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Monte Carlo Calculations of 14-MeV Neutron
Multiplication in Thick Beryllium Assemblies
and Comparison with Experimental Results

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Lawrence
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MONTE CARLO CALCULATIONS OF 14-MEV NEUTRON MULTIPLICATION IN THICK
BERYLLIUM ASSEMBLIES AND COMPARISON WITH EXPERIMENTAL RESULTS

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Abstract

Integral experiments performed at the Institute for Reactor Development at Julich, West Germany, have raised doubts about the adequacy of current nuclear data and calculational methods in predicting neutron multiplication and leakage from beryllium assemblies bombarded with 14-MeV neutrons. Experimental values of inferred neutron multiplication were reported to be less than calculated values by ~25%. We have performed calculations of the experiments using the TART Monte Carlo code. The ratio of measured leakage multiplication to our calculated leakage multiplication is 0.85 for 8-cm-thick beryllium and 0.99 for 12-cm-thick beryllium. However, much uncertainty exists in the procedure leading to the stated experiment values of "apparent multiplication." We also performed calculations for a series of experiments done at LLNL from 1955 to 1956. A 14-MeV neutron source was placed in the center of a cylindrical beryllium assembly 8 in. in radius and 24 in. in height. The beryllium assembly was encased in an aluminum can surrounded by a manganese bath. The ratio of experimental to calculated neutron leakage multiplication is 0.88. Much uncertainty exists in both series of experiments.

1. Introduction

Beryllium has been proposed as a material suitable for neutron multiplication in the blankets of fusion reactors.^{1,2} The use of beryllium appears attractive from a neutronics standpoint because of its relatively high (n,2n) cross section (~0.50b) and relatively low capture cross section (~0.) and threshold energy for (n,2n) reactions (1.7 MeV).

Integral experiments performed at the Institute of Reactor Development at Julich, West Germany, have cast doubt on the adequacy of current nuclear data and calculational methods in predicting neutron multiplication and leakage from beryllium assemblies 8 to 20 cm thick.^{3,4} A specific concern is the uncertainty of the angular and energy distribution of the secondary neutron in the laboratory system.

This report presents the results of TART Monte Carlo^{5,6} calculations of previously reported experimental assemblies.^{3,4} Comparisons are made with previously reported calculated and measured values.

We also present the results of TART Monte Carlo calculations of neutron multiplication in a beryllium cylinder. The neutron multiplication in this assembly was measured as a part of the Bulk Measurements Project at LLNL.⁷ This information has previously been unavailable in the open literature.

Finally, we compare the three experiments and discuss uncertainties in the available information relevant to comparisons of calculated to experimental values.

2. Discussion of German Experiment

This experiment was first reported at the 9th Symposium on Fusion Technology in 1976.³ The experimental assembly is shown in Fig. 1. A central beryllium assembly $38 \times 38 \times 65 \text{ cm}^3$ is surrounded by a polyethylene cube 1.2 m on a side. The polyethylene was modeled as CH_2 with a density of 0.92 g/cm^3 . A central channel $14 \times 14 \times 120 \text{ cm}^3$ is provided for the beam tube and target assembly of a deuteron accelerator. Thus, the beryllium assembly is a 12-cm-thick rectangular tube 65 cm long containing 150 kg of beryllium metal, which gives a beryllium density of 1.85 g/cm^3 .

The neutron capture measurements used to infer neutron multiplication were done using dysprosium foils as $1/v$ detectors in the polyethylene assembly with and without the beryllium assembly in place. In the present work, it is assumed, as stated in Ref. 3, that these measurements are taken at points representative of the entire polyethylene bulk. No calculated "correction" will be made to measured data to arrive at a "corrected experimental multiplication," as was done in Ref. 3. The ability to calculate neutron multiplication in beryllium should be well represented by the calculated ratio of captures in polyethylene with and without beryllium in the assembly. This is the only measured quantity in this experiment and is represented by the ratio of source-normalized activities in dysprosium foils with and without beryllium in place.

A comparison of the calculated and measured ratio of polyethylene captures with and without beryllium is shown in Table I. The values shown in parentheses are the TART uncertainties of one standard deviation.

The agreement between experimental and calculated values is considered good, especially when experimental uncertainties are considered. These experimental uncertainties include the change in neutron energy spectra at the detector locations that would occur when the beryllium mass is removed. This could change the activation of the dysprosium foils because of a change in self-shielding, which was apparently not considered. In addition, inserting the BF_3 counter or dysprosium foils would cause a localized perturbation in the thermal flux that may not be identical with or without the beryllium mass in place.

The calculations are shown for pure and nuclear-grade beryllium. The impurity levels used for nuclear-grade beryllium are those for Brush-Wellman N-50C specification beryllium which are given in Table A-III.

Calculated values are also shown with and without corrections for fast captures in carbon. This changes the results because the fast captures in carbon increase when the beryllium is removed. Thus, the relative fraction of fast and thermal captures in polyethylene changes and must be accounted for to correctly represent the $1/v$ absorptions.

3. Discussion of Indo-German Experiment

In a subsequent experiment⁴ conducted under the auspices of the Indo-German Collaboration Program, measurements were made in a similar assembly for beryllium thicknesses of 8, 12, and 20 cm with the outside dimensions of the polyethylene assembly held constant at $125 \times 120 \times 120 \text{ cm}^3$ and source channel dimensions of $125 \times 14 \times 14 \text{ cm}^3$.

A detector channel $1.6 \times 1.6 \text{ cm}^2$ was constructed in the polyethylene parallel to the axis of the assembly. A 1-cm-diameter BF_3 counter was moved along the channel and measurements were made at various points. The channel was then moved by rearranging the polyethylene and the procedure was repeated at several locations in a representative slab of the assembly. Initial BF_3 detector measurements with 12 cm of beryllium were also done with manganese wires. The agreement between the two techniques was described as good, and all subsequent measurements were done with BF_3 counters. The comparison technique between manganese wires and BF_3 counters was not explicitly stated, i.e., profiles were compared along a channel or ratio of counts and activity both with and without beryllium.

In the analysis of the measured data by Basu et al.,⁴ calculated corrections were applied to arrive at the "corrected true multiplication."

The procedure used in Ref. 4 is outlined as follows:

With no beryllium in the assembly,

$$1 = A_0 + L_0 ; \quad (1)$$

with the beryllium,

$$M = A_m + L_m , \quad (2)$$

Where A is the absorption in the polyethylene, L is the leakage from the polyethylene and M is defined as the true multiplication. The subscript 0 indicates no beryllium and the subscript m indicates that beryllium is inserted in the assembly. The apparent multiplication is defined as

$$M_a = \frac{A_m}{A_0} = \frac{(M - L_m)}{(1 - L_0)} . \quad (3)$$

Note that M_a is the only measured quantity given in Ref. 4. Thus,

$$M = M_a(1 - L_0) + L_m . \quad (4)$$

It is stated in Ref. 4 that the "true multiplication" is calculated from Eq. (4) using values of L_0 and L_m calculated by MORSE. We note that Eq. (4) yields the leakage multiplication rather than true multiplication because of captures in the beryllium mass.

Calculated values of L_m and L_0 from Ref. 4 and TART are shown in Table II. The leakages from TART are consistently lower than those from Ref. 4, particularly with beryllium in the assembly. The source of these differences is not known. It is also not known if the Ref. 4 values include leakage out the source channel.

Calculated values of beryllium (n,2n) reactions and captures with and without polyethylene surrounding the beryllium are shown in Table III. The calculation of (n,2n) reactions in beryllium is reasonably consistent between TART and Ref. 4. However, TART predicts up to 50% more absorptions in beryllium than does Ref. 4. The cause of this discrepancy is not known.

Calculated leakage corrections were made by Basu et al.⁴ to the measured experimental "apparent multiplication" to arrive at the "corrected true multiplication." It is stated that "the true multiplication was obtained by correcting for channel leakage, for backscattering of neutrons from polyethylene, and for leakage through the system."⁴ However, only L_0 and L_m were used to arrive at M (Eq. 4) from M_a . The magnitude of the backscattering correction was not identified. It was also not specified whether L_0 and L_m contain the leakage out the central channel or if this is a separate calculation.

Using the calculated values of L_0 and L_m from Ref. 4 and the measured value of M_a , the corrected true multiplication is obtained as shown in Table IV. Note that the experimental value of M is slightly different than the value quoted in Ref. 4 for ostensibly the same corrections.

We did not consider the data for the 20-cm beryllium thickness because of uncertainties in the geometry. The 20-cm data are noted as 2π geometry, but the actual 2π configuration, from four possible choices, is not specified. Judging from trends in the data, the 2π geometry results were not combined into an equivalent 4π geometry. This leaves the 8- and 12-cm data suitable for our comparison.

For reasons explained in Section II, the experimental value of M_a (the ratio of captures in polyethylene with and without beryllium) is the appropriate value to compare with the calculation. This comparison is given

in Table V for pure and nuclear grade beryllium. The TART results are virtually identical to the results given in Ref. 4 and are seen to be significantly greater than the experimental value of M_a . These calculated values are for the entire polyethylene volume.

If the data were integrated only over the "representative slab" and not integrated so as to represent the entire polyethylene volume (see further discussion below), the previous comparison would not be appropriate. Instead, the ratio of polyethylene absorptions with and without beryllium should be compared only in the "representative slab" region. This comparison is given in Table VI, which shows much better agreement between calculated and measured results. The 12-cm data are especially encouraging.

Simplicity is the essence of any experiment designed to test the accuracy of nuclear data. As much as possible, the experiment should be a test of nuclear data and not calculational techniques.

The Indo-German experiment has been designed in rectangular geometry. More than 200 measurements were taken for each assembly with the BF_3 detector in a representative slab, as shown in Fig. 1. These results were then integrated over an unspecified volume. An incorrect integration technique could give a misleading value of M_a even if all the individual measurements were "correct." For an example, the representative slab can be divided into two regions, A and B, as shown in Fig. 2. Note that the relative weighting of Region A values must be greater than that of Region B since the volume represented by Region A in the entire polyethylene volume is 16 times its actual volume and the volume represented by Region B in the entire polyethylene volume is eight times its actual volume. If this relative weighting were not done, the experimental values of M_a could be improperly weighted towards Region B where the different transport path through beryllium

and polyethylene would affect the flux in this region differently than the relatively straight-through penetration into Region A. Thus, the integrated results would give an incorrect value of M_a . In addition, this may not be a truly representative slab because polyethylene captures in regions adjacent to the beam tube are not accounted for.

This effect is seen in the TART calculations, shown in Table VII. The absorptions in Region B actually increase when the beryllium is removed. This is due to the effects noted above.

These concerns are also related to the variation of the thermal flux within the polyethylene (which the BF_3 counter detects) with the fast flux spectrum incident on the polyethylene.

Another interesting comparison is the neutron leakage from the surface of the bare beryllium assembly. This is the value calculated as the corrected true multiplication after correcting the apparent multiplication for leakage and backscatter from the polyethylene.⁴ The backscatter correction was not given in Ref. 4. The comparison between the MORSE-derived results and the TART directly calculated results is shown in Table VIII. These values should be very close in view of the small differences between the calculated values of M_a from TART and MORSE. The two sets of values represent the same physical quantity, namely the leakage from the surface of the beryllium assembly per source neutron at the center of the assembly. The source of this difference is not known.

4. Bulk Measurements Project Experiment

In the mid-1950s, a series of experiments was performed at LLNL to measure the neutron multiplication of various materials in a bulk assembly.⁷

A cylindrical beryllium assembly 8 in. in radius and 24 in. in height was one of the assemblies used. A 14-MeV neutron source was placed at the center of the assembly and the resultant leakage multiplication was measured using manganese bath techniques.

A cylindrical beryllium assembly was constructed using rectangular bars. Penetrations were provided in the beryllium for the accelerator beam tube and an α counter was used to monitor the target. The source was composed of 14-MeV neutrons produced by 500-keV deuterons incident on the target. The target consisted of a tungsten disc on which titanium metal was sputtered and tritium was adsorbed into the titanium.

The entire beryllium and target assembly was placed in a watertight cylindrical aluminum can with a 30-in. inside diameter, 30-in. inner height, and 1/8-in. wall thickness. The aluminum can was supported by an adjustable table in an 8-ft-high cylindrical aluminum tank with a 6.5-ft inner diameter. This tank was then filled to a depth of 6.5-ft with a solution containing MnSO_4 .

The experimental procedure was to irradiate the manganese bath with 14-MeV neutrons with or without the beryllium in place. The bath was then stirred to ensure uniformity and samples were taken. These samples were then counted to determine ^{56}Mn activity and were corrected back to the activity level at the end of irradiation. A correction was then made for relative neutron production in the target during the irradiation, and the "p" factor was determined. (The "p" factor is the ratio of corrected counts to neutrons produced in the target during the bombardment.) The ratio of "p" values with and without the beryllium in place gives the neutron leakage multiplication.

Several runs were made with and without the beryllium assembly in place for two different baths. The results of these runs were then combined to give a leakage multiplication of 1.93 ± 0.08 . (The reported uncertainty levels are apparently two standard deviations, i.e., 95% confidence level.) An earlier set of data gives a leakage multiplication of 2.10 ± 0.14 . However, the lower value was believed to be a better value because of better counting geometry, better internal consistency, and a larger number of samples.

The experimental assembly was modeled using the TART Monte Carlo code. A solid beryllium cylinder 8 in. in radius and 24 in. in height was placed inside a 1/8-in.-thick aluminum can with a 30-in. inside diameter and 30-in. inside height. A beryllium density of 1.92 was used to match the total beryllium weight of 335 pounds. The nuclear beryllium used in this case was the S-65 specification as shown in Table A-3. This region was surrounded by a bath region 6.5 ft in diameter and 6.5 ft high. Note that the target assembly and structure in the beryllium assembly and support structure in the tank are not included. In the final model the beam tube and alpha monitor tube were modeled as 0.3-cm-thick aluminum tubes 1.25 in. in diameter.

Two baths were used. Solution 1 was modeled as water and 16.15 wt.% MnSO_4 with a density of 1.25 g/cm^3 . Solution 2 was modeled as water and 18.44 wt. % MnSO_4 with density of 1.25 g/cm^3 . From the information given, the exact composition of the bath cannot be directly extracted.

The calculated ratio of captures with and without the beryllium in place is shown in Table IX. The ratio of experimental to calculated values for Mn captures is 0.88 (0.02).

5. Comparison of Experiments

An unexplained discrepancy exists between the German and Indo-German experiments. The German experiment reported a value of M_a for 12-cm-thick beryllium of 1.875; the Indo-German experiment reported a value of 1.70. This difference was never addressed in the Indo-German experiment.

The uncertainty in the experimental results is stated to be $\pm 3\%$. This seems too small for several reasons: The assembly must be completely or partially disassembled many times. The reassembly must be done carefully to eliminate voids in the polyethylene. The source normalization would also contribute to the uncertainty.

Both of these experiments were reported in relatively brief format (one is a summary in the 9th Symposium on Fusion Technology and the other as a Technical Note⁴ in Nuclear Science and Engineering), which makes a rigorous review impossible. The Indo-German Technical Note is very difficult to interpret. Neither experiment is well-documented to our knowledge.

However, the bulk measurements experiment is relatively well-documented in BIR-2 through BIR-11, although there is some uncertainty as to the bath composition and structure in the beryllium assembly and tank. In contrast to the experiments using an $1/v$ detector in polyethylene, the bulk measurements experiment used a bath, which, with thorough mixing, gives a value representative of the entire volume. Thus, the need to numerically reduce many data points to a single value is eliminated.

6. Conclusions

Based on our analysis, we have reached the following conclusions: Significant uncertainty exists in the German and Indo-German experiments.

Specifically, we are concerned about the discrepancy between the 12-cm beryllium data for M_a (i.e., 1.875 vs 1.70), which was not addressed. In addition, the method of arriving at a single value for M_a was not explicitly stated. It is not clear if M_a applies to the representative slab or the entire polyethylene volume. We also noted significant discrepancies between the TART- and MORSE-calculated beryllium absorptions and leakages. If these concerns can be answered, the information from the German and Indo-German experiments should be more useful.

The Bulk Measurement Project's experiment also contains uncertainties, including the bath and beryllium composition. In view of the time that has passed since the experiments were performed, it is unlikely that these uncertainties can be resolved. Our comparison of our calculations with the experiments is encouraging, and any further resolution of the experimental uncertainty would likely result in better agreement between calculated and experimental values.

Table I
Comparison of TART Calculated and Measured Ratio of
Captures in Polyethylene (for 12-cm beryllium thickness)

	Ratio of PE captures		
	Measured ^a	TART calculated	Measured/calculated
<u>Total PE captures</u>			
Pure Be	1.875	2.07 (0.05)	0.91
Nuclear-grade Be	1.875	2.01 (0.05)	0.93
Nuclear-grade Be with Al beam tube	1.875	1.97 (0.02)	0.95
<u>Fast PE captures subtracted</u>			
Pure Be	1.875	2.20 (0.05)	0.85
Nuclear-grade Be	1.875	2.13 (0.05)	0.88
Nuclear-grade Be with Al beam tube	1.875	2.09 (0.02)	0.90

^aFrom Ref. 3.

Table II
Calculated Neutron Leakage from Experimental Assembly
(Per Source Neutron Entering Beryllium)

Thickness, Be or void (cm)	MORSE ^a		TART ^b	
	L_m	L_0	L_m	L_0
8	0.16	0.12	0.09	0.11
12	0.17	0.15	0.11	0.13
20	0.22	0.22	0.12	0.20

^aThe MORSE results were originally labeled "leakage from polyethylene surface" and presumably include leakage out the central beam port cavity, which is included in the TART values.

^bThe TART values have been increased by 3% to convert to a "per source neutron entering beryllium" basis from a "per source neutron" basis. TART accuracy to displayed digits.

Table III
Calculation of Beryllium (n,2n) Reactions and
Captures With and Without Polyethylene
Surrounding the Assembly

Be thickness (cm)	Polyethylene ^c	MORSE ^a		TART ^b	
		Be (n,2n)	Be captures	Be (n,2n)	Be captures
8	No	0.805	0.075	0.812 (0.005)	0.080 (0.001)
8	Yes	0.880	0.105	0.828 (0.006)	0.121 (0.001)
12	No	1.064	0.118	1.082 (0.008)	0.142 (0.002)
12	Yes	1.113	0.170	1.096 (0.006)	0.216 (0.002)
20	No	1.368	0.221	1.371 (0.009)	0.318 (0.003)
20	Yes	1.381	0.299	1.388 (0.010)	0.445 (0.003)

^aFrom Ref. 4.

^bFrom Tables A-IV through A-VII, Pure Be.

^cThe polyethylene thicknesses quoted in the MORSE results are not consistent with the assembly dimensions. This particular comparison would not be significantly affected by the difference.

Table IV
Corrected True Experimental Multiplication Using
MORSE Calculated Leakages

Be thickness (cm)	M_g^a	M^b	M^a
8	1.33	1.33	1.35
12	1.70	1.62	1.58

^aFrom Ref. 4.

^bCalculated from data given in Ref. 4.

Table V
Comparison of TART Calculated and Experimental
Values of Apparent Multiplication in
Entire Polyethylene Volume

Be thickness (cm)	M_a (experimental)	M_a (TART)	Experimental/ TART
<u>Pure Be</u>			
8	1.33	1.78 (0.03) ^a	0.75
12	1.70	2.07 (0.05) ^a	0.82
<u>Nuclear-grade Be</u>			
8	1.33	1.76 (0.03) ^a	0.76
12	1.70	2.07 (0.05) ^a	0.85
<u>Pure Be</u>			
8	1.33	1.88 (0.03) ^b	0.71
12	1.70	2.20 (0.05) ^b	0.77
<u>Nuclear-grade Be</u>			
8	1.33	1.86 (0.03) ^b	0.72
12	1.70	2.13 (0.05) ^b	0.80

^aWith total PE captures.

^bWithout fast PE captures.

Table VI
Comparison of TART Calculated and Experimental Values of
Apparent Multiplication in Representative Slab

Be thickness (cm)	M _a (Experimental)	M _a (TART)	Experimental/ TART
<u>Pure Be</u>			
8	1.33	1.51 (0.04) ^a	0.88
12	1.70	1.71 (0.06) ^a	0.99
<u>Nuclear Be</u>			
8	1.33	1.49 (0.04) ^a	0.89
12	1.70	1.61 (0.06) ^a	1.06
 <u>Pure Be</u>			
8	1.33	1.59 (0.04) ^b	0.84
12	1.70	1.81 (0.06) ^b	0.94
<u>Nuclear Be</u>			
8	1.33	1.57 (0.04) ^b	0.85
12	1.70	1.71 (0.06) ^b	0.99

^aWith total PE captures.

^bWithout PE captures.

Table VII

Comparison of Polyethylene Captures in Regions A and B
With^a and Without Beryllium

	Region	
	A	B
<u>Total captures in region</u>		
With Be	0.6535 (0.0077)	0.1613 (0.0032)
Without Be	0.2868 (0.0041)	0.2249 (0.0040)
Ratio ($\frac{\text{with}}{\text{without}}$)	2.28	0.72
<u>Fast captures subtracted</u>		
With Be	0.6465 (0.0077)	0.1585 (0.0032)
Without Be	0.2657 (0.0041)	0.2127 (0.0040)
Ratio ($\frac{\text{with}}{\text{without}}$)	2.43	0.75

^a12-cm beryllium thickness.

Table VIII

Comparison of MORSE-Derived "Corrected True Multiplication" and
TART Calculated Leakage from a Bare Beryllium Assembly

Be thickness (cm)	MORSE-derived M	TART leakage M
8	1.79	1.72 (0.02)
12	2.03	1.93 (0.01)

Table IX

Calculated Ratio of Bath Captures with Beryllium to
Bath Captures Without Beryllium

	Total captures	Mn(n,g)	H(n,g)
<u>Solution 1 (16.15 wt% MnSO₄)</u>			
Pure Be	2.15 (0.03)	2.38 (0.05)	2.38 (0.05)
Nuclear Be ^a	2.04 (0.03)	2.25 (0.05)	2.25 (0.05)
<u>Solution 2 (18.44 wt% MnSO₄)</u>			
Nuclear Be ^a	2.06 (0.04)	2.28 (0.06)	2.28 (0.06)
Nuclear Be ^b with beam tube	2.00 (0.02)	2.19 (0.03)	2.19 (0.03)
<u>Ratio of experimental to calculated = $\frac{1.93 (0.04)}{2.19 (0.03)} = 0.88 (0.02)$</u>			

^aN-50C without BeO.

^bS-65 Be.

APPENDIX A: SUMMARY OF TART CALCULATIONS

Tables A-I through A-III summarize the TART Monte Carlo models and data used in this report. Tables A-IV through A-IX summarize the calculated values of interest.

Table A-1

Indo-German Experiment TART Model

```

name gbelh - 12 cm n-58c be al beam tube - german beryllium experiment
box uo4 gbelh
xplane 1 0.0
xplane 2 32.5
xplane 3 62.5
yplane 4 0.0
yplane 5 7.0
yplane 6 19.0
yplane 7 60.0
zplane 8 0.0
zplane 9 7.0
zplane 10 19.0
zplane 11 60.0
surf 12 5.89 1.0 0.0 0.0 0.0 0.0 1.0
surf 13 5.69 1.0 0.0 0.0 0.0 0.0 1.0
* zones 1 & 2 are beryllium
jb 1 -1 +2 -5 +6 -8 +10
jb 2 -1 +2 -4 +5 -9 +10
* zones 3 - 8 are central void
* zones 4 & 7 are beam tube
jb 3 -1 +2 -4 -8 +13
jb 4 -1 +2 -4 -8 +12 -13
jb 5 -1 +2 -4 +5 -8 +9 -12
jb 6 -2 +3 -4 -8 +13
jb 7 -2 +3 -4 -8 +12 -13
jb 8 -2 +3 -4 +5 -8 +9 -12
* zones 9 - 13 are polyethylene
* zones 9 & 10 are representative slab
jb 9 -1 +3 -6 +7 -8 +10
jb 10 -1 +3 -6 +7 -10 +11
jb 11 -1 +2 -4 +6 -10 +11
jb 12 -2 +3 -5 +6 -8 +11
jb 13 -2 +3 -4 +5 -9 +11
* zones 14 - 18 are outer zones
jb 14 -3 -5 -8
jb 15 -3 -4 +5 -9
* zone 16 is leakage zone for beam port
jb 16 -3 -4 +5 -8 +9
jb 17 -1 +3 -7 -2 +11
jb 18 -1 +3 -4 -11
* zones 19 - 21 are reflecting zones
jb 19 -1
jb 20 +4
jb 21 +8
* mcplane 25. 0.0 62.5 0.0 60.0 0.01 60.0 0 -1
matl 1 1.05 0.98986 4000 0.0006 13027 0.0010 6012 0.00075 26000 &
0.0005 12000 0.0006 14000 0.0001 24000 0.00005 27059 &
0.00015 29000 0.00002 82000 0.00012 25055 0.00002 42000 &
0.0002 28000 0.00000037 5010 0.00000163 5011 0.000002 48000 &
0.0001 28000 0.000000195 3006 0.000002005 3007 &
0.0002 7014 0.00000514 47107 0.00000486 47109 &
0.00076 8016
matl 2 0.92 1.0 6012 2.0 1001
matl 3 1.0e-4 1.0 7014
matl 4 2.699 1.0 13027
matz 0 16 thru 21
matz 1 1 2
matz 2 9 thru 13
matz 3 3 5 6 8
matz 4 4 7
reflx 19
refly 20
reflz 21
reacted 1
reacted 2
reacted 4
reacted 7
reacted 9
reacted 10
reacted 11
reacted 12
reacted 13
sentl 1 1 2 10 3 500 4 14.06
sentl 5 1 21 10 22 1 23 1 26 1
sourcel 3 0.001 0.001 0.001
end

```

Table A-II

Bulk Measurements Project TART Model

```

name bir15 Bin rad s-65 b0 cylinder d-t source - bulk meas proj
box ue4 bir15
jb 1 -2 +3 -8 +12 -14
jb 2 +2 -7 +13 -14
jb 3 -2 +3 +11 -12
jb 4 +3 +14 -15
jb 5 -3 +4 -8 +11 -15
jb 6 -2 +4 +10 -11
jb 7 +4 +15 -16
jb 8 -4 +5 -8 +10 -16
jb 9 -2 +5 +9 -10
jb 10 +5 +16 -17
jb 11 -5 +6 -8 +9 -17
jb 12 -2 +6 -9
jb 13 +6 +17
jb 14 -6 +8
jb 15 -6 +8
jb 16 +2 -9
jb 17 +6 +7
jb 18 +1 -7 +9 -13
jb 19 -2 +6 -7 +8
jb 20 -1 +2 -7 +9 -13
jb 21 +2 -7 +0 +13
cyl 1 1.2875
cyl 2 1.5875
cyl 3 20.32
cyl 4 30.10
cyl 5 30.4175
cyl 6 99.06
surf 7 1.2875 1.0 0.0 0.0 0.0 1.0 0.0
surf 8 1.5875 1.0 0.0 0.0 0.0 1.0 0.0
zplane 9 99.06
zplane 10 30.4175
zplane 11 30.10
zplane 12 30.40
zplane 13 0.0
zplane 14 -30.40
zplane 15 -30.10
zplane 16 -30.4175
zplane 17 -99.06
yplane 18 1.5875
yplane 19 -1.5875
matl 1 1.02 0.980788 4009 0.0015 13027 0.002 26000 &
0.003 12000 0.0007 14000 0.000002 27050 &
0.0005 29000 0.00025 25055 &
0.0005 28000 0.0000037 5010 0.00000163 5011 &
0.000000195 3006 0.000002005 3007 &
0.00000257 47107 0.00000243 47109 &
0.001 6012 0.0096 8016
matl 2 1.25 6.820e-2 1001 3.779e-2 8016 9.213e-4 16032 &
9.213e-4 25055
matl 3 2.639 1.000 13027
matl 4 1.0e-4 1.000 7014
matz 0 12 13 14 15 16
matz 1 1 2
matz 2 9 10 11
matz 3 6 7 8 19 20 21
matz 4 3 4 5 17 18
source1 1 0.0 0.0 0.001
sent1 1 1 2 10 3 500 4 14.06
sent1 5 1 21 10 22 1 23 1 26 1
cent'm 1.0e+9
reacted 1
reacted 2
reacted 9
reacted 10
reacted 11
reacted 6
reacted 7
reacted 3
reacted 19
reacted 20
reacted 21
end
qgo

```

Table A-III
Impurities in Nuclear Grade Beryllium

Component	Wt %	
	N-50C ^a	S-65 ^b
BeO	0.9	1.5
Be ₂ C	-	0.25
Al	0.06	0.15
C	0.10	-
Fe	0.075	0.2
Mg	0.05	0.3
Si	0.06	0.07
Cr	0.01	-
Co	0.0005	0.0002
Cu	0.015	0.05
Pb	0.002	-
Mn	0.012	0.025
Mo	0.002	-
Ni	0.02	0.05
B	0.0002	0.0002
Cd	0.0002	-
Ca	0.01	-
Li	0.0003	0.0003
N	0.02	-
Ag	0.001	0.0005
Zn	-	0.015
Be (by difference)	98.986	98.079

^aBrush-Wellman Beryllium Specification N-50C.

^bReactor Handbook, Volume 1, Materials,
C. D. Tipton, Jr., (Interscience Publishers,
New York, 1960).

Table A-IV

Indo-German Experiment
Beryllium-Polyethylene Assembly
12 cm Beryllium Thickness

	Pure Be	Nuclear Be ^a	Nuclear Be	Nuclear Be w/A ¹ beam tube	Void	Void w/A ¹ beam tube
Total captures in PE	1.8100 (0.0259)	1.7592 (0.0234)	1.7559 (0.0248)	1.7094 (0.0109)	0.8748 (0.0161)	0.8697 (0.0072)
Fast captures in PE	0.0199 (0.0005)	0.0200 (0.0005)	0.0205 (0.0005)	0.0199 (0.0003)	0.0619 (0.0009)	0.0597 (0.0004)
Total captures in Region A	0.8750 ^b (0.0222)	0.8501 ^b (0.0133)	0.8267 ^b (0.0181)	0.6535 (0.0077)	0.5130 ^b (0.0141)	0.2868 (0.0041)
Fast captures in Region A	0.0098 ^b (0.0003)	0.0100 ^b (0.0003)	0.0098 ^b (0.0003)	0.0070 (0.0002)	0.0345 ^b (0.0008)	0.0211 (0.0003)
Total captures in Region B	--	--	--	0.1613 (0.0032)	--	0.2249 (0.0040)
Fast captures in Region B	--	--	--	0.0028 (0.0001)	--	0.0122 (0.0002)
Captures in beam tube	--	--	--	0.0225 (0.0002)	--	0.0074 (0.0000)
Total captures in Be bulk	0.2155 (0.0022)	0.2411 (0.0022)	0.2378 (0.0022)	0.2359 (0.0010)	--	--
Be(n,2n)	1.0956 (0.0062)	1.0925 (0.0080)	1.0785 (0.0066)	1.0571 (0.0038)	--	--
Leakage from polyethy- lene surface	0.0524 (0.0028)	0.0538 (0.0037)	0.0514 (0.0039)	0.0506 (0.0018)	0.1178 (0.0047)	0.1154 (0.0024)
Leakage from beam port	0.0546 (0.0032)	0.0546 (0.0039)	0.0530 (0.0026)	0.0471 (0.0014)	0.0134 (0.0017)	0.0145 (0.0009)
Identifier	GRE1AC	GRE1CB	GRE1CA	GRE1HC	GRE1DA	GRE1IA

^aNo BeO.

^bTotal for Regions A & B.

Table A-V
Indo-German Experiment
Beryllium-Polyethylene Assembly
8 cm Beryllium Thickness

	Pure Be	Nuclear Be ^a	Void
Total captures in PE	1.6017 (0.0220)	1.5838 (0.0208)	0.8987 (0.0122)
Fast captures in PE	0.0293 (0.0005)	0.0285 (0.0006)	0.0620 (0.0009)
Total captures in regions A&B	0.8576 (0.0158)	0.8453 (0.0123)	0.5664 (0.0110)
Fast captures in regions A&B	0.0167 (0.0004)	0.0157 (0.0003)	0.0370 (0.0007)
Total captures in Be bulk	0.1214 (0.0014)	0.1357 (0.0016)	--
Be (n,2n)	0.8278 (0.0062)	0.8179 (0.0077)	--
Leakage from PE surface	0.0512 (0.0028)	0.0492 (0.0028)	0.0920 (0.0043)
Leakage from beam port	0.0450 (0.0036)	0.0416 (0.0029)	0.0124 (0.0020)
Identifier	GBE2AA	GBE2CA	GBE2DA

^aNo BeO.

Table A-VI
Indo-German Experiment
Beryllium-Polyethylene Assembly
20 cm Beryllium Thickness

	Pure Be	Nuclear Be ^a	Void
Total captures in PE	1.8760 (0.0253)	1.7734 (0.0274)	0.8118 (0.0129)
Fast captures in PE	0.0107 (0.0005)	0.0107 (0.0005)	0.0598 (0.0008)
Total captures in regions A&B	0.6791 (0.0155)	0.6790 (0.0168)	0.4110 (0.0082)
Fast captures in regions A&B	0.0040 (0.0003)	0.0040 (0.0004)	0.0289 (0.0007)
Total captures in Be bulk	0.4448 (0.0032)	0.4913 (0.0040)	--
Be (n,2n)	1.3882 (0.0095)	1.3743 (0.0103)	--
Leakage from PE surface	0.0590 (0.0038)	0.0574 (0.0030)	0.1828 (0.0054)
Leakage from beam port	0.0638 (0.0015)	0.0674 (0.0029)	0.0126 (0.0016)
Identifier	GBE3AA	GBE3CA	GBE3DA

^aNo BeO.

Table A-VII
Indo-German Experiment
Bare Beryllium Assembly

	Be(n,2n)	Total Captures in Be Bulk	Total Leakage from Be Bulk	Identifier
<u>8-cm Be</u>				
Pure Be	0.8116 (0.0053)	0.0800 (0.0008)	1.7092 (0.0138)	GBE2EA
Nuclear Be	0.8056 (0.0066)	0.0847 (0.0012)	1.7214 (0.0174)	GBE2FA
<u>12-cm Be</u>				
Pure Be	1.0817 (0.0077)	0.1424 (0.0016)	1.9272 (0.0166)	GBE1EA
Nuclear Be	1.0707 (0.0042)	0.1513 (0.0008)	1.9290 (0.0097)	GBE1FB
<u>20-cm Be</u>				
Pure Be	1.3708 (0.0086)	0.3177 (0.0034)	2.0528 (0.0125)	GBE3FA
Nuclear Be	1.3876 (0.0071)	0.3541 (0.0024)	2.0058 (0.0142)	GBE3FA

Table A-VIII

Bulk Measurements Project
Beryllium Bulk - Manganese Bath

Case	Be bulk		Rath captures			Remainder	Structure captures	
	Captures	(n,2n)	Total	H	Mn		Can	Tubes
Pure Be, solution 1 (BIR06B)	0.1519 (0.0046)	1.4513 (0.0087)	2.0830 (0.0154)	1.4144 (0.0141)	0.6322 (0.0063)		0.0413 (0.0009)	--
No Be, solution 1 (BIR07A)	--	--	0.9687 (0.0126)	0.5934 (0.0115)	0.2659 (0.0051)		0.0091 (0.0001)	--
Nuclear Be ^a , solution 1 (BIR08A)	0.4025 (0.0028)	1.4457 (0.0084)	1.9721 (0.0220)	1.3348 (0.0201)	0.5981 (0.0090)		0.0387 (0.0006)	--
Nuclear Be ^a solution 2 (BIR09A)	0.4061 (0.0037)	1.4542 (0.0071)	2.0112 (0.0192)	1.2898 (0.0170)	0.6791 (0.0089)		0.0388 (0.0007)	--
No Be solution 2 (BIR10A)	--	--	0.9764 (0.0157)	0.5658 (0.0139)	0.2981 (0.0073)		0.0090 (0.0002)	--
Nuclear Be ^b solution 2 (BIR11A)	0.4091 (0.0029)	1.4670 (0.0063)	1.9766 (0.0188)	1.2681 (0.0166)	0.6675 (0.0088)		0.0387 (0.0007)	--
Nuclear Be ^c solution 2 (BIR15C)	0.3580 (0.0015)	1.3325 (0.0043)	1.9413 (0.0082)	1.2430 (0.0073)	0.6544 (0.0038)		0.0354 (0.0002)	0.0166 (0.0001)
No Be, solution 2 (BIR16C)	--	--	0.9728 (0.0067)	0.5665 (0.0059)	0.2984 (0.0031)		0.0088 (0.0001)	0.0076 (0.0000)
Nuclear Be ^c , solution 2 ^d (BIR13A)	0.2037 (0.0019)	0.0127 (0.0002)	0.7770 (0.0116)	0.5023 (0.0103)	0.2644 (0.0054)		0.0163 (0.0005)	--
No Be, solution 2 ^d (BIR14A)	--	--	0.9941 (0.0130)	0.6418 (0.0115)	0.3381 (0.0060)		0.0075 (0.0003)	--

^aN-50C Be without BeO.
^bN-50C Be.

CS-65 Be.
^dQ-n source. Remainder are D-T source.

Table A-IX
Summary of Fast Captures in Manganese Bath

Reaction	Captures	
	With Be	Without Be
$O(n,p)$	0.0027(0.0001)	0.0202(0.0002)
$O(n,d)$	0.0006(0.0000)	0.0066(0.0001)
$O(n,\alpha)$	0.0128(0.0002)	0.0599(0.0004)
$S(n,p)$	0.0014(0.0000)	0.0057(0.0000)
$S(n,\alpha)$	0.0005(0.0000)	0.0026(0.0000)
Identifier	BIR15C	BIR16C

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Fig. 1 Schematic diagram of TARI model geometry

Fig. 2 Schematic of representative slab in entire assembly