni} (n, p)^{59}\text{Co}$	$^{58}\text{Ni} (n, 2n)^{57}\text{Ni}$	$^{65}\text{Cu} (n, 2n)^{64}\text{Cu}$	$^{90}\text{Zr} (n, 2n)^{89}\text{Zr}$	$^{115}\text{In} (n, n')^{115m}\text{In}$	$^{197}\text{Au} (n, 2n)^{196g}\text{Au}$	$^{232}\text{Th} (n, f)$ tracks	$^{235}\text{U} (n, f)$ tracks + [^{235}Mo]
Reaction No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Trial Spectrum														
1	60.6	60.5	37.6	53.3	39.4	69.3	36.8	64.3	58.7	64.4	24.9	59.7	59.2	48.9
2	36.0	35.3	31.0	29.4	33.1	38.2	31.8	35.3	32.5	35.4	33.4	33.7	41.4	35.9
3 (14.60)	33.9	33.4	29.8	28.1	32.1	35.8	31.0	34.4	31.0	34.1	34.6	31.9	40.0	35.1
3 (14.67)	34.2	33.6	30.3	27.9	32.6	36.4	31.4	33.3	30.8	33.6	34.6	32.0	40.0	34.8
3 (14.75)	34.4	34.2	31.0	27.7	32.9	36.7	31.9	32.4	30.6	32.8	34.6	32.2	40.0	34.6
4 (70)	33.0	32.4	29.7	26.8	31.9	35.0	31.0	32.0	29.5	32.2	35.7	30.8	38.8	33.9
4 (75)	33.0	32.4	29.7	26.8	31.9	35.0	31.0	32.0	29.5	32.2	34.4	30.8	38.8	33.9
4 (80)	33.0	32.4	29.7	26.8	31.9	35.0	31.0	32.0	29.5	32.2	33.1	30.8	38.8	33.9
5 (70)	30.9	30.4	28.9	25.0	31.3	32.9	30.3	29.9	27.7	30.1	38.2	28.8	37.1	32.5
5 (75)	30.9	30.4	28.9	25.0	31.3	32.9	30.3	29.9	27.7	30.1	36.6	28.8	37.1	32.5
5 (80)	30.9	30.4	28.9	25.0	31.3	32.9	30.3	29.9	27.7	30.1	35.0	28.8	37.1	32.5
6	28.5	28.0	27.7	22.9	30.2	30.4	29.3	27.4	25.3	27.5	42.1	26.4	34.7	30.7
7	26.3	25.9	26.7	21.1	29.1	28.3	28.4	25.3	23.4	25.4	46.9	24.4	32.7	29.2
8	49.5	50.9	25.5	66.1	26.2	56.0	24.6	88.7	69.5	86.4	23.2	74.4	51.9	43.4
9	39.2	39.5	25.6	41.5	27.6	34.9	25.5	51.0	44.0	52.0	27.0	41.1	44.3	37.4
10	31.7	31.4	25.8	28.6	28.3	33.9	26.5	34.4	30.9	34.4	34.0	30.9	37.7	32.9
11	28.2	27.8	25.9	23.7	28.0	31.1	27.1	28.5	26.1	28.7	40.4	26.8	34.5	30.5
12	26.7	26.3	25.9	21.9	28.2	29.3	27.5	26.3	24.2	26.4	44.3	24.8	33.2	29.4
13	25.5	25.0	26.1	20.9	28.4	27.1	27.9	24.4	22.6	24.5	49.2	23.6	31.9	28.4
V	40.5	40.4	29.0	34.5	30.8	43.2	28.9	41.3	38.0	41.5	25.9	39.0	43.5	38.2

Y	30.9	30.6	27.5	25.5	29.6	33.2	28.5	30.5	28.2	31.6	34.7	29.3	36.7	32.2
X (70)	32.6	32.1	27.7	26.8	29.8	34.6	28.5	32.1	29.6	32.2	32.3	30.7	37.7	32.9
X (75)	32.6	32.1	27.7	26.8	29.8	34.6	28.5	32.1	29.6	32.2	31.2	30.7	37.7	32.9
X (80)	32.6	32.1	27.7	26.8	29.8	34.6	28.5	32.1	29.6	32.2	30.1	30.7	37.7	32.9
W (70)	33.9	33.6	28.1	28.3	30.1	36.2	28.7	33.8	31.2	34.0	30.6	32.2	38.9	33.8
W (75)	33.9	33.6	28.1	28.3	30.1	36.2	28.7	33.8	31.2	34.0	29.7	32.2	38.9	33.8
W (80)	33.9	33.6	28.1	28.3	30.1	36.2	28.7	33.8	31.2	34.0	28.8	32.2	38.9	33.8
Z	28.0	27.5	26.8	22.6	29.0	30.1	28.2	27.0	25.0	27.1	40.5	26.1	34.1	30.1
AA (14.60)	33.0	32.6	27.6	27.7	29.6	35.0	28.4	34.0	30.5	33.7	31.9	31.4	38.3	33.7
AA (14.67)	33.2	32.9	28.0	27.5	30.0	35.4	28.6	32.9	30.4	33.1	31.9	31.5	38.3	33.5
AA (14.75)	33.7	33.4	28.5	27.3	30.3	35.8	29.2	32.0	30.2	32.5	31.9	31.7	38.3	33.2
A (14.60)	30.7	30.3	27.0	25.7	29.1	32.7	28.1	31.4	28.3	31.1	34.7	29.1	37.4	32.5
A (14.75)	31.3	31.2	28.1	25.3	30.0	33.3	29.0	29.6	27.9	30.0	33.4	29.4	36.7	31.9
B (14.60)	29.6	29.1	27.2	24.5	29.4	31.4	28.5	29.8	27.0	29.6	37.3	27.8	36.4	31.6
B (14.75)	30.2	30.0	28.2	24.1	30.3	32.0	29.4	28.1	26.6	28.6	35.6	28.0	35.9	31.2
C (14.60)	28.5	28.0	27.3	23.7	29.7	30.3	28.8	28.5	25.7	28.3	40.4	26.6	35.7	31.1
C (14.75)	29.0	28.8	28.5	23.0	30.6	30.8	29.9	26.8	25.4	27.2	38.3	26.9	35.1	30.7
M	34.0	33.3	30.2	27.2	33.0	36.2	31.5	32.5	30.1	32.7	31.9	31.4	39.5	34.3
N	34.0	33.3	31.5	27.2	33.0	36.2	32.4	32.5	30.1	32.7	24.1	31.4	38.4	32.9
O	34.0	33.3	30.2	27.2	33.0	36.2	31.4	32.5	30.1	32.7	36.8	31.4	40.0	35.2
D	31.3	31.2	28.4	25.3	30.2	33.5	29.2	29.6	27.9	30.0	32.8	29.2	36.7	31.9
E	31.5	31.3	28.4	25.4	30.2	33.6	29.5	29.7	28.1	30.1	32.4	29.3	36.9	32.0
F	31.7	31.5	28.5	25.6	30.3	33.8	29.4	29.8	28.2	30.3	32.2	29.5	37.0	32.1
G	31.9	31.7	28.5	25.7	30.4	34.0	29.4	30.0	28.4	30.5	31.5	29.7	37.2	32.2
H	32.3	32.1	28.8	26.0	30.5	34.5	29.5	30.5	28.8	30.9	30.7	30.0	37.4	32.4
I	32.6	32.5	28.9	26.4	30.7	34.9	29.7	30.8	29.2	31.3	29.9	30.4	37.7	32.6
J	33.5	33.3	29.4	27.0	31.1	35.7	30.0	31.5	29.9	32.0	28.7	31.1	38.3	33.0

*Multiply all values by 10^6 to obtain $\text{m}/\text{cm}^2 - \text{sec}$.

Fig. 6.9—Relative neutron fluence of several activation foils at 0° as a function of the "14 MeV" fraction of various trial spectra.

Several conclusions and comments can be derived from the above analysis:

1. An exact neutron spectrum cannot be determined by foil activations unless cross sections and activation activities are precisely known. Otherwise, only the general shape of the spectrum can be inferred.
2. The data show a strong sensitivity to the fraction of "14 MeV" neutrons present.
3. The data are insensitive to the shape of the spectrum below the "14 MeV" peak. (See, for instance, the standard deviations for spectrum 4, 10, A, Y, M, N, O, and H).

TABLE 6.3. AVERAGE FLUENCE RATES AND STANDARD DEVIATIONS FOR THE TRIAL SPECTRA.

Trial Spectrum	Average Fluence Rate (n/cm ² - sec)**	Standard Deviation (± %)	"14 MeV" Fraction	Trial Spectrum	Average Fluence Rate (n/cm ² - sec)**	Standard Deviation (± %)	"14 MeV" Fraction
1	52.69	24.9	0.380	X (75)	31.32	9.06	0.760
2	34.46	8.85	0.693	X (80)	31.24	9.15	0.760
3 (14.60)*	33.20	8.83	0.731	Y	30.64	9.62	0.800
3 (14.67)	33.30	8.71	0.731	Z	28.12	15.0	0.904
3 (14.75)	33.30	8.74	0.731	AA (14.60)	32.00	9.47	0.741
4 (70)	32.34	9.13	0.763	AA (14.67)	31.90	9.22	0.741
4 (75)	32.24	8.86	0.763	AA (14.75)	32.00	9.06	0.741
4 (80)	32.15	8.71	0.763	A (14.60)	30.57	10.13	0.801
5 (70)	31.00	11.10	0.816	A (14.75)	30.51	9.19	0.801
5 (75)	30.89	10.37	0.816	B (14.60)	29.94	11.50	0.842
5 (80)	30.77	9.77	0.816	B (14.75)	29.87	10.63	0.842
6	29.36	15.6	0.892	C (14.60)	29.47	14.2	0.882
7	28.08	21.8	0.966	C (14.75)	29.36	13.1	0.882
8	52.59	42.8	0.275	M	32.70	8.9	0.750
9	37.92	23.2	0.478	N	32.12	10.80	0.750
10	31.53	10.6	0.710	O	32.14	9.71	0.705
11	29.09	14.3	0.855	D	30.51	9.02	0.798
12	28.17	19.0	0.928	E	30.59	8.97	0.795
13	27.54	24.8	1.000	F	30.71	8.87	0.790
V	36.76	15.9	0.591	G	30.79	8.86	0.785
W (70)	32.39	9.61	0.721	H	31.03	8.78	0.775
W (75)	32.32	9.78	0.721	I	31.26	8.81	0.765
W (80)	32.26	10.00	0.721	J	31.75	9.18	0.747
X (70)	31.40	9.08	0.760				

*See text for explanation of number in parenthesis.

**Multiply numbers in this column by 10⁶.

Fig. 6.10—Standard deviations as a function of "14 MeV" fraction for all trial spectra.

4. For these experimental conditions, the "14 MeV" fraction of the fluence above 0.5 MeV was probably between 0.70 and 0.80.

5. Trial spectrum H represents the spectrum at 0° for Run No. 40.

The neutron yield from Run No. 40 was somewhat representative of the yield for Phase I of Operation HENRE. However, for Phase II, the average yield was higher. All 14 targets averaged 5×10^{12} n/sec for an average beam current of about 300 ma.

Considering the above evaluation, it is concluded that spectrum D represents an adequate neutron spectrum at 0° for all of Operation HENRE (see Fig. 6.8).

6.4 DIRECTIONAL NEUTRON OUTPUT

The NDL data for the $^{24}\text{Mg}(n,p)^{24}\text{Na}$, $^{27}\text{Al}(n,\alpha)^{24}\text{Na}$, and the $^{90}\text{Zr}(n,2n)^{89}\text{Zr}$ reactions in Table 4.2 were used to determine the directional neutron output for the 13- to 15-MeV component. Since all three reactions have cross-section thresholds above 6 MeV, the resulting activities will be primarily sensitive to the 13- to 15-MeV peak. The calculated spectra given in Chapter 5 were assumed, and the saturated activities due only to the "14 MeV" neutrons were derived. An effective energy of 14.75 MeV was taken at 0° . The 13- to 15-MeV neutron fluences were derived from the data in Table 4.2 and the results tabulated in Table 6.4 and plotted in Fig. 6.11.

The fluence is about the same over a wide angle below the target. The horizontal "shadow" begins to appear at about 70° . The width at half the maximum depression is from 10° to 12° , and the fluence at the low point at 88° is only 18 percent of that directly below the target. The neutron output at angles above the depression appears to be on the order of 15 percent less than below. Measurements were not made by NDL at angles above 130° because of intersection with the accelerator framework. The calculations follow the experimental data in Fig. 6.11 closely, except between 88° and 98° where the calculations are about 25 percent high. Some of this difference may be due to the fact that the experimental data were taken in a direction that intersected the copper "ears" of the target, i.e., the cooling system headers. In this direction, the outer copper ring thickness is actually 7.3 cm rather than the 5.13 cm assumed in the calculations. Perhaps a more rigorous calculation, considering the exact geometry and a disk source, would account for all of the differences. Nevertheless, the agreement is excellent, even to the point of showing the peaks and valleys between 90° and 110° .

The experimental data are very consistent among themselves, lending confidence to the directional output of the 13- to 15-MeV component.

6.5 ENERGY SPECTRUM (ABOVE 0.5 MeV) AT $\sim 90^\circ$

The NDL, Stanford U., and EG&G data in Tables 4.2, 4.5, and 4.7, respectively, were used to evaluate the spectrum at about 90° (horizontal). The spectrum in Fig. 5.10 was assumed and effective cross sections determined for each reaction. (The (D-D) contribution would be negligible in this direction.) The neutron fluences were then calculated from the activation data given in the tables.

The results are tabulated in Table 6.5, along with averages and standard deviations for each set of data. Values for 0° , 45° , and 60° are also given for comparison purposes, assuming spectrum H to apply at these angles. In all cases, the effective energy of the 13- to 15-MeV component was assumed to be that given by Seagrave.² The NDL data were taken on an arc in the direction of Program 9 experimental area, 38° off center. The Stanford U. data were taken in a direction straight out from the tower. The EG&G data were taken on both arcs. The NDL and EG&G data were taken on the same run. The quantitative comparisons at small angles are not as good as expected.

Next, trial spectrum 9 was assumed (for comparison purposes), and effective cross sections and fluences were determined and tabulated in Table 6.5. The NDL data show a slight preference for the spectrum in Fig. 5.10 at 88° and a strong preference for this spectrum at 90° . The EG&G data show a strong preference for spectrum 9 at 90° .

TABLE 6.4. . 13 - 15 MeV FLUENCE* AS DERIVED FROM
NDL FOIL DATA.

Angle (deg)	Mg (n/cm ²)	Al (n/cm ²)	Zr (n/cm ²)	Angle (deg)	Mg (n/cm ²)	Al (n/cm ²)	Zr (n/cm ²)
0	2.16	2.14	2.10	85	0.76	0.78	0.73
5	2.15	2.04	2.11	86	0.59	0.61	0.57
10	2.09	2.07	2.15	87	0.47	0.48	0.45
15	2.12	2.07	2.14	88	0.36	0.35	0.34
20	2.10	2.14	2.02	89	0.43	0.45	0.45
25	1.99	2.10	2.02	90	0.57	0.54	0.55
30	2.06	2.05	2.07	91	0.68	0.71	0.71
35	2.11	2.02	2.04	92	0.71	0.70	0.79
40	2.16	2.04	2.02	93	0.83	0.87	0.87
45	2.15	2.04	2.03	94	1.09	1.13	1.09
50	2.02	2.06	2.04	95	1.25	1.27	1.25
55	2.10	2.02	1.98	96	1.35	1.44	1.43
60	2.07	1.97	2.04	97	1.64	1.58	1.62
62.5	2.07	1.93	1.94	98	1.64	1.71	1.74
65	2.05	1.89	1.94	100	1.68	1.78	1.53
67.5	1.99	1.83	1.91	102.5	1.57	1.64	1.73
70	1.85	1.82	1.78	105	1.57	1.64	1.73
72.5	1.90	1.72	1.78	107.5	1.61	1.71	1.80
75	1.69	1.65	1.56	110	1.70	1.71	1.79
77.5	1.56	1.52	1.61	112.5	1.68	1.87	1.85
80	1.37	1.41	1.36	115	1.75	1.81	1.96
82	1.18	1.15	1.03	120	1.78	1.89	2.05
83	1.08	1.06	1.04	125	1.96	1.86	2.03
84	0.90	0.93	0.89	130	1.88	1.49	1.90

*Multiply all values by 10¹¹.

Fig. 6.11—Fluence 13 to 15 MeV vs. polar angle.

No strong conclusions about the spectrum near 90° are apparent from the experimental data. Some generalities, however, can be inferred:

1. Spectrum H appears to provide a good fit for the data at small angles 0° to 60° .
2. The "14 MeV" fraction in the horizontal direction is probably between 0.5 and 0.7.

TABLE 6.5. NEUTRON FLUENCES ABOVE 0.5 MeV AS
DETERMINED FROM SELECTED FOIL DATA
AND ASSUMED SPECTRA.

Reaction	Spectrum H Assumed						Spectrum in Fig. 5.10 Assumed				Spectrum 9 Assumed	
	0°		45°		60°		88°	90°		88°	90°	
	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(1)	(2)	(1)	(1)	(2)

NDL Data from Table 4.2. n/cm^2 (Multiply Data by 10^{11})

$^{24}\text{Mg}(n, p)^{24}\text{Na}$	2.77		2.79		2.69		0.523	0.770		0.589	0.874	
$^{27}\text{Al}(n, \alpha)^{24}\text{Na}$	3.05		2.90		2.82		0.597	0.808		0.694	0.939	
$^{90}\text{Zr}(n, 2n)^{89}\text{Zr}$	2.91		2.83		2.83		0.510	0.832		0.704	1.148	
$^{32}\text{S}(n, p)^{32}\text{P}$	2.87		2.71		2.67		0.589	0.738		0.626	0.784	
Avg	2.90		2.81		2.75		0.555	0.757		0.653	0.936	
Stand Div.	4.0%		2.8%		3.1%		8.0%	5.3%		8.4%	16.5%	

Stanford U. Data from Table 4.5. n/cm^2 - sec (Multiply data by 10^6)

$^{58}\text{Ni}(n, p)^{58}\text{Co}$		89.0		82.5					23.7			26.0
$^{58}\text{Ni}(n, 2n)^{57}\text{Ni}$		69.1		76.0					21.6			30.3
$^{32}\text{S}(n, p)^{32}\text{P}$		93.0		92.7					25.7			27.3
Avg		83.7		83.7					23.7			27.9
Stand Div.		15.3%		10.1%					8.7%			7.9%

EG&G Data from Table 4.7. n/cm^2 (Multiply data by 10^{11})

$^{58}\text{Ni}(n, p)^{58}\text{Co}$	2.18	2.25			2.60	2.39		0.892	0.778		0.977	0.852
$^{32}\text{S}(n, p)^{32}\text{P}$	2.44	2.34			2.48	2.33		0.845	0.755		0.898	0.802
$^{58}\text{Ni}(n, 2n)^{57}\text{Ni}$	2.35	2.01			2.27	1.85						
$^{90}\text{Zr}(n, 2n)^{89}\text{Zr}$	2.35	2.45			2.24	2.15		0.716	0.567		0.990	0.784
Avg	2.33	2.26			2.40	2.18		0.818	0.700		0.955	0.813
Stand Div.	4.7%	8.3%			7.2%	11.1%		11.1%	16.5%		5.2%	4.3%

(1) Toward Program 9 Area (37° off center)

(2) Center

The calculation assumed emerging neutrons from inelastic scattering were isotropic. The spectrum in Fig. 5.10 resulted from these calculations. Actually, neutrons generated by the inelastic scattering process having higher energies tend to go in the same direction. This would have the effect of putting more neutrons having higher energies (7 to 13 MeV) in the horizontal direction. The resulting spectrum would probably look like 9 rather than that given in Fig. 5.10. However, no conclusions can be drawn from the experimental data.

6.6 GAMMA RAY OUTPUT

The primary sources of gamma rays present near the targets were:

(1) gamma rays from (n,γ) , inelastic and activation processes in the copper, aluminum, and steel at, or near, the target; (2) x rays generated by the interaction of backstreaming electrons with material of the drift tube and ion source anode; (3) gamma rays from neutron interaction with nitrogen and oxygen in the air.

The activation of aluminum in the corona dome was high. The exposure rate at a meter immediately after a 4-hour run was several R/hr. Activation of the copper and steel was small. The production cross section, given in BNL-325,⁵ for producing gammas in natural copper by 14-MeV neutrons are:

<u>Gamma Energy (MeV)</u>	<u>Cross Section (Barns)</u>
4.0 - 5.0	0.47
5.0 - 6.1	0.25
6.1 - 7.5	0.14
4.433	0.26

From the values and information in Chapter 4, one obtains: For each 100 neutrons produced, about 13 gamma rays, ranging in Energy between 4 and 8 MeV, are emitted from the copper.

Electrons were generated when the deuterium beam interacted with the target material. Even though most of these electrons were suppressed, some returned up the drift tube. These energetic particles produced x rays of 150 kev or less energy when they collided with any material at ground potential. The radiation level from these x rays at a meter was several R/hr.

For the intercalibration run on November 1, 1968, the neutron dose at 1-1/2 m was 1320 rads (from NDL data). If we assume an x-ray exposure of 40 R, an aluminum activation exposure of 40 R and an exposure of 50 R from the copper, a total of 130 R due to gamma radiation generated by the target and accelerator components is estimated.

From the NDL data in Table 4.2 and the spectrum calculated in Chapter 5, neutron doses at 1-1/2 m were calculated for each angle. From the TLD data in Table 4.8 gamma exposures were estimated for each angle. These are tabulated in Table 6.6. The TLD's were assumed to respond to neutrons by the following: 10 R for each 100 tissue rads of 14 MeV neutrons; 6 R for each 100 tissue rads of 5 to 13 MeV neutrons, and 2 R for each 100 tissue rads of 0.5 to 5 MeV neutrons.⁷ The resulting gamma exposures in Table 6.6 are spread widely among themselves. The values for angles from 0° to 60° range from 150 to 303 R with an average of 229 R $\pm$ a standard deviation of 17 percent.

However, the values are reasonable. The neutron to gamma dose ratio is 5.8 at this point. Other measurements with TLD's for Program 11 at a meter or less showed an n/ γ dose ratio of 4.9.

TABLE 6.6. ESTIMATED GAMMA EXPOSURE AS DERIVED
FROM TLD DATA AT 1-1/2 METERS ON THE
INTERCALIBRATION RUN, NOVEMBER 1, 1968

Angle (deg)	Gamma Dose (R)	Angle (deg)	Gamma Dose (R)
0	303	85	145.3
5	182	86	109.5
10	194	88	119.8
15	256	90	138
20	150	92	132
25	242	94	135
30	268	96	145
35	188	98	252
40	250	99	152
45	254	100	174
50	232	102.5	146
55	210	105	171
60	224	107.5	159
62.5	191	110	202
65	254	112.5	217
67.5	230	115	149
70	272	120	97
75	195	125	280
77.5	226	130	201
80	207	135	281
81	123	140	262
82	139.5	145	156
84	200.5		

If we assume 130 R of gamma radiation come from the source system at our point at 1-1/2 m, this leaves 99 R from secondary gamma radiation produced in the air. Since these values seem reasonable, we shall adopt those assumptions. Therefore, the following gamma ray sources at 1 m from the targets can be assumed:

Gamma Ray Energy (MeV)	Exposure Level at 1 Meter (R/source neutron)
0.150	5.3×10^{-16}
2.75	5.3×10^{-16}
6.0	6.6×10^{-16}

This analysis of the gamma ray component has been very rough and, admittedly, inaccurate. Nevertheless, it is hoped it will be useful to the reader.

6.7 TOTAL 4π OUTPUT

As was mentioned in Chapter 4, for each run and each target, a sulfur pellet was placed 3 meters below the target. Sulfur cross sections at 210 mb and 206 mb were used, respectively, by Quam and Haywood. At the beginning of Phase II, many sulfur pellets were counted both by Quam and Haywood. The activities, as reported by Quam, were consistently 18.7 percent lower than those reported by Haywood after correction for cross-section difference. The error was attributed to calibration of counting equipment.

During the HENRE runs, there were many opportunities to compare fluence values as reported by different organizations. After the HENRE operation, sulfur pellets were exposed to a neutron fluence at the LRL-ICT facility specifically to check the calibration of the counting equipment.⁸ Corrections to be applied to Quam's data and Haywood's data to obtain the average fluence for the particular comparison (after normalizing to common cross sections) are given in Table 6.7.

It is noted that EG&G's fluence results were consistently lower, and ORNL's data consistently higher than the average fluence each time a comparison was made. An evaluation of counting techniques at different laboratories was not attempted. An average correction factor of 1.081 was arbitrarily assigned to Quam's data and 0.935 to Haywood's data to more properly align their results to an average from several laboratories.

During Phase I, Haywood estimated a correction of 0.75 to account for the effect of anisotropy of the source. During Phase II, an isotropic source was assumed. From data in Chapter 5 (which we adopt), the actual total 4π neutron output (above 0.5 MeV) was 80.7 percent of what an isotropic source would emit.

From the results in Section 6.3, we assume that spectrum D adequately represents the neutron spectrum at 0° for all of Operation HENRE. The effective cross section for the $^{32}\text{S}(n,p)^{32}\text{P}$ reaction for this spectrum is 203 mb.

To obtain the correct total 4π neutron output above 0.5 MeV, the following equations are used:

$$N_1 = A_1 \times C_1 \times B_1 \times n_1 \quad (1)$$

and

$$N_2 = A_2 \times C_2 \times B_2 \times n_2 \quad (2)$$

where

N_1 = the correct total 4π neutron output above 0.5 MeV for Phase I (1966 and 1967).

N_2 = the correct total 4π neutron output above 0.5 MeV for Phase II (1968).

A_1 = Correction for sulfur cross sections used in Phase I:
 $206/203 = 1.016$.

A_2 = Correction for sulfur cross sections used in Phase II:
 $210/203 = 1.035$.

TABLE 6.7. CORRECTIONS TO BE APPLIED TO QUAM'S AND HAYWOOD'S SULFUR
DATA TO OBTAIN AN AVERAGE FLUENCE.

Fluence Measurement Location	Min. No. of Samples Each Org. Used In Comparison	Number of Independent Organizations Participating	Correction for Quam's Data to Obtain Average	Correction for Haywood's Data to Obtain Avg
3 meters below target	30	2	1.115	0.897
3 meters below target	2	4	1.013	0.935
27 ft from tower	2	5	1.094	0.967
1-1/2 meter area	8	2	1.115	
LRL - ICT	4	3	1.070	0.942

C_1 = The counting system correction factor assigned for Phase I:
0.935.

C_2 = The counting system correction factor assigned for
Phase II: 1.081.

B_1 = Factor to correct for the anisotropy of the source for
Phase I: $0.807/0.75 = 1.076$

B_2 = Factor to correct for the anisotropy of the source for
Phase II: 0.807.

n_1 = 4π neutron output previously issued for Phase I.

n_2 = 4π neutron output previously issued for Phase II.

Using the above values for A, C, and B the following values for N/n were calculated:

Phase I: $N_1/n_1 = 1.021$

Phase II: $N_2/n_2 = 0.904$

To obtain the 4π output for neutrons within a specific energy interval, correction factors were calculated and the results tabulated in Table 2.1. The spectrum in Fig. 5.11 was assumed with a 1.0 percent (D-D) component added between 2 and 3 MeV. As one can see, the corrections for the previously assumed 13- to 15-MeV component are substantial.

6.8 ERROR ESTIMATES

It is difficult to estimate the uncertainties in the absolute magnitude of the 4π neutron output. Nevertheless, an attempt was made to do this in order to provide guidance for quantitative comparisons of experimental and theoretical calculations.

The uncertainty in the neutron spectrum introduces an uncertainty in the effective sulfur cross section of about ± 8 percent. The uncertainty of the sulfur cross section at "14.75 MeV" is estimated at about ± 10 percent.

After correcting for counting-system intercalibrations and normalizations, an uncertainty for this factor still remains high, say ± 8 percent.

The correction for neutron output because of the anisotropy of the source is reliable to about ± 8 percent.

Combining the above errors results in an uncertainty of about ± 17 percent for the total 4π neutron output. The uncertainty of the 4π output of the 12.2- to 14-MeV component is a little better than this, say ± 15 percent.

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CIVIL EFFECTS TEST OPERATIONS REPORT SERIES (CEX)

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