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A NEUTRON FLUENCE MAP
FOR THE
ROTATING TARGET NEUTRON SOURCE

ERDA Research and Development Report

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Rockwell International

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ROTATING TARGET NEUTRON SOURCE

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ABSTRACT

Nine nickel, niobium, and gold dosimetry foils incorporated in a neutron irradiation experiment at the Rotating Target Neutron Source (RTNS) facility were analyzed to construct a three-dimensional neutron fluence map. The purpose of the map was to determine the exact neutron fluences received by several pure element specimens irradiated for helium generation studies. However, the map alone provides the most detailed profile yet obtained of the RTNS neutron fluence distribution at the highest flux region accessible for irradiation experiments. This report gives details of the map, and provides a dosimetry procedure for use in future irradiations requiring accurate fluence information. The map also provides precise relative cross sections for the Ni, Nb, and Au dosimetry reactions for 14.8-MeV neutrons. The $^{58}\text{Ni}(n,p)^{58}\text{Co}$ cross section is significantly lower than the current published evaluation.

An analytical expression was derived to describe the measured fluence distribution; this was compared with an existing mathematical model of the RTNS neutron fluence profile. The model was found to represent approximately the fluence profile for a range of source parameters, but it cannot be used for an accurate determination of the fluence variation in a given irradiation experiment.

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I. INTRODUCTION

One of the key technological problems to be overcome before the feasibility of a controlled thermonuclear reactor (CTR) can be demonstrated for commercial power production is the damage of CTR materials induced by high energy plasma-produced neutrons. Investigation of this problem requires a high intensity ($\geq 10^{14}$ neutrons/cm²-s), high energy (14-15 MeV, assuming a D-T fusion reaction) neutron source. Since a plasma-based neutron source with this energy will not be available in the near future, such studies must be made with neutrons generated by other means. Neutron environments presently available for CTR studies include, for example, the D-T Rotating Target Neutron Source (RTNS) at the Lawrence Livermore Laboratory (LLL),⁽¹⁾ the neutron spectra generated by the D-Be reaction at cyclotron facilities such as those at the Crocker Nuclear Laboratory (University of California, Davis)⁽²⁾ and the ORIC at Oak Ridge National Laboratory,⁽³⁾ and spallation-evaporation neutrons from the 800-MeV proton beam stop at the Los Alamos Meson Physics Facility.⁽⁴⁾ The Experimental Breeder Reactor-II (EBR-II) and other fission reactor environments (HFIR, ORR) are also being used. A number of other neutron sources appropriate for CTR studies are in the design stage.⁽⁵⁾

Effective use of these neutron facilities for materials studies requires a knowledge of the neutron energy and fluence distributions in the volume occupied by the irradiated samples. The RTNS has been the object of only a few neutron profile studies. Goldberg, Griffith, and Logan⁽⁶⁾ constructed a simple mathematical model to represent the RTNS neutron fluence at a given position as a function of neutron source spot size, axial distance from the source, and radial distance from the source axis. Peak neutron flux values were shown to be strong functions of the source spot size and the distance from the source. They compared this model with experimental results from zirconium and sulfur disc irradiations to infer source spot diameters and minimum spacings from the source.

A neutron energy distribution measurement was made by Heinrich,⁽⁷⁾ who irradiated a 5.1-cm square gold dosimetry foil and cut it into 25 equal sections. The measured ratio of the $^{197}\text{Au}(n,2n)^{196}\text{Au}$ and $^{197}\text{Au}(n,\gamma)^{198}\text{Au}$ reactions for

each section provided information on the low energy neutron contribution to the spectrum. Van Konynenburg also measured the radial variation of the neutron fluence (relative to the source spot axis), by irradiating and subsequently segmenting and analyzing a niobium dosimetry foil.⁽⁸⁾ Such information does not characterize the neutron profiles for all experiments, however, because of variations in source parameters resulting, for example, from changes in the deuteron beam tuning. Nevertheless, it provides a valuable guide for the design and analysis of irradiation experiments in which the total fluence and the uniformity of neutron parameters are important.

As one phase of an Atomics International (AI) research investigation to determine the helium generation rates and spectrum-integrated (n,α) cross sections of a number of pure elements for typical CTR high energy neutron spectra,⁽⁹⁾ a group of samples of twelve pure elements was irradiated at the RTNS in May 1975. The need to know the neutron fluence variation precisely over the volume occupied by these samples led to the design of detailed dosimetry procedures for this experiment. Analysis of the dosimetry information provides the most detailed study yet undertaken of the innermost fluence variation of the RTNS neutron field. This report describes the results of a joint effort between AI, LLL, and Argonne National Laboratory (ANL) to carry out the irradiation and the dosimetry analysis. While the fluence profiles reported here are also not universal, they do provide a check of a more approximate model,^(6,10,11) and they give an estimate of what can be expected in irradiations performed under similar conditions. The results are also valuable for establishing procedures to study the neutron profiles of other less well characterized high-energy neutron sources, and provide input for the design of future sources.

II. EXPERIMENTAL DESCRIPTION

The irradiation assembly used in this experiment is shown in Figure 1. Multiple specimens of ten pure elements (C, Al, Ti, V, Fe, Ni, Cu, Zr, Nb, and Mo), plus specimens of Type 316 stainless steel, were sandwiched between two stacks of foils. The foils included two additional pure element specimens (Au and Pt) and three sets of dosimetry foils. These materials were packaged in a 2.54-cm square, 1.6-mm thick stainless steel plate with concentric holes milled out of the center to hold the various components and provide alignment of the foils. Single 0.13-mm thick Type 316 stainless steel sheets were spot-welded to the front and back to hold the package together, resulting in a total package thickness of 1.9 mm.

The specimens sandwiched between the foil stacks were included for the measurement of helium generation cross sections. Additionally, the Au and Pt foil specimens will be analyzed as possible encapsulating materials for future irradiations of pure elements and compounds. The Al, Cu, and Fe wires (0.58-mm, 0.76-mm, and 0.51-mm diameters, respectively) held the other specimens and foils in place. These wires will be used to augment the fluence profile determinations from the dosimetry foils, by segmenting them and measuring the helium generated in the individual pieces. The Al wires are of particular interest, because the $^{27}\text{Al}(n, \alpha)^{24}\text{Na}$ reaction is an important standard for 14-MeV neutron dosimetry, normally analyzed by radiometrically counting the ^{24}Na reaction product. For long irradiations such as this experiment, the 15-h ^{24}Na half-life is too short to provide an accurate determination of the total neutron fluence, because of time variations of the flux. The analysis of helium generation in the aluminum samples can extend the usefulness of this standard, although it is anticipated that a significant (and measurable) contribution to the helium will come from the $^{27}\text{Al}(n, n\alpha)^{23}\text{Na}$ reaction.

The radiometric dosimetry foils, the analysis of which this report describes, consisted of three sets of Au, Nb, and Ni foils prepared from material supplied by the Dosimetry and Damage Analysis Center (DADAC) at ANL. Two sets of thin foils (to be designated "front" and "middle," respectively) sandwiched the helium specimens, and a third set of thicker foils (designated "back") was

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Figure 1. Helium-Generation Assembly Irradiated at the RTNS

located behind the sandwich. The back set, which also included Fe and Pt foils, was intended principally for helium generation measurements, but the Au, Nb, and Ni foils were nevertheless first analyzed radiometrically.

The gold foils, providing dosimetry information through the $^{197}\text{Au}(n,2n)^{196}\text{Au}$ reaction, furnished the bulk of the fluence profile information, because their high induced activities allowed them to be segmented into smaller pieces for individual counting. This procedure provided the information used to map the neutron fluence profile as a function of distance from the neutron source axis. The niobium dosimetry foils were included to provide a normalization of the gold results. The nickel foils were included to determine the average energy of the neutrons, by comparing the energy-sensitive ratio of the $^{58}\text{Ni}(n,p)^{58}\text{Co}$ and $^{58}\text{Ni}(n,2n)^{57}\text{Ni}$ cross sections with the activity ratio of their reaction products.

The assembled package was attached to the RTNS marker plate, immediately behind the target's water catch cage, and was irradiated for 77.55 h within the period May 19-24, 1975. This experiment was run in tandem with an ANL irradiation experiment of M. Kaminsky, whose apparatus was located immediately behind the AI package. After a three-day post-irradiation waiting period to allow for the decay of high-level, short-lived activities in the source region, the package was disassembled. The nine dosimetry foils were then segmented along pre-scribed lines. The geometries of the segmented foils are shown in Figures 2 and 3. In these diagrams the 0^0 neutrons are directed into the paper. The Ni and Au foil segments were immediately shipped to ANL for radiometric counting and weighing. The Nb segments were counted at LLL and then shipped to ANL for further counting and weighing. All of the foils were subsequently shipped to AI, where they were reweighed, using a substitution weighing scheme and standard weights traceable to the U.S. National Bureau of Standards, and stored for later helium analysis.

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Figure 2. Orientation and Geometry of the Gold Dosimetry Foil Segments

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FRONT (UPSTREAM) NIOBIUM
FOIL SANDWICHING HELIUM
GENERATION SPECIMENS

FRONT (UPSTREAM) NICKEL
FOIL SANDWICHING HELIUM
GENERATION SPECIMENS

MIDDLE NIOBIUM
FOIL SANDWICHING HELIUM
GENERATION SPECIMENS

MIDDLE NICKEL
FOIL SANDWICHING HELIUM
GENERATION SPECIMENS

BACK, THICKER NIOBIUM
FOIL MOUNTED BEHIND SANDWICH

BACK, THICKER NICKEL
FOIL MOUNTED BEHIND SANDWICH

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Figure 3. Orientation and Geometry of the Niobium and
Nickel Dosimetry Foil Segments

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III. DOSIMETRY FOIL FLUENCES

The neutron fluences averaged over the areas intercepted by the individual foil segments were calculated from the measured foil weights, foil activities, and irradiation history by an analysis procedure similar to that previously documented.⁽¹⁰⁾ The irradiation history was obtained from the output of two proton recoil counters used as monitors during the experimental irradiation at LLL. Two of the nuclear parameters used in the calculations, the residual nuclei half-lives and the reaction cross sections, are listed in Table 1. The fluences calculated for the 62 dosimetry foil segments are listed with their 1σ relative uncertainties in Tables 2 and 3. To insure maximum internal consistency for the relative fluence values, only the ANL counting results were used in the calculation of the niobium fluences listed in Table 3. The fluences determined from the LLL niobium counting data agreed with these results to within an average of 1%.

The cross sections for the $^{58}\text{Ni}(n,p)^{58}\text{Co}$ and $^{58}\text{Ni}(n,2n)^{57}\text{Ni}$ reactions vary rapidly with neutron energy in the 14- to 15-MeV region.⁽¹²⁾ Since the $(n,2n)$ cross section increases and the (n,p) cross section decreases with increasing energy, the ratio of the disintegration rates of the reaction products also varies rapidly with neutron energy. Comparison of the measured activity ratio from the two reactions for each foil segment with the ratio of the published cross sections⁽¹²⁾ then gives, after appropriate decay corrections, the average neutron energy for that segment. Once the average energy is established, the fluence averaged over each foil segment is calculated using the cross sections corresponding to that energy. Only one value of the fluence is obtained from the two reactions, of course, since the calculation requires the assumption of common fluence values.

The average neutron energies and fluences calculated using this procedure are included in Table 3. The tabulated energy values omit the uncertainties in the evaluated cross sections (derived from data with relatively large uncertainties; see Section IV.D), and hence must not be used in an absolute sense to the accuracy shown. Relative accuracies, and therefore relative energy variations from segment to segment, however, are much less dependent on these cross

TABLE 1

NUCLEAR PARAMETERS FOR THE NEUTRON FLUENCE CALCULATIONS

Reaction	Half-Life	Cross Section
$^{197}\text{Au}(n,2n)^{196}\text{Au}$	6.183 d	2110 mb
$^{93}\text{Nb}(n,2n)^{92\text{m}}\text{Nb}$	10.16 d	458 mb
$^{58}\text{Ni}(n,p)^{58}\text{Co}$	71.23 d	329.4 to 316.0 mb*
$^{58}\text{Ni}(n,2n)^{57}\text{Ni}$	1.50 d	35.0 to 37.5 mb*

*Energy-dependent values, interpolated from the ENDF/B-IV dosimetry file (Ref. 12)

TABLE 2

FLUENCES OBTAINED FROM THE GOLD FOIL SEGMENTS

Foil Location	Segment Number	Fluence ($\text{n}/\text{cm}^2 \times 10^{-17}$)	Foil Location	Segment Number	Fluence ($\text{n}/\text{cm}^2 \times 10^{-17}$)
Front	G-20	2.568 ± 0.024	Middle	G-1	1.968 ± 0.019
	G-21	2.517 ± 0.027		G-2	1.969 ± 0.020
	G-22	2.505 ± 0.026		G-3	2.039 ± 0.014
	G-23	2.406 ± 0.025		G-4	2.053 ± 0.020
	G-24	2.454 ± 0.024		G-5	1.683 ± 0.014
	G-25	2.413 ± 0.032		G-6	1.831 ± 0.017
	G-26	2.242 ± 0.020		G-7	1.818 ± 0.016
	G-27	2.068 ± 0.018		G-8	1.789 ± 0.016
	G-28	2.328 ± 0.020		G-9	1.362 ± 0.014
	G-29	2.151 ± 0.028		G-10	1.360 ± 0.012
	G-30	2.033 ± 0.019		G-11	1.577 ± 0.013
	G-31	1.846 ± 0.025		G-12	1.476 ± 0.019
	G-32	1.866 ± 0.019	Back	G-40	1.731 ± 0.011
	G-33	1.742 ± 0.015		G-41	1.572 ± 0.010
	G-34	1.629 ± 0.015		G-42	1.624 ± 0.011
	G-35	1.420 ± 0.015		G-43	1.764 ± 0.011
	G-36	1.793 ± 0.015		G-44	1.730 ± 0.010

TABLE 3

FLUENCES OBTAINED FROM THE NIOBIUM AND NICKEL FOIL SEGMENTS

Niobium			Nickel			
Foil Location	Segment Number	Fluence ($\text{n/cm}^2 \times 10^{-17}$)	Foil Location	Segment Number	Fluence ($\text{n/cm}^2 \times 10^{-17}$)	Neutron Energy (MeV)*
Front	Nb-10	2.472 ± 0.018	Front	Ni-10	2.266 ± 0.013	14.92 ± 0.02
	Nb-11	1.764 ± 0.013		Ni-11	1.662 ± 0.014	14.88 ± 0.03
	Nb-12	1.834 ± 0.013		Ni-12	1.627 ± 0.014	14.85 ± 0.03
	Nb-13	2.136 ± 0.015		Ni-13	1.952 ± 0.011	14.86 ± 0.02
	Nb-14	1.988 ± 0.014		Ni-14	1.840 ± 0.014	14.79 ± 0.03
Middle	Nb-2	1.429 ± 0.010	Middle	Ni-4	1.820 ± 0.015	14.96 ± 0.03
	Nb-3	1.404 ± 0.010		Ni-5	1.318 ± 0.012	14.91 ± 0.03
	Nb-4	1.654 ± 0.012		Ni-6	1.389 ± 0.012	14.89 ± 0.03
	Nb-5	1.555 ± 0.011		Ni-7	1.567 ± 0.013	14.91 ± 0.03
	Nb-6	1.950 ± 0.014		Ni-8	1.442 ± 0.013	14.89 ± 0.03
Back	Nb-21	1.519 ± 0.010	Back	Ni-21	1.624 ± 0.012	14.98 ± 0.03
	Nb-22	1.485 ± 0.010		Ni-22	1.652 ± 0.010	14.96 ± 0.02
	Nb-23	1.617 ± 0.011		Ni-23	1.768 ± 0.008	14.96 ± 0.02
	Nb-24	1.593 ± 0.011		Ni-24	1.716 ± 0.008	15.00 ± 0.02

*Neglecting ENDF/B-IV cross section uncertainties for the $^{58}\text{Ni}(n,2n)$ and $^{58}\text{Ni}(n,p)$ reactions.

section uncertainties. Examination of the $^{93}\text{Nb}(n,2n)^{92\text{m}}\text{Nb}$ and $^{197}\text{Au}(n,2n)^{196}\text{Au}$ literature cross sections in this energy region^(13,14) shows a relatively flat energy dependence, and the data scatter was such that constant cross section values have been adopted.⁽¹⁵⁾ The cross section uncertainties were omitted from the fluence calculations for the purpose of mapping the profile. The estimated uncertainty in the $^{93}\text{Nb}(n,2n)^{92\text{m}}\text{Nb}$ cross section is $\pm 5\%$, which is the primary contribution to the $\pm 6\%$ absolute uncertainties of the final Nb fluence results.

The fluence results given in Tables 2 and 3 have not been adjusted for neutron attenuation due to upstream foils and samples, since this is inappropriate for the calculation of neutron fluences for the helium generation specimens. In Section IV, however, neutron attenuation corrections are made for the fluence map constructed to describe the neutron fluence profile for "free-space."

Close examination of the fluence results in Tables 2 and 3 shows a consistent nonsymmetrical distribution about the centers of the foils, indicating that the time-averaged incident neutron field was not exactly centered on the helium generation package. This package offset was the first information to be determined in constructing the fluence map.

Comparison of the fluences for successive foils in each of the three dosimetry sets shows some inconsistency, indicating a discrepancy in the cross sections adopted in Table 1 for the dosimetry reactions. This will be examined in Section IV.D, where it will be shown that comparison of the fluence results for the different dosimetry foils provides significantly more precise relative cross section information than can be extracted from the published cross section tabulations.⁽¹²⁾

IV. NEUTRON FLUENCE MAP

A. IRRADIATION ASSEMBLY OFFSET

The first information calculated from the segmented dosimetry foils was the offset of the irradiation assembly relative to the 0^0 neutron source axis. The offset is small, but is important to know in order to map the neutron fluence variation precisely over the two gold foils that sandwiched the helium generation specimens in the capsule. Two techniques were employed to determine the assembly (and dosimetry foil) offset: measurement of the density variation across autoradiograph negatives, and mathematical quadratic surface fits to the average fluences calculated for the front and middle gold dosimetry foil segments.

The autoradiographs, made of the assembly three days after the end of the irradiation, were analyzed by scanning with a recording microphotometer. This produced logarithmic plots of the radioactivity density variations across the negatives of the stainless steel capsule back after the samples had been removed. The backing had a 6-mm diameter hole through its center, requiring interpolation to deduce the beam axis, but also providing a convenient means of determining the center of the capsule. A density (and hence fluence) profile could not be readily obtained without unwarranted extensive line-shape fitting, due to a large density fall-off near the foil edges. The fall-off is associated with the isotropic emission of radiation from the backing, producing a contribution to the negative beyond the foil edges and a missing contribution before the edges. The assembly offset was determined by interpolation using straight-line approximations to the logarithmically-plotted profiles on both sides of the central hole.

The mathematical quadratic surface fits were generated by assuming a fluence variation over the surface of each gold foil of the form:

$$\begin{aligned}\Phi(x,y) &= (ax^2 + bx + c)(dy^2 + ey + f) \\ &= b_1x^2y^2 + b_2xy^2 + b_3y^2 + b_4x^2y + b_5xy + b_6y + b_7x^2 + b_8x + b_9 \quad \dots(1)\end{aligned}$$

and integrating over each foil segment to equate with the product of the measured average fluence ($\bar{\Phi}$) times the segment area (A):

$$\bar{\Phi} = \frac{\int \Phi dA}{\int dA} \quad \dots(2)$$

or

$$\begin{aligned}\bar{\Phi} \cdot A &= \iint \Phi(x,y) dx dy \\ &= b_1 \iint x^2 y^2 dx dy + b_2 \iint xy^2 dx dy + \dots + b_9 \iint dx dy. \quad \dots(3)\end{aligned}$$

A computer code (listed in the Appendix) was written to evaluate the integrals numerically for each foil segment, construct a set of nine simultaneous equations (in matrix form) for each set of nine foil segments to be used, and solve the simultaneous equations to evaluate the nine constants. A quadratic fit was chosen because a linear fit does not reproduce the fluence variation, and orders higher than quadratic generally involve more unknown constants than there are segments in each foil. The position of the beam axis relative to the foils was then calculated from each fit by setting

$$\frac{\partial \Phi}{\partial x} = \frac{\partial \Phi}{\partial y} = 0. \quad \dots(4)$$

Several fits were made with different combinations of segments for each foil. As expected, the fits were not entirely consistent, indicating that the form chosen for $\Phi(x,y)$ did not exactly represent the fluence variation. Those fits that best reproduced the fluence variations near the centers of the gold foils were used to estimate the dosimetry foil offset.

The offset determined from the quadratic fits is $X_0 = -0.07$ mm and $Y_0 = +0.62$ mm, relative to the 0° neutron source axis. X_0 is the horizontal offset, measured positively to the right as viewed from the RTNS side of the

foils, and Y_0 is the vertical offset, measured positively toward the zenith. There was a large spread in values between different sets of front and middle gold foil segments.

The autoradiograph results gave a dosimetry foil (and assembly) offset of $X_0 = -0.08 \pm 0.09$ mm and $Y_0 = +0.57 \pm 0.07$ mm. A straight average of the quadratic fit and autoradiograph results, which (perhaps fortuitously) were in excellent agreement, yielded an adopted foil offset of $X_0 = -0.08$ mm and $Y_0 = +0.59$ mm. The estimated uncertainty in the adopted values is ± 0.08 mm.

B. RADIAL NEUTRON FLUENCE PROFILES

After the assembly offset was determined, the neutron fluence profiles were recalculated for the front and middle gold dosimetry foils, by assuming a symmetrical distribution of neutrons about the beam axis, and radial fluence variations of the form:

$$\Phi(R) = C_1 + C_2 R + C_3 R^2 + C_4 R^3, \quad \dots(5)$$

where R is the radial distance (in mm) from the beam axis. The C_i 's were evaluated numerically by computer (see Appendix) using the same technique used for the quadratic fits:

$$\bar{\Phi} \cdot A = \iint \Phi(R) dA \quad \dots(6)$$

for each foil segment, including corrections for the dosimetry foil offset. Fits were then calculated for all possible segment combinations along radial lines for each foil. The nonphysical fits (curves having inflection points within the radial dimensions of the foils yielding rapid fluence variations that did not correspond to the data) were thrown out, and the results were averaged. The evaluated constants are listed in Table 4 both for the fluence values actually realized within the AI assembly, and for their equivalent "free-space" values. The latter values, which were derived from the measured values by applying neutron attenuation correction factors, are those fluences

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Figure 4. Attenuation-Corrected (Free-Space) Radial Cubic Fits to the Front and Middle Gold Dosimetry Foil Data

that would have occurred had there been no assembly material present. The number of decimal places given in Table 4 does not reflect the $\sim 1\%$ accuracy of the fits. These numbers are those used in subsequent calculations to eliminate roundoff errors, particularly at large values of R . The resulting curves, which are plotted in Figure 4, are valid only across the dimensions of the foils (6.35-mm radius). The individual points plotted in Figure 4 are averages of the measured fluences for each annular foil segment, plotted at average radii (area inside = area outside). They can be considered only as approximations of the measured fluences for comparison with the fits, since the radial fluence variation is not linear, and since the averaged values were not corrected for the foil offset.

TABLE 4
EVALUATED CONSTANTS FOR THE RADIAL NEUTRON FLUENCE PROFILES

Constant*	Within AI Assembly		Free Space	
	Front Au	Middle Au	Front Au	Middle Au
C_1	2.58848	2.07920	2.59859	2.11140
C_2	0.01215	0	0.01219	0
C_3	-0.04723	-0.03380	-0.04742	-0.03432
C_4	0.00280	0.00207	0.00281	0.00210

*Multiply by 10^{17} to obtain fluence values [Equation (5)] in units of n/cm^2 .

Evaluation of $\Phi(R)$ for the middle gold foil required an additional assumption. Since there were four unknown constants and three annular foil segments, the fourth constant was evaluated by noting that the fluence must vary smoothly through $R = 0$, or

$$\left. \frac{\partial \Phi(R)}{\partial R} \right|_{R=0} = 0. \quad \dots(7)$$

This was satisfied by setting $C_2 = 0$. This constraint was not placed on the fits to the front gold foil. However, the consistent radial profile shapes for the two foils and the small value of C_2 for the front foil provided a check on the calculations. A quadratic radial fluence profile of the form:

$$\Phi(R) = C_1 + C_2 R + C_3 R^2 \quad \dots(8)$$

was also fit to the middle gold foil data. This curve, which was not used further, agreed with the cubic fit for all but the $R \approx 0$ region of the foil, where it did not approach the Equation (7) criterion.

The free-space neutron fluence profiles were derived from the fits to the measured fluences, by dividing the constants for each foil by the average neutron transmission through the upstream assembly material. The transmission T through each component was calculated from $T = \exp(-n\sigma x)$, where n is the atomic density of the material, x is its thickness, and σ its total neutron cross section.⁽¹⁶⁾ An average transmission of 98.9% was used for the helium specimen region between the front and middle gold foils. This was calculated by weighting the transmission through each specimen by the middle gold foil area it shadowed. The validity of using an average value was verified by calculating the neutron attenuation for each individual middle gold foil segment from those helium specimens in front of it. The middle foil radial cubic fit calculated for the attenuation-corrected segments agreed with that derived from the average attenuation correction to within 1% over the dimensions of the foil. The average neutron transmission through the entire AI capsule was 96.4%.

The profile calculations were further extended to find a single expression that describes the radial fluence profiles for both gold foils, as well as the results for the nickel and niobium dosimetry foils. The following form, which includes a dependence upon the axial foil distance (Z) from the RTNS neutron source spot, was found to reproduce the measured fluences within about 2%:

$$\Phi(R, \Delta Z) = \alpha [C_1 + C_2 (\beta R) + C_3 (\beta R)^2 + C_4 (\beta R)^3]. \quad \dots(9)$$

The variable ΔZ is the axial distance (in mm) from the front face of the AI assembly, measured positively in the deuteron beam direction. The C_i 's are the values evaluated for the front Au foil (Table 4), α is the normalization of the whole radial profile as a function of ΔZ (discussed in Section IV.C), and β is a correction factor to the radial shape of the fluence curve, reflecting the decreasing solid angle (for given R) with increasing Z. The value of β , given by the following expression:

$$\beta = \frac{14.30797}{14.12382 + \Delta Z}, \quad \dots(10)$$

was found by comparing the front and middle Au foil values of C_3 , and applies to both the actual and free space fluences. The expression reduces to $\Phi(R)$, defined by Equation (8), for the front Au foil. The free-space profile for the middle gold foil is plotted as a dashed line in Figure 4 (with $\alpha = 0.94388$). It agrees with the middle gold foil cubic fit to within 1% over the dimensions of the foil.

C. AXIAL NEUTRON FLUENCE PROFILE

The axial neutron fluence profile was determined by first noting that $\Phi(R, \Delta Z)$, defined by Equation (9), is a good representation of the radial profiles for all ΔZ within the irradiation capsule. This is substantiated by the consistency in the profile shape from front to middle Au foils, and the wide spacing between these foils in the capsule. This expression was then used to calculate axial fluence values $[\Phi(0, \Delta Z)]$ for all nine radiometric dosimetry foils, assuming a linear ΔZ dependence for α , which further analysis showed to best represent the data. The axial fluence results were normalized to the measured average fluences, to eliminate their dependence on α , by comparing the products of the measured fluences multiplied by the associated segment areas with the integrals of the fluence expression:

$$\sum_i \bar{\Phi}_i \cdot A_i = \int_0^{2\pi} \int_0^r K \Phi(R, \Delta Z) R dR d\theta. \quad \dots(11)$$

Figure 5. Attenuation-Corrected Axial Neutron Fluence Profile

The constant K is the normalization factor. The dosimetry foil offset was ignored in these calculations, as the integral extended over 2π , and the match between averaged data points and the radial profile (Figure 4) suggests that the offset effect is negligible. The term α was then reevaluated to best fit these data for the neutron fluence within the capsule:

$$\alpha = 1.04379 - 0.23781 \Delta Z \quad \dots(12)$$

and for the attenuation-corrected free-space profiles:

$$\alpha = 1.04236 - 0.23002 \Delta Z \quad \dots(13)$$

The results are plotted in Figure 5, where the solid line represents the axial curve $\Phi(0, \Delta Z)$. The data points are the integral-normalized [Equation (11)] axial fluences for the nine foils. Since they are independent of α , and since β is relatively insensitive to ΔZ over the extent of the capsule, they provide a measurement of the Z-dependence of the neutron fluence. The multiple points for each of several foils correspond to integrals from the foil origin to different segment outside radii.

Two discrepancies may be noted in Figure 5. First, the back gold foil data are low with respect to the other Au and Nb data, suggesting that this foil could have been interchanged with another back foil when the capsule was assembled. (The fact that the other gold foils could not have been misloaded was verified by macrophotographs of the assembly.) This can be examined later by helium analysis of the back Au, Pt, and Fe foils. Second, the data for the nickel foils are consistently low. This discrepancy will be discussed in Section IV.E.

The choice of a linear axial fluence dependence was made on the basis of using the simplest mathematical form that accurately represents the measured fluence variation. The good fit is attributed to the finite and variable neutron source spot size (~1-cm diameter), and the close capsule proximity to the D-T target (estimated from the experimental geometry to be 3 to 4 mm). A

$1/Z^2$ α -dependence, which was not expected to fit well due to this close geometry, and a $1/Z$ α -dependence were also examined for comparison.

The value of α was calculated to be $[7.5139/(7.3298 + \Delta Z)]^2$ for the $1/Z^2$ -dependence, and $3.6868/(3.5026 + \Delta Z)$ for the $1/Z$ -dependence. These values were calculated from the front and middle gold foil axial fluences. The bottom constant in each case represents an effective source distance (in mm). The resulting $1/Z^2$ axial fluence profile is plotted as a dotted line in Figure 5, and the $1/Z$ curve has a similar shape. Neither curve matches the measured data well. Normalization to the larger-Z axial fluence value determined for the back niobium foil produced similar curves.

D. CALCULATED AVERAGE NEUTRON ENERGIES

The 0° RTNS neutron energy was 15.0 MeV, as determined from reaction kinematics⁽¹⁷⁾ for 400-keV deuteron bombardment of the thick tritium-titanium RTNS target. However, most of the neutrons hitting the irradiation capsule were from non- 0° laboratory neutron angles, therefore having lower neutron energies. This is a result of the close proximity of the capsule to the large-diameter neutron source spot. For example, the axial point on the front nickel dosimetry foil intercepted neutrons with 0° to 54° laboratory angles and a corresponding energy range of 15.0 to 14.6 MeV. Average neutron energies were thus determined by folding the experimental irradiation geometry into the reaction kinematics.

The average neutron energy was calculated at each of four foil positions by performing a coarse numerical integration over the extent of the source spot. The relative source area and solid angle factors were folded into the energy contribution from each segment of the target spot. The target spot was assumed to be 10 mm in diameter, and the capsule front face was assumed to be 3.5 mm from the target. No corrections were made for the nonuniform deuteron beam profile or for the more precise evaluations of the stopping cross section parameters that have been made since the reaction kinematics⁽¹⁷⁾ were calculated.

The neutron energies were determined to be 14.81, 14.84, and 14.86 MeV at the axial locations of the front nickel, middle nickel, and back niobium foils, respectively, neglecting uncertainties in the assumed parameters. The increase in value is due to the decreasing source solid angle at greater source distances. The average neutron energy at the edge of the front nickel foil was calculated to be 14.69 MeV. This gives an energy variation of 0.12 MeV across the front nickel foil, which is consistent with the experimentally-determined average energy variation between the front nickel foil segments (Section III).

E. DOSIMETER CROSS SECTION COMPARISON

Two conclusions can be drawn from a comparison of neutron fluence values derived from the Au, Nb, and Ni dosimetry foils, as shown in Figure 5:

- 1) The adopted $^{197}\text{Au}(n,2n)$ and $^{93}\text{Nb}(n,2n)$ reaction cross sections (Table 1) gave consistent dosimetry results within the $\sim 2\%$ experimental accuracies.
- 2) There is a discrepancy in the adopted $^{58}\text{Ni}(n,2n)$ and $^{58}\text{Ni}(n,p)$ cross sections relative to those for the $^{197}\text{Au}(n,2n)$ and $^{93}\text{Nb}(n,2n)$ reactions. The dashed line in Figure 5 is the curve $\Phi(0, \Delta Z)$ multiplied by the constant factor 0.931 (± 0.020 uncertainty, not shown) to match the measured nickel dosimetry foil fluence results. This offset shows that the two nickel cross sections (Table 1) must be lowered ($7.4 \pm 2.3\%$) to agree with the dosimetry results for the Au and Nb foils. A discrepancy of this magnitude is not unexpected, considering the large uncertainties in the tabulations of the individually-measured cross sections: $\pm 5\%$ for $^{93}\text{Nb}(n,2n)$ ⁽¹³⁾ and $^{197}\text{Au}(n,2n)$ ⁽¹⁵⁾ $\sim \pm 10\%$ for $^{58}\text{Ni}(n,2n)$ ⁽¹²⁾ and $\sim \pm 50\%$ for $^{58}\text{Ni}(n,p)$ ⁽¹²⁾

These comparisons provided sufficient information to determine the relative cross sections for the four dosimetry reactions at the 14.8-MeV average axial neutron energy. The relative $^{197}\text{Au}(n,2n)/^{196}\text{Au}$ and $^{93}\text{Nb}(n,2n)/^{92m}\text{Nb}$ cross sections were obtained by comparing the axial neutron fluences directly. The

$^{58}\text{Ni}(n,p)^{58}\text{Co}$ and $^{58}\text{Ni}(n,2n)^{57}\text{Ni}$ cross sections required further analysis, as they are strongly energy-dependent over the experimental geometry. Both cross sections were obtainable from the data, since equating the fluences derived from the two reactions to determine the neutron energy variations, as discussed in Section III, gave the cross section ratio.

The nickel cross sections were evaluated by determining the experimental neutron energy (from the nickel foils) at 0^0 , finding the associated cross sections from Reference 12, and multiplying these values by the nickel offset normalization factor (0.931 ± 0.020) obtained from the axial fluence comparison shown in Figure 5. There are two important considerations that introduce uncertainties in this analysis. First, since the axial data points are derived from normalized integrals over the data, they are dependent upon the variation of the cross section with the neutron energy over the face of each foil. The maximum variations in the cross section and disintegration rate ratio were 4.2% and 11.9%, respectively. However, these variations are much larger than the uncertainties in the data points. This arises because the relative slopes of curves drawn through the different sets of available cross section data⁽¹²⁾ are very similar, even though the data show considerable variation in absolute value. The scatter in the present axial fluence data (Figure 5), calculated over different energy spans, includes the errors that would be generated by using incorrect slopes for the cross section curves.

The second consideration is the determination of the experimental axial neutron energy. This is the 0^0 extrapolation of the average neutron energies listed in Table 3, as determined from the disintegration rate ratios for the two nickel reactions. This value is needed because it corresponds to those tabulated nickel cross sections that must be normalized to give the correct relative dosimetry cross sections. It does not necessarily agree with the 14.8-MeV average axial energy determined directly from reaction kinematics (Section IV.D), because of the cross section discrepancy indicated by Figure 5. The average neutron energies listed in Table 3 give insufficient information to calculate the 0^0 neutron energy, but do provide a lower limit. An upper

limit was calculated by assuming the RTNS was a point source 3.5 mm from the capsule face, and by using reaction kinematics⁽¹⁷⁾ to calculate the 0^0 neutron energies consistent with the measured foil segment neutron energies at average segment laboratory angles. This analysis gave an estimated axial neutron energy of 15.0 ± 0.1 MeV. The two tabulated nickel cross sections corresponding to this energy are those which were corrected for the fluence offset in Figure 5.

The nickel cross sections calculated from this information are given in Table 5, Column 3, normalized to the 458-mb $^{93}\text{Nb}(n,2n)^{92\text{m}}\text{Nb}$ cross section. The quoted uncertainties are relative values, omitting the 5% niobium cross section uncertainty.

Table 5 also includes a comparison with a recent unpublished set of cross sections made by Nethaway⁽¹⁸⁾ at 15.0 MeV. For this comparison, the present results (Column 3) were adjusted to 15.0 MeV, by assuming constant $^{93}\text{Nb}(n,2n)^{92\text{m}}\text{Nb}$ and $^{197}\text{Au}(n,2n)^{196}\text{Au}$ cross sections in this energy region, and by using the energy dependences given by the ENDF/B-IV evaluations⁽¹²⁾ for the $^{58}\text{Ni}(n,p)^{58}\text{Co}$ and $^{58}\text{Ni}(n,2n)^{57}\text{Ni}$ cross sections. These energy-adjusted values were then renormalized to Nethaway's new $^{93}\text{Nb}(n,2n)^{92\text{m}}\text{Nb}$ cross section measurement.⁽¹⁸⁾ Table 5 shows that both the $^{197}\text{Au}(n,2n)^{196}\text{Au}$ and $^{58}\text{Ni}(n,p)^{58}\text{Co}$ cross sections are consistent with Nethaway's results. If Nethaway's revised $^{93}\text{Nb}(n,2n)^{92\text{m}}\text{Nb}$ cross section were used in this work, the map fluence values given in this report would be lowered by 2.3%.

TABLE 5
NEUTRON CROSS SECTIONS OF ^{58}Ni , ^{93}Nb , AND ^{197}Au AT 14.8 AND 15.0 MeV

Reaction	Cross Sections (mb) and 1σ Relative Uncertainties			
	14.8 MeV		15.0 MeV	
	Literature Values	This Work Normalized to Nb (Ref. 13)	Unpublished Data (Ref. 18)	This Work Adjusted to 15 MeV*
$^{58}\text{Ni}(n,p)^{58}\text{Co}$	329 (Ref. 12)	294 ± 8	283	289 ± 8
$^{58}\text{Ni}(n,2n)^{57}\text{Ni}$	35.1 (Ref. 12)	34.9 ± 1.3	--	38.2 ± 1.4
$^{197}\text{Au}(n,2n)^{196}\text{Au}$	2110 (Ref. 14,15)	2110 ± 40	2150	2160 ± 40
$^{93}\text{Nb}(n,2n)^{92m}\text{Nb}$	458 (Ref. 13)	$458^{\dagger}$	469	$469^{\dagger}$

*See text.

† The results of this work (Columns 3 and 5) are normalized to the Nb cross section values in References 13 and 18 (Columns 2 and 4), respectively.

V. COMPARISON WITH A MATHEMATICAL FLUENCE MODEL

The fluence map for the present irradiation was compared with an LLL-derived mathematical model^(6,10) of the RTNS flux. The purpose of the comparison was to evaluate the accuracy, and hence usefulness, of the mathematical model for describing a given irradiation experiment. The radial profiles were of particular interest, because no such detailed comparisons have been made previously between experimental measurements and the model.

The neutron flux at a given point P is expressed by the LLL model as:^(6,10)

$$\phi = \frac{Y}{4\pi w^2} \ln \left[\frac{\sqrt{(w^2 + Z^2 - R^2)^2 + 4Z^2 R^2} + (w^2 + Z^2 - R^2)}{2Z^2} \right]. \quad \dots(14)$$

Here Y is the total neutron emission rate over the entire 4π solid angle in neutrons/sec, and w is the radius of the target spot, assumed to be a uniform, isotropically-emitting circular disc of zero thickness. The variable Z is the axial distance from the source spot to point P; and R is the radial distance of point P from the source axis. To compare this model with the present fluence calculations, Y was interpreted to be the total neutron emission integrated over the period of the irradiation, and w was assumed to remain constant during the irradiation. The flux ϕ then becomes the total fluence Φ (neutrons/cm²). All dimensions are in cm.

The LLL model was compared to the experimental fluence map described in this report [Equation (9)] by setting Equation (14) equal to the measured fluences at three representative points, solving the simultaneous equations for the three parameters Y, w, and Z, and generating fluence profiles to compare with the $\Phi(R, \Delta Z)$ fits. Three cases were considered:

- 1) Three points on the front gold foil, at R = 0, 2, and 4 mm, were used to evaluate the parameters. The calculated values of the three parameters were then: Y = 1.216×10^{18} neutrons, w = 0.5064 cm, and Z₀ = 0.4904 cm (4.9 mm), where Z₀ represents the axial distance from

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Figure 6. Comparison of the Measured Free-Space Gold Radial Fluence Profiles with the LLL Mathematical Model

the source spot to the front face of the AI capsule. Figures 6 and 7, respectively, compare the radial and axial profiles (dashed lines), calculated using these parameters, with the corresponding experimental data fits [$\Phi(R, \Delta Z)$ from Equation (9)] which are shown as solid curves. The LLL model profiles agree with the experimental fits to within 2.5% for the two gold radial profiles, and to within 9% over the total extent of the capsule.

- 2) Two points on the front gold foil ($R = 0$ and 3 mm) and the $R = 0$ point on the middle gold foil were used to evaluate the parameters. The results are: $Y = 1.826 \times 10^{18}$ neutrons, $w = 0.3181$ cm, and $Z_0 = 0.6959$ cm (7.0 mm). The corresponding profiles, plotted as dotted lines in Figures 6 and 7, fit the data only to within 20% over the volume occupied by the capsule.
- 3) Three points on the neutron source axis were used for parameter evaluation. No solution was obtained.

The figures show that, for an appropriate choice of source parameters, the LLL model can provide a reasonable representation of the neutron fluence over the volume of interest in this experiment. However, the calculated values of Z_0 are inconsistent with the 2.5- to 4-mm estimated distance of closest approach of an irradiation sample to the source.⁽⁶⁾ For comparison, further calculations were made by setting $Z_0 = 3.5$ mm and calculating w and Y for several pairs of points from the front and middle gold foil fits. The subsequent LLL model fluence curves showed considerable variation and generally did not fit Equation (9) as well as Case 2, above.

These results demonstrate, as expected, that the LLL mathematical model produces fluence profiles that approximately characterize the RTNS source. However, the model is not a satisfactory means of determining the neutron fluence variation accurately. This is attributed in part to the nonuniform deuteron beam profile and to changing source parameters both during and between experiments. It is further complicated by the difficulty of measuring these

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Figure 7. Comparison of the Measured Free-Space Axial Fluence Profile with the LLL Mathematical Model

parameters. A preferable method of characterizing the neutron fluence in these experiments is to use a dosimetry procedure similar to that described in this report.

The present fluence results were also compared qualitatively with Van Konynenburg's coarser RTNS niobium radial profile foil measurements.⁽⁸⁾ The purpose was to get an estimate of the agreement between Van Konynenburg's measurements and the present map. The profiles (Figure 8) were found to agree approximately over dimensions comparable to the AI dosimetry foils. Comparisons cannot be made at larger radii, as the radial equation used to make the fits [Equation (5)] has an inflection point, and thus becomes nonphysical, beyond the dimensions of the foils. The observable differences are explainable by differences in source parameters. A more quantitative comparison would require a more detailed analysis of Van Konynenburg's niobium profile foil.

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Figure 8. Approximate Fluence Comparison between the LLL Niobium Profile Foil and the Present Measurements

VI. SUMMARY

A. NEUTRON FLUENCE MAP

The dosimetry foils in the AI helium generation capsule have been used to map out the RTNS neutron fluence variation over the volume of the capsule (12.7-mm diameter by 1.9-mm thick). The map is represented by the analytical expression given by Equation (9):

$$\Phi(R, \Delta Z) = \alpha [C_1 + C_2(\beta R) + C_3(\beta R)^2 + C_4(\beta R)^3],$$

where R is the radial distance (in mm) from the RTNS source, ΔZ is the axial distance (in mm) inward from the front face of the capsule, and β is given by Equation (10). The C_i 's are the values for the front gold foil and are listed in Table 4. The value of α is given by Equation (12) for the actual fluence distribution within the capsule. For the free-space (attenuation-corrected) fluence distribution over the volume occupied by the capsule, α is given by Equation (13). The latter case is of interest for characterizing the D-T neutron source as an irradiation facility to evaluate candidate CTR materials. The resultant fluence values have an estimated uncertainty of $\pm 2\%$ relative to the measured fluences (including the relative errors of the measurements), and an absolute uncertainty of $\pm 6\%$.

The LLL mathematical model of the RTNS neutron fluence distribution, obtained by integration over the finite area of the source spot, approximately represents the measured profiles. However, it is not satisfactory for irradiation experiments in which an accurate knowledge of the fluence variation is required. The present report provides details of a dosimetry procedure that gives this information.

The detailed mapping of the fluence profile and subsequent comparison of the fluences obtained has provided sufficient information to calculate the relative cross sections of the dosimetry reactions. A new value was determined for the $^{58}\text{Ni}(n,p)^{58}\text{Co}$ cross section at 14.8 MeV that is significantly different

than the published evaluation.⁽¹²⁾ The cross sections will be examined further when the helium in the pure elements has been measured, and helium generation cross section data are available for comparison.

B. DOSIMETRY MAPPING FOR FUTURE IRRADIATIONS

The fluence analysis of the dosimetry foils described in this report has produced a fluence-mapping procedure that can readily be applied to future irradiations. This is particularly useful for cases like the RTNS, where the fluence profiles can vary from irradiation to irradiation. Future analyses will be greatly simplified through the use of the fitting programs given in the Appendix, and the fact that free-space profiles and model comparisons would not be needed for the analysis of irradiated material. Comments on suggested steps to be followed in the procedure are listed in the following sections.

1. Design of the Dosimetry Foil Geometry

The dosimetry foils should yield sufficient irradiation-induced activity that they can later be segmented into small pieces for counting. Segmenting is facilitated by scribing the foils before the irradiation; the use of radially-cut annular segments such as those shown in Figures 2 and 3 simplifies the fluence analysis. The gold foils used in the present work produced adequate activities (for $E_n \cong 14-15$ MeV) and gave results consistent with the niobium reference foils. The foils should sandwich the entire spatial region of interest, and at least three well-spaced foils of the same composition should be used. The foil orientation and centering must be accurately known. The use of other types of foils should be considered as a normalization check and as a monitor for neutron flux levels in other parts of the energy spectrum. Foils producing other neutron-induced activation reactions might also be included for relative cross section comparisons.

2. Neutron Irradiation

Careful attention must be given to the positioning of the irradiation assembly relative to the neutron source. This includes centering the assembly

on the source axis and aligning the plane of the assembly normal to this axis. Centering is readily done by first irradiating a foil with a high neutron-induced activation cross section, such as copper, for a short period, and visually inspecting an autoradiograph made of the foil activity to deduce the neutron source axis. A neutron monitor, such as a proton recoil counter, should be included to provide a time-history of the irradiation.

3. Fluence Determinations

These include the foil segment counting and weighing, the latter requiring careful handling and measurement techniques for the small (1-10 mg) segment sizes. The fluence calculations, including γ -ray self-attenuation and time-history corrections, are well established.⁽¹⁰⁾ The use of dosimetry foils with energy-sensitive cross sections in the region of interest may require neutron energy measurements across the foils, depending on the required accuracy of the measurements. This information can be obtained, for example, by the use of segmented nickel foils.

4. Dosimetry Foil/Irradiation Assembly Offset Determination

The assembly offset must be determined accurately in order to produce an accurate fluence map. The small offset deduced for the present experiment (Section IV.A) gave fluences in the capsule that differed by up to 10% from values calculated had the presence of the offset not been known. Determination of the offset by quadratic fits to the individual foil segments (see Appendix for program) and the subsequent calculation of the point of maximum fluence was the most time-consuming calculation of the present analysis, and was not entirely satisfactory. The analysis of autoradiographs was considerably simpler. Future irradiations should include one or more foils or backings (more to check the perpendicular alignment of a thick assembly) which, unlike the present experiment, are designed for this purpose. While avoiding the interfering center hole, they must still incorporate some feature that provides a well-defined reference point on the autoradiograph negatives. The foil edge is not adequate, at least for a logarithmic density scan, due to the gradual

density fall-off into a nonuniform background. One possibility is to scan across small reference holes drilled in the foil near the outside edge.

5. Integral Radial Fits to the Dosimetry Foil Segment Fluences

The calculation of the radial fluence profiles is straightforward, as described in Section IV.B. The computer program used is listed in the Appendix. The average curves are calculated by simply averaging the C_i 's determined for the individual fits, after discarding those that are clearly nonphysical.

6. Extrapolation of the Radial Fits to a Three-Dimensional Expression

The three-dimensional expression used in the present analysis, Equation (9), was evaluated in two steps. First β , representing the change in the radial fluence profile as a function of source solid angle, was evaluated by comparing C_3 's from fits to different foils. The form chosen for β was somewhat arbitrary, since only two foils produced sufficient information to calculate radial fits. Then α , the normalization of the whole radial profile as a function of the distance within the assembly, ΔZ , was determined by finding the form best representing the axial fluences of the dosimetry foils. This required at least three foils, whose fluences were derived from the generalized radial profile, normalized to the measured average fluences.

The resultant expression $\Phi(R, \Delta Z)$ gives the fluence at any point within the volume encompassed by the dosimetry foils. Fluences for individual samples can then be obtained by integrating analytically (for simple geometrical shapes) or numerically (irregular shapes) over large sample volumes, or by using the center-of-mass values for small samples. The value of R used in these calculations must include the assembly offset from the source axis.

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APPENDIX

The FORTRAN IV programs used to calculate the integral quadratic surface and cubic radial fluence fits to the front and middle gold foil segments are listed below. These programs were run on an IBM 370/168 computer using card input.

RADSF calculates the cubic radial fits for NRUN sets of four foil segments, solving the simultaneous equations

$$\bar{\Phi}_i \cdot A_i = \sum_j \left[C_1 + C_2 R_j + C_3 R_j^2 + C_4 R_j^3 \right] \Delta x \Delta y \quad \dots (A1)$$

in the form

$$\frac{\bar{\Phi}_i \cdot A_i}{\Delta x \Delta y} = C_1 \sum_j 1 + C_2 \sum_j R_j + C_3 \sum_j R_j^2 + C_4 \sum_j R_j^3 \quad \dots (A2)$$

for the constants C_1 , C_2 , C_3 , and C_4 . The terms $\bar{\Phi}_i$ and A_i are the measured fluence and area, respectively, of foil segment i . The term R_j is the distance from the neutron source axis for each area increment $\Delta x \Delta y$, and the summations are over the area of the segment. The program first evaluates the weighted area summations $S(I,K)$ ($K = 1,4$) for all I segments in the front ($NFOIL = 1$) or middle ($NFOIL = 2$) gold foil, where $S(I,1) = \sum_j 1$, $S(I,2) = \sum_j R_j$, etc. This is done by looping through the foil area in increments of $H = \Delta x = \Delta y$ and assigning R_j^0 , R_j^1 , R_j^3 , and R_j^4 calculated at each step to the appropriate foil segment, by comparing the coordinates with the foil geometry in subroutine ASGNF or ASGNB. The list of foil segments to be used in each fit is then read in, a set of simultaneous equations is constructed in matrix form using the appropriate $S(I,K)$'s, and the equations are solved using the mathematical routine DMSEQ. The program listed provides a cubic radial fit for the front gold foil and a quadratic radial fit for the middle gold foil. A cubic fit to the middle foil of the form:

$$\Phi(R) = C_1 + C_2 R^2 + C_3 R^3 \quad \dots (A3)$$

will be generated by replacing the second and third statements following Statement 400 by

$$\begin{aligned} S(I,2) &= S(I,2) + RBEAM**2 \\ S(I,3) &= S(I,3) + RBEAM**3. \end{aligned}$$

The same foil segment areas must be used in the data card input as in the subroutines ASGNF and ASGNB. This was done in the present analysis by assuming that all foil segments in the same annular ring have equal areas and by defining the foil boundaries to be at 90° increments in the subroutines.

QUADSF calculates two-dimensional integral quadratic fits to the measured fluences over the surfaces of the gold foils in a manner identical to RADSF. In this case, the simultaneous equations are of the form:

$$\begin{aligned} \frac{\bar{\Phi}_i \cdot A_i}{\Delta x \Delta y} &= b_1 \left[\sum_j x_j^2 y_j^2 \right] + b_2 \left[\sum_j x_j y_j^2 \right] + b_3 \left[\sum_j y_j^2 \right] + b_4 \left[\sum_j x_j^2 y_j \right] + b_5 \left[\sum_j x_j y_j \right] \\ &+ b_6 \left[\sum_j y_j \right] + b_7 \left[\sum_j x_j^2 \right] + b_8 \left[\sum_j x_j \right] + b_9 \left[\sum_j 1 \right], \end{aligned} \quad \dots (A4)$$

to be solved for the constants b_i . The subscripts of the weighted area sums are reversed in this program. Another version of QUADSF (not listed here) was also written, in which the matrix equations were solved by matrix inversion, using the IBM subroutine MINV, and matrix multiplication. This version gave identical results. The evaluated constants give a fluence map of the form:

$$\Phi = b_1 x^2 y^2 + b_2 x y^2 + b_3 y^2 + b_4 x^2 y + b_5 x y + b_6 y + b_7 x^2 + b_8 x + b_9. \quad \dots (A5)$$

The fluence maximum, and hence the foil offset from the beam axis, can be determined from the condition:

$$\frac{\partial \Phi}{\partial x} = \frac{\partial \Phi}{\partial y} = 0. \quad \dots (A6)$$

This gives (after some algebra) the following two equations:

$$\begin{aligned}
 & (8b_1^2b_7 - 2b_1b_4^2)x^5 \\
 & + (16b_1b_2b_7 + 4b_1^2b_8 - 3b_2b_4^2 - 2b_1b_4b_5)x^4 \\
 & + (16b_1b_3b_7 + 8b_2^2b_7 + 8b_1b_2b_8 - 4b_2b_4b_5 - 4b_3b_4^2)x^3 \\
 & + (2b_1b_5b_6 - b_2b_5^2 - 2b_2b_4b_6 + 16b_2b_3b_7 + 8b_1b_3b_8 + 4b_2^2b_8 - 6b_3b_4b_5)x^2 \\
 & + (2b_1b_6^2 + 8b_3^2b_7 + 8b_2b_3b_8 - 4b_3b_4b_6 - 2b_3b_5^2)x \\
 & + (b_2b_6^2 + 4b_3^2b_8 - 2b_3b_5b_6) \\
 & = 0 \qquad \dots(A7)
 \end{aligned}$$

and

$$y = - \frac{(b_4x^2 + b_5x + b_6)}{2(b_1x^2 + b_2x + b_3)} \dots(A8)$$

These were solved numerically in the present analysis using a programmable hand calculator.

ASGNF and ASGNB are subroutines used to identify foil coordinates with the appropriate foil segments in the front and middle gold foils, respectively. They are applicable only to the foil geometries used in the present analysis, but are listed to show their relation to the main programs. They are of the form ASGNF(I,R,DEG), where I is the foil segment number, R is the radius of the foil coordinates in question, and DEG is the polar angle, in degrees, of the coordinates.

DMSEQ is a Rockwell International Corporation computing library mathematical routine for the solution of linear algebraic equations, determinant evaluation

of a matrix, and matrix inversion. It is written in assembly language and is thus not listed in this report, but similar routines are available in other computer libraries. DMSEQ is used to solve the matrix equation $AX = B$ by including the statement `RET = DMSEQ(J,N,M,A,B,L,DET,SCALE)`. Here, A and B are double precision matrices, J is the maximum number of rows possible in Matrix A, and N is the number of rows. M is the number of columns in Matrix B, L(N) is an integer matrix used for temporary storage, DET is a double precision variable used to calculate and retain (for DET = 1 initially) the determinant of A, and SCALE(N) is a double precision matrix used for column scaling. The variable RET returns a value of 0 if A is singular and 1 if the matrix equation is solved.

RADSF

```

C      RADSF
C
C      PGM TO CALC RADIAL SURFACE FIT TO NEUTRON FLUENCE
C      AU FOILS, RTNS MAY 1975
C      INPUT (DATA) CARDS:
C      CARD 1 -- NRUN,NFOIL,H,X0,Y0 (215,3F10.6)
C              NRUN = NUMBER OF FITS
C              NFOIL = 1 (FRONT AU) OR 2 (MIDDLE AU)
C              H = DX = DY, INCREMENT IN MM
C              (X0,Y0) = FOIL OFFSET (MM) FROM NEUTRON BEAM AXIS
C      17(NFOIL=1) OR 12(2) CARDS -- J,PHI,DPHI,AREA,DAREA (15,4F10.6)
C              J = FOIL SEGMENT LABEL NUMBER
C              PHI = AVE FLUENCE, UNITS E-17 N/CM**2
C              AREA = AREA OF FOIL SEG, UNITS MM**2
C              DPHI,DAREA = MEASUREMENT UNCERTAINTIES
C      WARNING: AREAS MUST CORRESPOND TO WEIGHTED SUMS
C      LAST NRUN CARDS -- 4-SEGMENT LISTS TO BE FIT (415)
C      LAST SEGMENT NUMBER IGNORED FOR AU MIDDLE
C
C      DIMENSION PHI(17),DPHI(17),AREA(17),DAREA(17),NSEG(4)
C      DIMENSION S(17,4),LWORK(4)
C      DOUBLE PRECISION A(4,4),B(4,2),SCALE(4),DET
C      PI = 3.141592654
C      RTD = 180./PI
C      PI2 = PI*2.0
C      RADIUS = 6.350
C
C      ZERO ARRAYS
C
C      DO 30 K=1,4
C      NSEG(K) = 0
C      LWORK(K) = 0
C      B(K,1) = 0.000
C      B(K,2) = 0.000
C      DO 28 J=1,4
C      28 A(K,J) = 0.000
C      DO 30 I=1,17
C      30 S(I,K) = 0.0
C      DO 32 I=1,17
C      PHI(I) = 0.0
C      AREA(I) = 0.0
C      32 DAREA(I) = 0.0
C
C      READ IN FOIL SEGMENT DATA
C
C      READ (5,801) NRUN,NFOIL,H,X0,Y0
C      IF (NFOIL.EQ.1) GO TO 55
C      DO 50 I=1,12
C      50 READ (5,802) J,PHI(J),DPHI(J),AREA(J),DAREA(J)
C      GO TO 200
C      55 DO 60 I=1,17
C      60 READ (5,802) J,PHI(J-19),DPHI(J-19),AREA(J-19),DAREA(J-19)
C
C      STEP THROUGH AREA INCREMENTS
C
C      200 NXMAX = (RADIUS+ABS(X0))/H+1.
C      NYMAX = (RADIUS+ABS(Y0))/H+1.
C      210 DO 600 IX=1,NXMAX
C      X = (IX-0.5)*H
C      XSQ = X**2
C      215 XFOIL = X-X0
C      XFSQ = XFOIL**2
C      220 DO 500 IY=1,NYMAX
C      Y = (IY-0.5)*H
C      225 YFOIL = Y-Y0
C
C      CALC POLAR COORDS REL TO FOIL ORIGIN (TO IDENTIFY SEG INCREMENTS)
C
C      230 R = SQRT(XFSQ+YFOIL**2)
C      IF (R.GT.RADIUS) GO TO 490
C      232 THETA = ARSIN(ABS(YFOIL/R))
C      IF (YFOIL.LT.0.) GO TO 240
C      IF (XFOIL.LT.0.) THETA=PI-THETA
C      GO TO 250

```

```

240 IF (X.LT.0.) GO TO 245
    THETA = PI2-THETA
    GO TO 250
245 THETA = PI+THETA
250 DEG = RTD*THETA
C
C    ASSIGN TO FOIL SEGMENTS
C
300 IF (NFOIL.EQ.2) GO TO 305
    CALL ASGNF(I,R,DEG)
    GO TO 400
305 CALL ASGNB(I,R,DEG)
C
C    RUNNING SUM OF WEIGHTED AREA INCREMENTS
C
400 RBEAM = SQRT(XSQ+Y**2)
    S(I,1) = S(I,1) + 1.
    S(I,2) = S(I,2) + RBEAM
    S(I,3) = S(I,3) + RBEAM**2
    S(I,4) = S(I,4) + RBEAM**3
C
    IF (Y.LT.0.) GO TO 500
    Y = -Y
    GO TO 225
490 IF (Y.GT.0.0) GO TO 510
500 CONTINUE
510 IF (X.LT.0.) GO TO 600
    X = -X
    GO TO 215
600 CONTINUE
C
C    OUTPUT SUMMATIONS
C
    WRITE (6,860)
    IMAX = 12
    IF (NFOIL.EQ.1) IMAX=17
    WRITE (6,861)
    DO 605 I=1,IMAX
        ISEG = I
        IF (NFOIL.EQ.1) ISEG=ISEG+19
605 WRITE (6,862) ISEG,S(I,1),S(I,2),S(I,3),S(I,4)
C
C    READ IN FOIL SEGMENT NUMBERS TO FIT
C
    NEQ = 4
    IF (NFOIL.EQ.2) NEQ=3
610 DO 700 IRUN=1,NRUN
    READ (5,820) (NSEG(I),I=1,4)
C
C    CONSTRUCT MATRICES
C
    DO 615 L=1,NEQ
        IF (NFOIL.EQ.1) NSEG(L)=NSEG(L)-19
        J = NSEG(L)
        B(L,1) = (PHI(J)*AREA(J))/H**2
        B(L,2) = SQRT((AREA(J)*DPHI(J))**2+(PHI(J)*DAREA(J))**2)/H**2
        DO 615 M=1,NEQ
615 A(L,M) = S(J,M)
C
C    SOLVE MATRIX EQUATIONS
C
    SCALE(1) = 0.000
    DET = 1.0
    RET = DMSEQ(4,NEQ,2,A,B,LWORK,DET,SCALE)
C
C    OUTPUT SOLUTION VALUES
C
650 WRITE (6,866)
    DO 660 L=1,NEQ
        MS = NSEG(L)
        IF (NFOIL.EQ.1) NSEG(L)=NSEG(L)+19
660 WRITE (6,867) NSEG(L),PHI(MS),DPHI(MS),AREA(MS),DAREA(MS)
        IF (RET.NE.0.000) GO TO 665
        WRITE (6,865)
        GO TO 700
665 WRITE (6,830) DET
        WRITE (6,868)
    DO 670 L=1,NEQ

```



```

670 WRITE (6,869) L,A(L,1),L,A(L,2)
    WRITE (6,870)
    IF (NFOIL,EQ.2) WRITE (6,871)
C
700 CONTINUE
C
801 FORMAT (2I5,3F10.6)
802 FORMAT (15,4F10.6)
860 FORMAT ('1','WEIGHTED AREA SUMS')
861 FORMAT ('0','FOIL',4X,'S(1,1)',7X,'S(1,2)',7X,'S(1,3)',7X,
1      'S(1,4)')
862 FORMAT ('1',1X,I2,4(3X,E10.3))
820 FORMAT (4I5)
866 FORMAT ('1','FOIL SEGS USED -- J,PHI,DPHI,AREA,DAREA')
867 FORMAT ('1',5X,I3,4(5X,F10.6))
865 FORMAT ('0','SINGULAR EQUATION SET')
830 FORMAT ('0','MATRIX A DETERMINANT = ',D13.6)
868 FORMAT ('0','SOLUTION -- RADIAL SURFACE FIT CONSTANTS')
869 FORMAT ('1',5X,'C(1,I1,') = ',D13.6,5X,'DC(1,I1,') = ',D13.6)
870 FORMAT ('0','C(I) TIMES R FACTORS IN MM GIVES PHI(R) IN N/CM**1,
1      '2 E-17'/' RELATIVE TO NEUTRON BEAM AXIS'/' PHI(R) = C',
2      '1 + C2*R + C3*R**2 + C4*R**3')
871 FORMAT ('1','C4 = 0 FOR BACK AU (INSUFFICIENT RADIAL SECTIONS)')
C
STOP
END

```

QUADSF

```

C QUADSF
C
C PGM TO CALC CART QUADRATIC SURFACE FIT TO NEUTRON FLUENCE
C RTNS MAY 1975
C INPUT: PHI = AVE FLUENCE, UNITS E-17 N/CM**2
C AREA = AREA FOIL SEG J, UNITS MM**2
C H = DX = DY, INCREMENT IN MM
C NFOIL = 1 (FRONT AU) OR 2 (MIDDLE AU)
C NRUN = NUMBER OF 9-FOIL GROUPS TO FIT
C FIRST CARD: NRUN,NFOIL,H (2I5,F10.6)
C 17(NFOIL=1) OR 12(2) CARDS: J,PHI,DPHI,AREA,DAREA (15,4F10.6)
C LAST NRUN CARDS: 9 SEGMENT LIST EACH CARD (9I5)
C
C DIMENSION PHI(17),DPHI(17),AREA(17),DAREA(17),NSEG(9)
C DIMENSION S(9,17),LWORK(9)
C DOUBLE PRECISION A(9,9),B(9,2),SCALE(9),DET
C PI = 3.141592654
C RADIUS = 6.350
C NEQ = 9
C RTD = 180./PI
C PI2 = PI*2.0
C
C ZERO ARRAYS
C
C DO 30 K=1,9
C   NSEG(K) = 0
C   LWORK(K) = 0
C   B(K,1) = 0.000
C   B(K,2) = 0.000
C   DO 20 J=1,9
C     A(K,J) = 0.000
C   DO 30 I=1,17
C     S(K,I) = 0.0
C   DO 32 I=1,17
C     PHI(I) = 0.0
C     DPHI(I) = 0.0
C     AREA(I) = 0.0
C   32 DAREA(I) = 0.0
C
C READ IN FOIL SEGMENT DATA
C

```

```

      READ (5,801) NRUN,NFOIL,M
      IF (NFOIL.EQ.1) GO TO 55
      DO 50 I=1,12
50  READ (5,802) J,PHI(J),DPHI(J),AREA(J),DAREA(J)
      GO TO 200
55  DO 60 I=1,17
60  READ (5,802) J,PHI(J-19),DPHI(J-19),AREA(J-19),DAREA(J-19)
C
C      STEP THROUGH AREA INCREMENTS
C
200 NRMAX = RADIUS/M + 1.
210 DO 600 IX=1,NRMAX
      X = (IX-0.5)*M
      XSQ = X**2
220 DO 500 IY=1,NRMAX
      Y = (IY-0.5)*M
C
C      CALCULATE POLAR COORDINATES
C
230 R = SQRT(XSQ+Y**2)
      IF (R.GT.RADIUS) GO TO 510
232 THETA = ASIN(ABS(Y/R))
      IF (X.LT.0.) THETA = PI-THETA
      GO TO 250
240 THETA = PI2-THETA
250 DEG = RTD*THETA
C
C      ASSIGN TO FOIL SEGMENTS
C
300 IF (NFOIL.EQ.2) GO TO 305
      CALL ASGNF(I,R,DEG)
      GO TO 400
305 CALL ASGNB(I,R,DEG)
C
C      RUNNING SUM OF WEIGHTED AREA INCREMENTS
C
400 S(1,I) = S(1,I) + (X*Y)**2
      S(2,I) = S(2,I) + X*Y**2
      S(3,I) = S(3,I) + Y**2
      S(4,I) = S(4,I) + Y*X**2
      S(5,I) = S(5,I) + X*Y
      S(6,I) = S(6,I) + Y
      S(7,I) = S(7,I) + X**2
      S(8,I) = S(8,I) + X
      S(9,I) = S(9,I) + 1
C
490 IF (Y.LT.0.) GO TO 500
      Y = -Y
      GO TO 240
500 CONTINUE
510 IF (X.LT.0.) GO TO 600
      X = -X
      GO TO 220
600 CONTINUE
C
C      OUTPUT SUMMATIONS
C
      WRITE (6,860)
      IMAX = 12
      IF (NFOIL.EQ.1) IMAX=17
      WRITE (6,861)
      DO 605 I=1,IMAX
      ISEG = 1
      IF (NFOIL.EQ.1) ISEG = ISEG+19
605  WRITE (6,862) ISEG, S(1,I), S(2,I), S(3,I), S(4,I), S(5,I)
      WRITE (6,863)
      DO 607 I=1,IMAX
      ISEG = 1
      IF (NFOIL.EQ.1) ISEG = ISEG+19
607  WRITE (6,864) ISEG, S(6,I), S(7,I), S(8,I), S(9,I)
C
C      READ IN FOIL SEGMENT NUMBERS TO FIT
C
610 DO 700 IRUN=1,NRUN
      READ (5,820) (NSEG(I),I=1,9)
C
C      CONSTRUCT MATRICES
C

```

```

DO 615 L=1,9
IF (NFOIL.EQ.1) NSEG(L)=NSEG(L)-19
J = NSEG(L)
B(L,1) = (PHI(J)*AREA(J))/H**2
B(L,2) = SQRT((AREA(J)*DPHI(J))**2+(PHI(J)*DAREA(J))**2)/H**2
DO 615 M=1,9
615 A(L,M) = S(M,J)
C
C SOLVE MATRIX EQUATIONS
C
SCALE(1) = 0.000
DET = 1.0
RET = DMSEQ(9,9,2,A,B,LWORK,DET,SCALE)
C
C OUTPUT SOLUTION VALUES
C
650 WRITE (6,866)
DO 660 L=1,9
MS = NSEG(L)
IF (NFOIL.EQ.1) NSEG(L)=NSEG(L)+19
660 WRITE (6,867) NSEG(L),PHI(MS),DPHI(MS),AREA(MS),DAREA(MS)
IF (RET.NE.0.000) GO TO 665
WRITE (6,865)
GO TO 700
665 WRITE (6,830) DET
WRITE (6,868)
DO 670 L=1,9
670 WRITE (6,869) L,A(L,1),L,A(L,2)
WRITE (6,870)
C
700 CONTINUE
C
801 FORMAT (2I5,F10.6)
802 FORMAT (I5,4F10.6)
860 FORMAT ('1','WEIGHTED AREA SUMS')
861 FORMAT ('0','FOIL',4X,'S(1,I)',7X,'S(2,I)',7X,'S(3,I)',7X,
1 'S(4,I)',7X,'S(5,I)')
862 FORMAT ('1',1X,I2,5(3X,E10.3))
863 FORMAT ('0','FOIL',4X,'S(6,I)',7X,'S(7,I)',7X,'S(8,I)',7X,
1 'S(9,I)')
864 FORMAT ('1',1X,I2,4(3X,E10.3))
865 FORMAT ('0','SINGULAR EQUATION SET')
820 FORMAT (9I5)
866 FORMAT ('1','FOIL SEGS USED -- J,PHI,DPHI,AREA,DAREA')
867 FORMAT ('1',5X,I3,4(5X,F10.6))
830 FORMAT ('0','MATRIX A DETERMINANT = ',D13.6)
868 FORMAT ('0','SOLUTION -- QUADRATIC FIT CONSTANTS')
869 FORMAT ('1',5X,'B(',I1,') = ',D13.6,5X,'DB(',I1,') = ',D13.6)
870 FORMAT ('1','B(I) TIMES X,Y FACTORS IN MM GIVES PHI(X,Y) IN N/C',
1 'M**2 E-17'/' PHI(X,Y) = B1X2Y2 + B2XY2 + B3Y2 + B4X2Y +',
2 ' B5XY + B6Y + B7X2 + B8X + B9')
C
STOP
END

```

ASGNF

```

SUBROUTINE ASGNF(I,R,DEG)
C
C ASSIGNMENT OF AREA INCREMENTS TO FRONT AU FOIL, RTNS MAY 1975
C
R1 = 0.8865
R2 = 2.2401
R3 = 3.7266
R4 = 4.9578
C
IF (R.LE.R4) GO TO 320
IF (DEG.LE.45.) GO TO 311
IF (DEG.LE.135.) GO TO 312
IF (DEG.LE.225.) GO TO 313

```



```

      GO TO 390
311 I = 10
      GO TO 390
312 I = 9
      GO TO 390
313 I = 12
      GO TO 390
C
320 IF (R,LE,R1) GO TO 330
      IF (DEG,LE,45,) GO TO 321
      IF (DEG,LE,135,) GO TO 322
      IF (DEG,LE,225,) GO TO 323
      IF (DEG,LE,315,) GO TO 324
321 I = 6
      GO TO 390
322 I = 5
      GO TO 390
323 I = 8
      GO TO 390
324 I = 7
      GO TO 390
C
330 IF (DEG,LE,90,) GO TO 331
      IF (DEG,LE,180,) GO TO 332
      IF (DEG,LE,270,) GO TO 333
      I = 3
      GO TO 390
331 I = 2
      GO TO 390
332 I = 1
      GO TO 390
333 I = 4
C
390 RETURN
      END

```