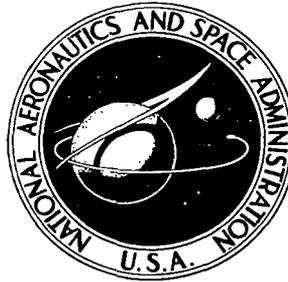


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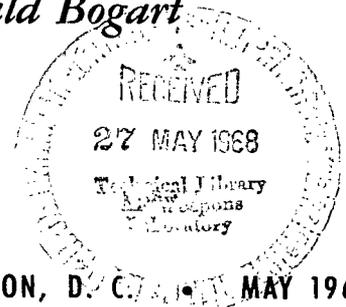
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AGES OF  $D(d,n)He^3$  AND  $T(d,n)He^4$  NEUTRONS  
IN WATER AND TUNGSTEN-WATER MIXTURES

*by Roger L. Alexander, Donald F. Shook, and Donald Bogart*

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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## ABSTRACT

Ages for D-D and D-T neutrons in water and tungsten-water mixtures were measured. Experimental and calculated ages were in agreement for water, but measured ages exceeded calculated ages for tungsten-water mixtures. The discrepancy increases with an increase in the volume fraction of metallic tungsten in the tungsten-water mixture. The most probable reasons for the discrepancy are incomplete data for the partial inelastic cross sections of the tungsten isotopes and the inadequacy of the evaporation model used to represent inelastic scattering above 1.5 MeV in the GAM II cross-section compilation.

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# AGES OF D(d, n)He<sup>3</sup> AND T(d, n)He<sup>4</sup> NEUTRONS IN WATER AND TUNGSTEN-WATER MIXTURES

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## SUMMARY

Spatial indium-resonance activity distributions were measured in water and in tungsten-water mixtures. The source neutrons were obtained from the D(d, n)He<sup>3</sup> and T(d, n)He<sup>4</sup> reactions using 0.135 MeV deuterons.

Experimental D-D flux ages at 0<sup>0</sup> and 90<sup>0</sup> to the beam direction were corrected for beam-duct perturbations with the use of both published Monte Carlo calculations and the present experimental data. Point-isotropic source ages calculated with the GAM II code and cross-section set were anisotropy corrected by using published Monte Carlo calculations. Experimental 0<sup>0</sup> D-T ages could not be directly compared with point-source ages because the needed corrections were not available.

Corrected D-D ages and uncorrected D-T ages are summarized in the following table:

Neutron source	Angle of measurements to beam, deg	Neutron energy, MeV	Age in water, cm <sup>2</sup>		Age in tungsten-water mixture, cm <sup>2</sup>			
			Experimental	Calculated	15.0 Tungsten - 85 water percent by volume		26.7 Tungsten - 73.3 water percent by volume	
					Experimental	Calculated	Experimental	Calculated
D-D	90	2.47	31.0±2.6	30.6	30.7±3.9	27.3	-----	----
D-D	0	2.84	38.0±2.3	37.1	35.7±2.5	32.5	35.7±2.6	30.5
D-T	0	14.68	<sup>a</sup> 175.4±5.0	<sup>b</sup> 166.0	<sup>a</sup> 112.7±5.0	<sup>b</sup> 91.6	-----	----

<sup>a</sup>Not corrected for beam-duct perturbation.

<sup>b</sup>Not corrected for anisotropy in energy and intensity.

Experimental ages for tungsten-water mixtures are lower than for pure water because of the large inelastic scattering effects of tungsten. The experimental and calculated ages for D-D source neutrons in water are in good agreement. Lower calculated ages than experimental D-D ages in tungsten-water mixtures suggest that the evaporation model used to represent inelastic scattering for tungsten above 1.5 MeV probably overestimates down-scattering effects. This result is supported by the considerably greater difference between the calculated and experimental ages in the D-T tungsten-water mixture than in the corresponding pure water case.

## INTRODUCTION

Tungsten is of interest as a possible reactor and shielding material for space nuclear power applications. With an inelastic neutron cross-section in the MeV range that is relatively large (ref. 1), tungsten combines desirable neutron- and gamma-attenuating properties. An analysis of the measured spatial distribution of neutrons slowing down in tungsten-water mixtures can be used to test the accuracy of available information on the cross sections and the calculational model used to account for neutron energy loss by inelastic scattering. In such a test, the experimental indium-resonance age, which is one-sixth of the second spatial moment of the measured spatial distribution of indium-resonance activity, is compared with the calculated age for the mixture.

The methods for measuring ages are well known, and a large number of measurements have been made of neutron ages in water and in metal-water mixtures with the use of fission and  $(\alpha, n)$  neutron sources (ref. 2). Calculated and experimental ages for neutrons from point-isotropic sources are generally in good agreement for water and metal-water mixtures where the cross sections are well known. The recent measurement by Stooksberry (ref. 3) of the age of 2.85-MeV neutrons from a  $T(p, n)He^3$  source is in good agreement with calculations and is an example of an integral age experiment made for the purpose of testing the precision of cross sections.

For source neutrons of energies greater than 2 MeV, calculated monoenergetic ages for tungsten-water mixtures are lower than water ages because of the large inelastic cross sections of tungsten. A measurement (ref. 4) of the age in water and tungsten-water mixtures with a plutonium-beryllium ( $Pu-Be(\alpha, n)$ ) source has confirmed this expectation. However, calculated ages were lower than measured ages for tungsten-water mixtures, although good agreement was obtained for water. This discrepancy suggests that inaccuracies existed in the tungsten inelastic cross sections used.

The use of monoenergetic neutron sources should provide more specific information on the validity of evaluated sets of cross sections, particularly of the tungsten inelastic-scattering cross sections above 1.5 MeV where partial cross sections for all isotopes have not been measured. A direct comparison of calculated and experimental ages for 2.5-MeV D-D and 14-MeV D-T neutron sources used herein is complicated by anisotropy of these sources and by the perturbation to the slowing-down media introduced by the presence of the deuteron beam duct. To compare the calculated age for a point-isotropic monoenergetic source to the experimental age, detailed Monte Carlo calculated corrections to the experiments are required. Cooper (ref. 5) has studied the effects of source anisotropy and beam-duct size as they apply to the D-D water age experiments of Spiegel, et al. (ref. 6). In the present study, experimental beam-duct corrections were measured and are used in conjunction with the Monte Carlo results of Cooper (ref. 5) so as to permit a direct comparison of experimental ages for D-D sources with point-isotropic

monoenergetic source ages calculated with a widely used set of evaluated cross sections, GAM II (ref. 7).

Comparable Monte Carlo calculations to correct D-T sources to point-isotropic sources have not been published, so the present results for D-T neutrons must be compared with uncorrected calculations.

## METHOD OF MEASUREMENT

Ages were determined from measured cadmium-covered indium-foil activity distributions by evaluating the equation

$$\tau_{1.4\text{eV}} = \frac{1}{6} \frac{\int_0^{\infty} A_S(r)r^2 4\pi r^2 dr}{\int_0^{\infty} A_S(r)4\pi r^2 dr} \quad (1)$$

where  $\tau_{1.4\text{eV}}$  is the flux age to indium-resonance energy and  $A_S(r)$  is the saturated cadmium-covered indium foil count rate at foil distance  $r$  from the neutron source. The count rate  $A_S(r)$  was measured at both  $0^\circ$  and  $90^\circ$  to the deuteron beam. At distances greater than about 25 centimeters for D-D activity distributions and 40 centimeters for D-T activity distributions, the following expression for the foil activity was used:

$$A_S(r)r^2 = e^{-r/L} \times \text{Constant} \quad (2)$$

where  $L$  is the relaxation length of indium-resonance activity.

The numerical integrations of equation (1) and the determination of  $L$  in expression (2) were performed with a FORTRAN IV computer program (ref. 8).

## EXPERIMENT

Spatial indium-resonance activity distributions with a D-D neutron source in a 6-centimeter-diameter beam duct were measured in mixtures (by volume percent) of 15 tungsten (W) - 85 water ( $\text{H}_2\text{O}$ ) and 26.7 W - 73.3  $\text{H}_2\text{O}$ . D-D distributions were measured in water with two beam ducts, 3 and 6 centimeters in diameter. Indium-resonance activity distributions were measured for a D-T neutron source in a 6-centimeter-diameter beam duct in water and in the 15 W - 85  $\text{H}_2\text{O}$  mixture.

## Geometry

Tungsten-water measurements. - The experimental geometry of the tungsten-water measurements is shown in figure 1. Measurements were made in a cylindrical tank 1.83 meters in diameter by 1.52 meters in height. The tank was filled with demineralized water, maintained at a resistivity of 200 000 ohm-centimeters or greater. The tungsten used was in the form of metallic rods 1.2 centimeters in diameter by about 1.7 meters in length arranged in a hexagonal array and supported by edge-bored aluminum bars mounted on an aluminum angle frame. The two sets of bars were separated 122 centimeters, and the distance from the source target to the aluminum support bars in the direction of measurement was 76 centimeters. The 450 tungsten rods were arranged in 12 hexagonal rings about the central tungsten rod. An aluminum tube with a 6.03-centimeter outside diameter and a 0.16-centimeter wall thickness was passed through the center of the array and through the tank wall. To make room for the aluminum tube, the central tungsten rod and the first ring of six rods were removed. The aluminum tube was precisely centered in the hexagonal array and was divided near the center by a welded aluminum bulkhead. One end of the aluminum tube was open to accommodate the beam tube of the accelerator. Figure 2 shows a section of the aluminum tube near the target. The end of the aluminum tube opposite the source contained methyl methacrylate (plastic) inserts to simulate water. These inserts held the first row of hexagonal tungsten rods and were also used to center the foil holder. The cadmium-covered foils for forward direction measurements were positioned in the plastic foil-holder tube and inserted through this end of the aluminum tube. After the foil-holder tube was inserted, this end of the aluminum tube was closed and the tube filled with water. Segments of the central tungsten rod were centered between the foils in the holder by plastic disks at either end of each section.

In all experiments with tungsten-water media, the accelerator beam tube used is as shown in figure 2. The diameter of the aluminum duct that enclosed the beam tube was the same on the beam tube side, but the diameter was larger on the foil-holder side in the 15 W - 85 H<sub>2</sub>O and H<sub>2</sub>O experiments. All the indium foils used were 0.013 centimeter thick, and all the cadmium covers were 0.089 centimeter thick. In general, foils were irradiated no closer than 7.6 centimeters apart; the only exception was the use of a normalizing foil, 0.98 centimeter in diameter, at the end of the foil-holder tube. This foil was irradiated as close as 4.1 centimeters to the nearest large foil. Source-foil distances are accurate to  $\pm 0.04$  centimeter for the forward direction measurements.

For the 26.7 W - 73.3 H<sub>2</sub>O experiment, the indium foils were 2.54 centimeters in diameter, and the rod spacing was 2.20 centimeters.

For the 15 W - 85 H<sub>2</sub>O experiment, a larger diameter aluminum tube was required on the side of the bulkhead in the direction of measurement. Indium foils 1.27, 2.54,

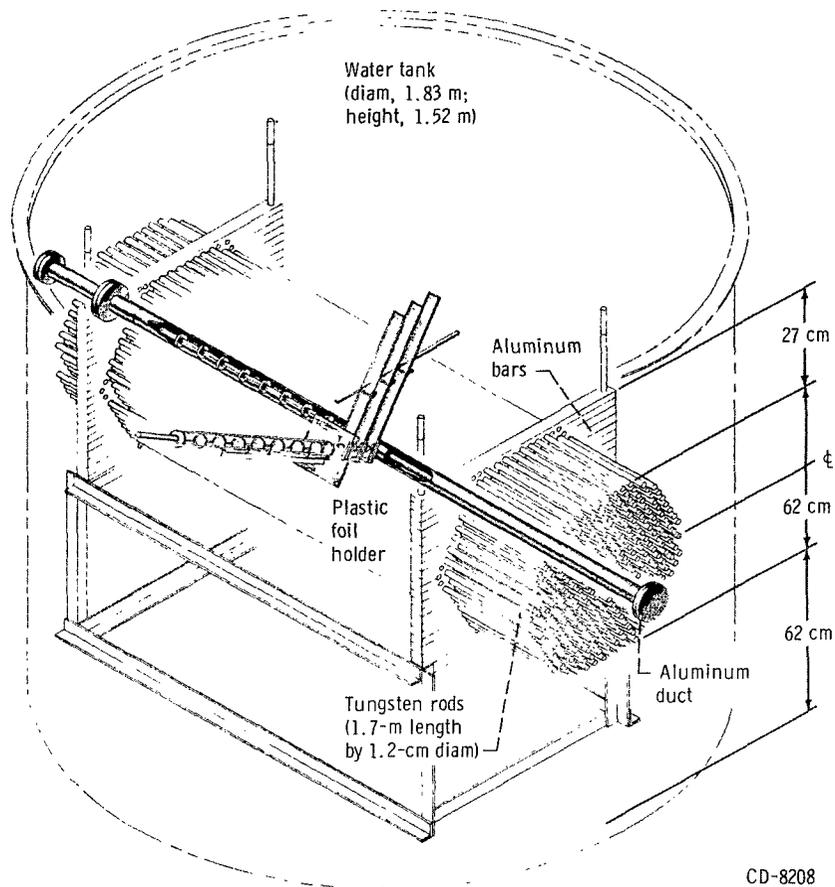


Figure 1. - Experimental geometry for age measurements in tungsten-water mixtures.

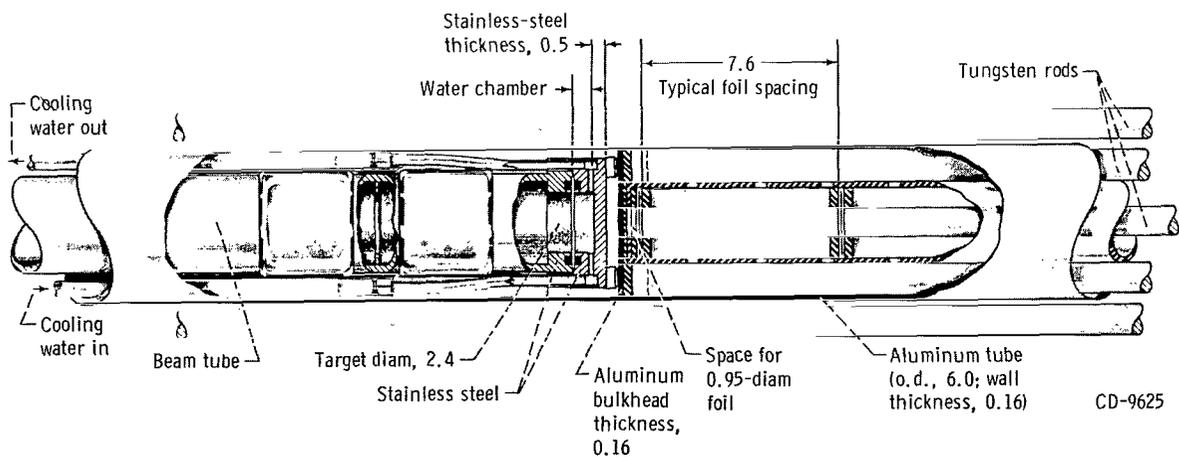


Figure 2. - Target and foil holder for mixture of 26.7 W - 73.3 H<sub>2</sub>O percent by volume. (All dimensions are in centimeters.)

and 3.49 centimeters in diameter were irradiated in the forward direction. The foil holder for this experiment just held the largest foil covers. Smaller foils were irradiated in cadmium covers just large enough to hold them. Plastic rings centered the smaller cadmium covers in the holder. The tungsten-rod spacing was 2.93 centimeters for this array.

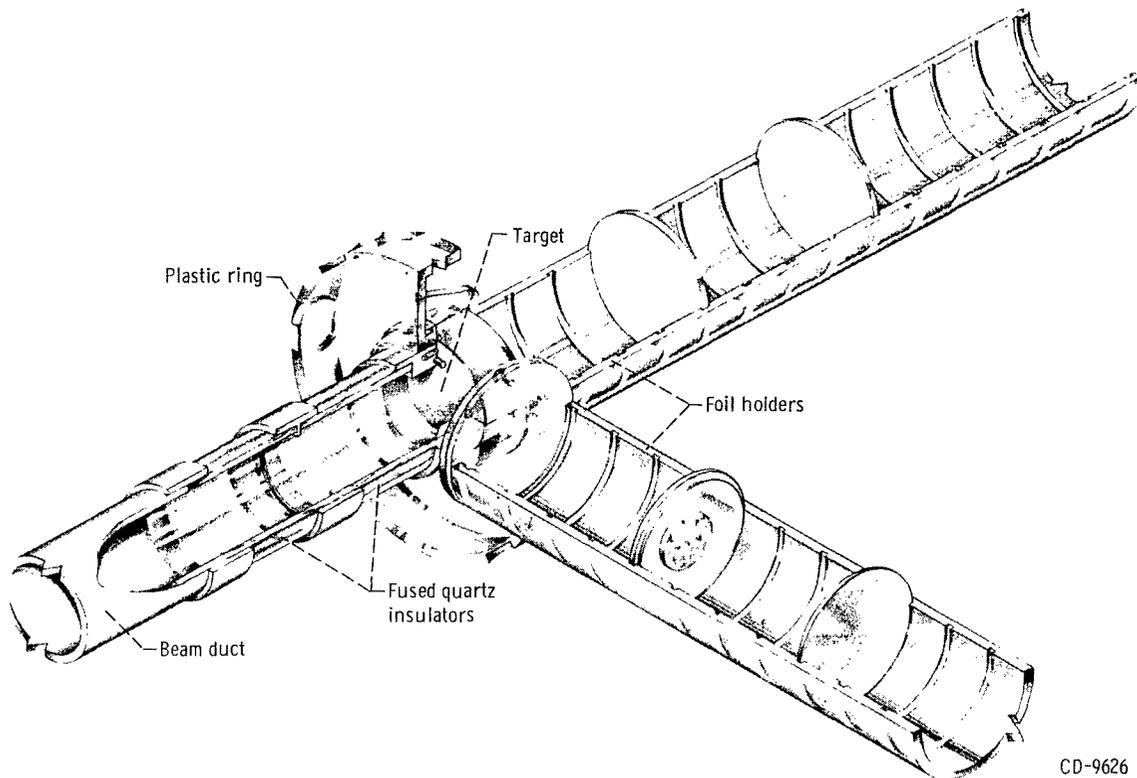
Measurements at  $90^{\circ}$  in the 15 W - 85 H<sub>2</sub>O experiment (see fig. 1) were made with foils 1.27, 2.54, and 3.81 centimeters in diameter. Foil holders were constructed of thin sheets of plastic. The sheets were made thicker at the foil cover end to fill the space between the hexagonal rows. A plastic clamp was fixed to the sheet at a measured distance, and the foil holder was slipped between the hex rows. The clamp rested on the top row of bars. The position of the holder along the rods was fixed by placing the foil holder next to an aluminum bar clamped to the tungsten rods. To extend the measurements into the water, a plastic support was fixed to the outer row of tungsten rods. The foil covers were held in a plastic foil holder that was positioned by the fixture. This holder consisted of three plastic rods with slots milled at intervals. Source-foil distances at  $90^{\circ}$  are accurate to  $\pm 0.1$  centimeter.

Water measurements. - D-D and D-T measurements in water were made with the 6-centimeter-diameter aluminum tube and beam duct used in the 15 W - 85 H<sub>2</sub>O experiment. Sections of plastic rod replaced the sections of tungsten rod in the spacers between foils. For measurements at  $90^{\circ}$ , a plastic fixture was attached to the aluminum tube and a plastic foil holder was held by the fixture. Source-foil distances at  $90^{\circ}$  are accurate to 0.05 centimeter.

D-D neutron distributions at  $0^{\circ}$  and  $90^{\circ}$  in water were also measured with a 3-centimeter-diameter beam tube to evaluate the magnitude of the beam-duct correction for the 6-centimeter-duct measurements. The beam duct (fig. 3) in this experiment extended 76 centimeters into the water tank. The duct diameter at the target was 3 centimeters. This diameter was maintained for a distance of 28 centimeters, at which point the duct widened to a 5.1-centimeter diameter. At 36 centimeters from the target, the beam was collimated by placing a tantalum disk, with a 1.6-centimeter-diameter aperture, in the beam tube.

The 3-centimeter-diameter beam duct was constructed of stainless steel except for the two fused quartz insulator sections shown (fig. 3). The target was a 0.25-millimeter-thick copper disk plated with titanium and filled with deuterium in a tritium-free facility. The target was O-ring sealed to the end of the beam duct and was cooled by water from the tank.

The beam duct was attached to the accelerator by means of a bellows. Beam alignment was secured in the following manner. A plastic ring (shown in fig. 3) was attached concentrically with the end of the beam duct. Cadmium-covered indium foils, 1.25 centimeters in diameter by 0.127 millimeter in thickness, were positioned at  $90^{\circ}$  separations



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Figure 3. - Beam tube and foil-holder arrangement for measurements of beam-duct effects in water.

in grooves machined in the circumference. The duct position was changed until the foil activities were within  $\pm 2$  percent of each other, which indicated that the beam was centered within 0.2 centimeter.

The foil holders were made from sectioned plastic tubes that had grooves cut in the inside surface at intervals. A thin plastic disk was glued to one machined end to aid in positioning. The indium foils were 3.18 centimeters in diameter by 0.013 centimeter in thickness, and 1.25 centimeters in diameter by 0.013 centimeter in thickness. The cadmium covers for the larger foils snapped into position in the holder.

Plastic disks of the same diameter as the cadmium foil holders were made with an extra 0.51 millimeter of thickness. In the center of the disk, a circular well, with a 0.51-millimeter bottom thickness, held the 1.25-centimeter-diameter foils in the same plane as the larger foils.

Foil-holder tubes were held at the end away from the source by a plastic support. At the source, the plastic ring mentioned earlier aided in the positioning of the foils. At  $0^\circ$ , four machined plastic spacers were glued to the plastic ring. These allowed water to flow over the target and both supported and determined the spacing of the  $0^\circ$  foil holder. At  $90^\circ$ , a thin plastic disk was glued to the plastic ring. A hole and a slot in this disk

mated with a small screw in the face of a corresponding disk on the end of the 90° holder.

Foil distances from the target at 0° are known to within ±0.025 centimeter. At 90° the precision is ±0.015 centimeter from the geometric center.

## Data Taking and Data Reduction

Several sets of 0.127-millimeter-thick indium foils ranging in diameter from 0.95 to 3.82 centimeters were used. Each set of cadmium-covered foils was calibrated in air by simultaneous irradiation on a rotating wheel with the NASA zero power reactor - I (ZPR-I) as a thermal neutron source. Relative foil efficiency factors obtained in this calibrating flux varied ±3 percent. Foil front and back surfaces were counted separately with several internal-flow  $2\pi$  proportional counters. Counter plateaus were maintained to better than 1 percent per 100 volts, and a standard source was counted daily.

The dominant foil activity of interest is an isotope of indium,  $\text{In}^{116}$ , which has a 54-minute half-life. A number of other important radioactive indium nuclides are formed, but most of these isomeric states have short half-lives and decay away in several minutes. The metastable isotope  $\text{In}^{115}$  is formed by inelastic excitation and has a 4.5-hour half-life. This activity is induced primarily near the source and can interfere with measurements in the region surrounding the source. The foil data were corrected for a 4.5-hour activity by separation of the foil decay curves into long- and short-lived components. A small amount of 50-day  $\text{In}^{114}$  activity gradually builds up with continued foil use. An irradiation history for each foil was maintained.

A 0.95-centimeter-diameter foil was positioned in the end of the foil holder (as shown in fig. 2) to normalize the large foil data in the distributions measured with the 6-centimeter-diameter beam duct. When data were desired closer to this position than 4.1 centimeters, the data point was normalized by means of the foil data farther from the source.

Foil normalization in the 3-centimeter-duct measurements was as follows: In the first run, 3.18-centimeter-diameter foils A and B were irradiated at a 14.0-centimeter distance from the target at 0° and 90°, respectively. In the next three runs, foil A was irradiated at the same 0° position. In the last run, foil B was irradiated at the same 90° position. After all counts were normalized to end-of-irradiation values and were averaged front and back, the averages were normalized by the ratio of foil A counts or foil B counts to the respective counts in run 1. Small foil activities were normalized to large foil activities by means of a foil irradiation on a cadmium-covered wheel, as previously described. Changing the foils from counter to counter revealed that the count rates of all the foils of a given size and all the counter efficiencies were identical to better than ±1 percent.

# EXPERIMENTAL RESULTS AND DISCUSSION

## Spatial Distributions

The spatial distributions of indium-resonance activity from D-D source neutrons in pure water are shown in figure 4 for two beam ducts of 3- and 6-centimeter diameter, respectively. The ordinates are relative counts per minute  $A_s$  times the square of the target-to-foil distance  $r$ . The data for the 3-centimeter-diameter duct in the forward direction ( $0^\circ$ ) were normalized to that for the 6-centimeter-diameter duct at about

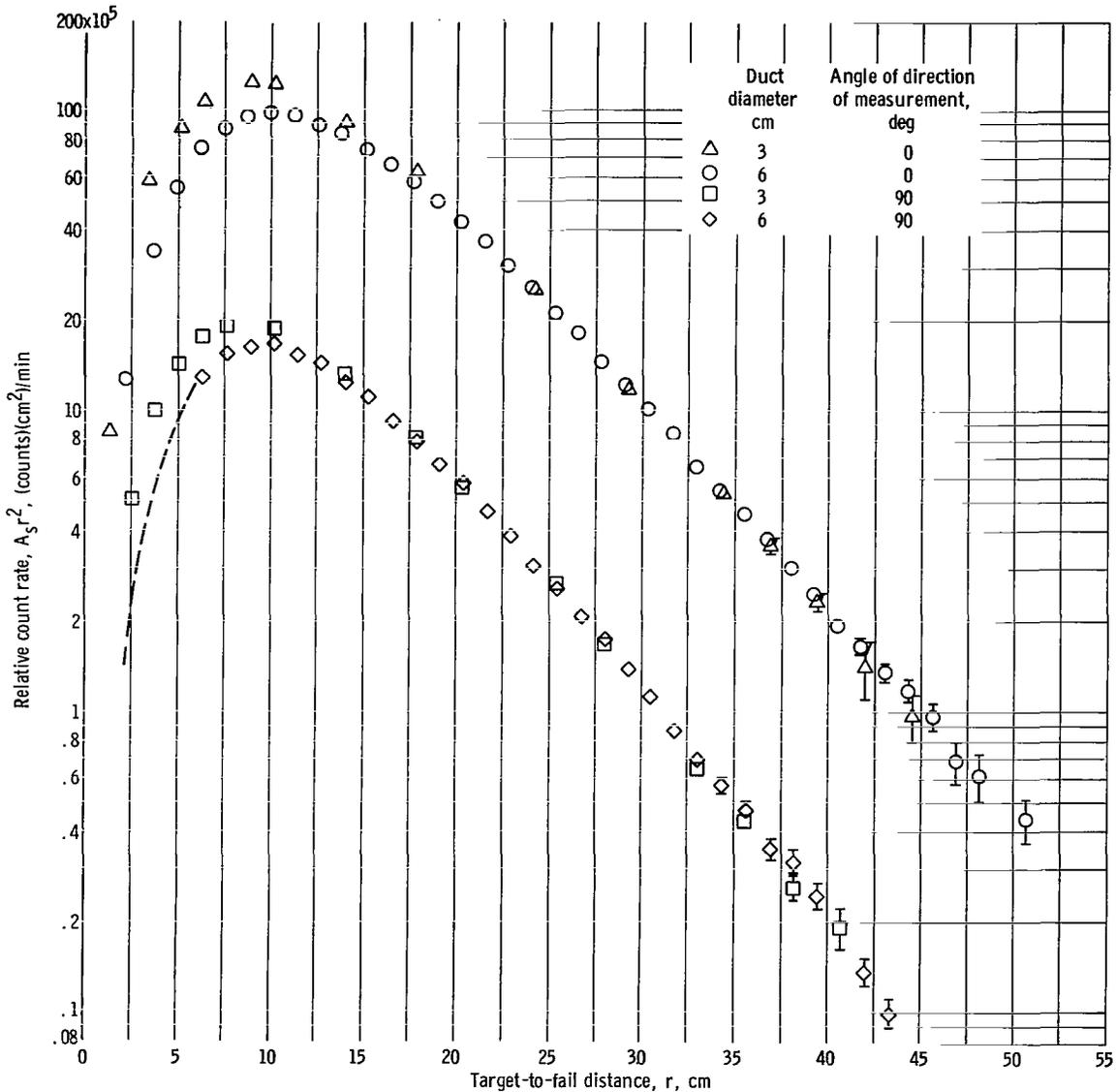


Figure 4. - Spatial distribution of indium-resonance activity in water from D-D neutrons.

30 centimeters from the source. The same normalization factor was applied to the data for the 3-centimeter-diameter duct at  $90^\circ$ . The shape and the ratio of the  $90^\circ$  data to the  $0^\circ$  data are nearly the same at source-to-foil distances greater than 25 centimeters for the two beam-duct diameters. However, data for the 6-centimeter duct are progressively lower at distances of less than 15 centimeters. The effect of a duct on the second moment of the spatial distribution is thus to provide too large a value and, hence, a correspondingly larger age.

The spatial distributions for D-D neutrons in tungsten-water media are shown in figure 5. The measurements are made with the 6-centimeter duct, and the data are similar in shape to the water measurements made with the 6-centimeter duct. The 15 W - 85  $H_2O$  data at  $90^\circ$  are extrapolated beyond  $r = 27$  centimeters by using the shape of the

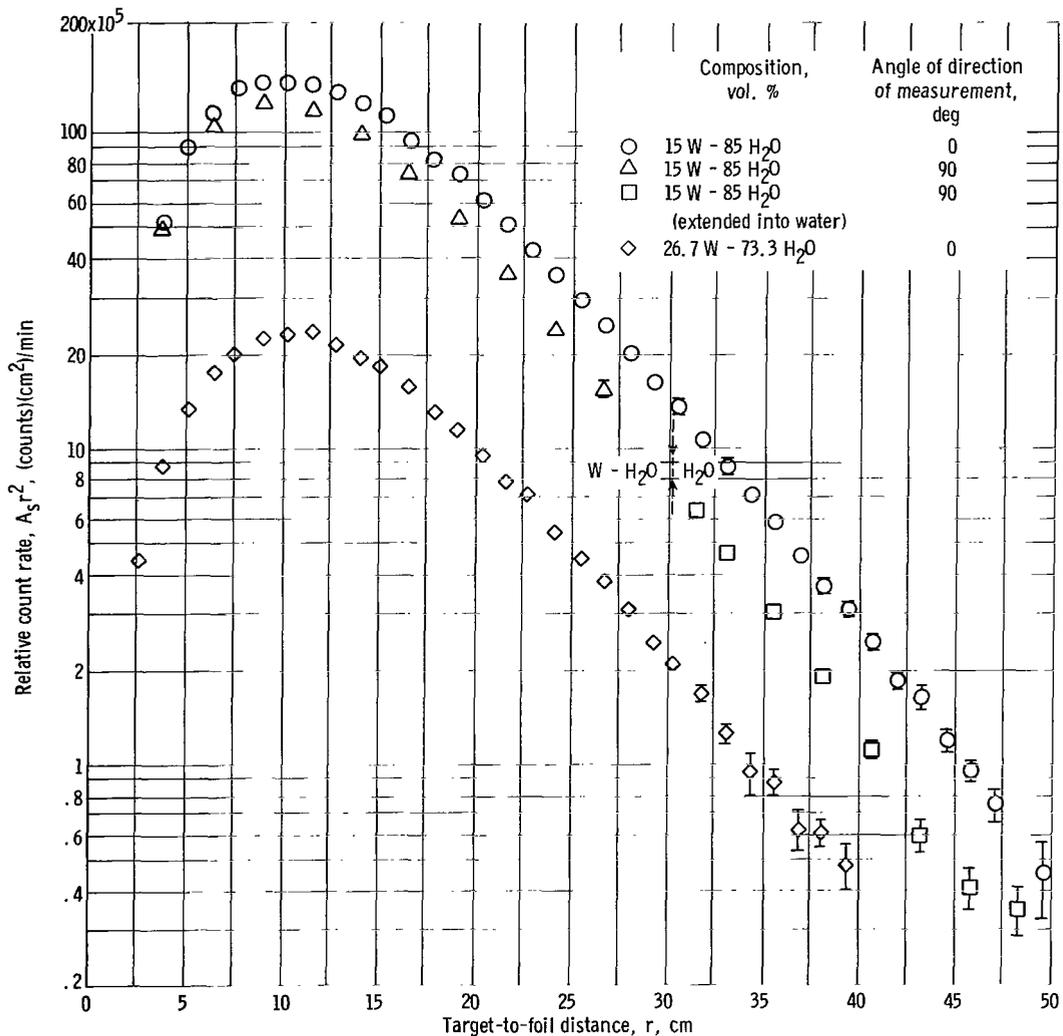


Figure 5. - Spatial distribution of indium-resonance activity in tungsten-water mixtures from D-D neutrons.

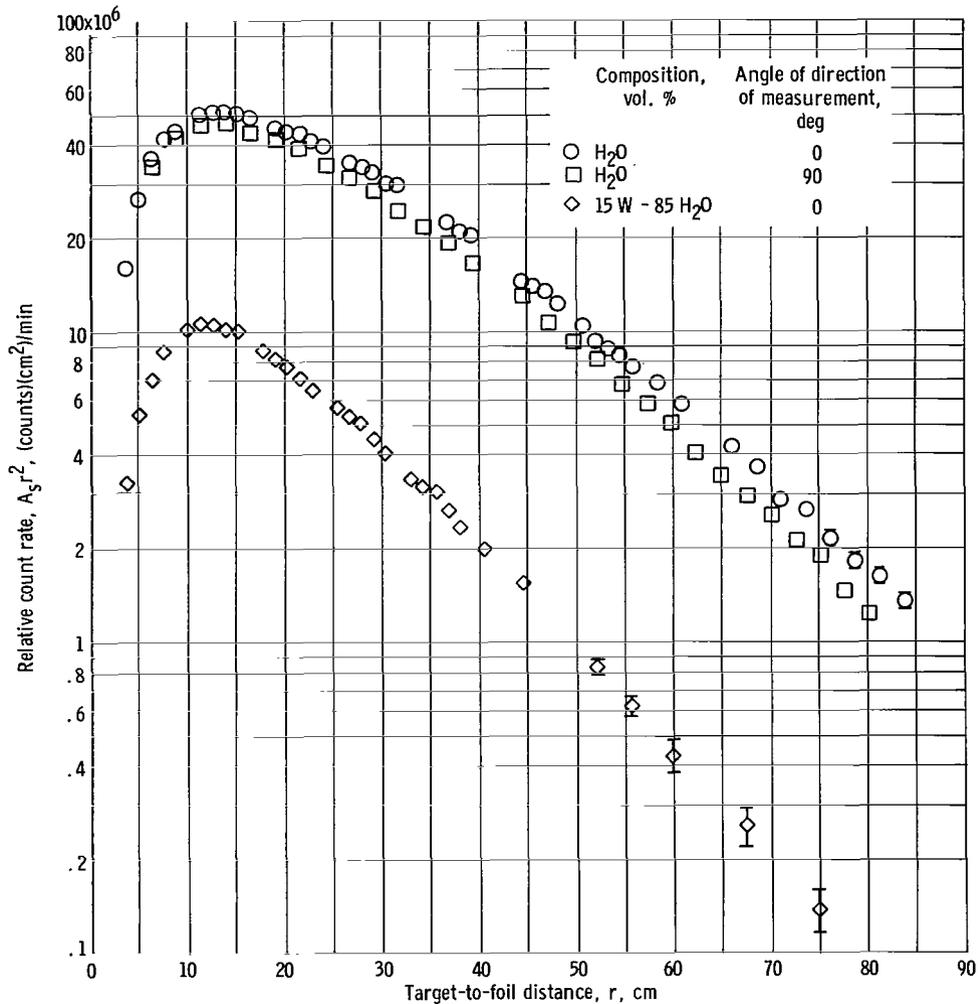


Figure 6. - Spatial distribution of indium-resonance activity from D-T neutrons in water and tungsten-water mixtures.

measurements made in 15 W - 85 H<sub>2</sub>O at 0°. This extrapolation is a reasonable upper limit to the distribution. The square symbols beyond r = 30 centimeters are measured points in the surrounding water medium.

The spatial distributions for water and 15 W - 85 H<sub>2</sub>O from D-T neutrons are shown in figure 6. In most of these distributions, the slope of the curve of indium-resonance activity  $A_s r^2$  against the target-to-foil distance r becomes steeper at larger values of r. However, since the extrapolated portions of the integrals used to determine the age are small, these variations in slope are not too important.

## Experimental Ages

Table I presents the experimental ages derived from the spatial distributions. The nominal energy is the energy of neutrons emitted in the given direction of measurement (ref. 9). The data have been extrapolated past the distance  $R$  with a relaxation length  $L$ . The contributions to the numerator and denominator of equation (1) past the distance  $R$  are the extrapolated fractions expressed as percentages. Also shown in the table are two corrections to the experimental ages. These corrections account for the finite beam-duct and foil-flux detector effects.

After the corrections and questions of the medium heterogeneity and size are discussed, the experiment is analyzed as a point-anisotropic source in an infinite medium.

Foil detector correction. - The variation of the point flux from the finite foil activity measured has been investigated in detail (refs. 10 to 12) and is small.

The finite radius of the foil results in greater source-foil distances at the edge of the foil than at the center. The correction for this geometric effect due to the foil and target was made according to the equation

$$A(r_0) - A_m(r_0) = \frac{-(a_t^2 + a_f^2)}{4r_0} \left( \frac{dA}{dr} \right)_{r_0}$$

where  $A(r_0)$  is the activity at distance  $r_0$  from the source,  $A_m(r_0)$  is the measured foil activity at  $r_0$ ,  $a_t$  is the effective target radius,  $a_f$  is the foil radius, and  $(dA/dr)_{r_0}$  is the rate of change of activity with distance from the source, evaluated at  $r_0$ . A correction of +0.51 square centimeter to the measured fission neutron age in water is computed in reference 11 to account for foil detector blackness. A second correction of +0.11 square centimeter is computed to account for the variation of effective cadmium cutoff energy with neutron angular distribution. These corrections are used herein as upper limits to a foil detector correction in the D-D neutron measurements.

The foil activity of a cadmium-covered indium foil sandwiched between sections of tungsten rod is depressed at the rod center by about 20 percent from the water activity. This depression was measured in reference 4 and was indicated not to have any effect on the measured age. Additional measurements with different foil sizes are presented herein. Distributions were measured in the 15 W - 85 H<sub>2</sub>O medium with the D-D neutron source. Foils of 3.49, 2.54, and 1.27 centimeters in diameter were used. The 2.54-centimeter foils showed a 5.5±2 percent lower specific activity than that of the 3.49-centimeter-diameter foils at each foil position in the region of overlap from 5 to 16 centimeters. Too much scatter existed in the data for the 1.27-centimeter foils to make an accurate comparison; but when these data were corrected by the +16 percent predicted by

TABLE I. - SUMMARY OF EXPERIMENTAL AGE DATA FOR WATER AND TUNGSTEN-WATER MIXTURES

Neutron reaction	Angle of measurements to beam, deg	Nominal energy, MeV	Medium volume composition, vol. %	Beam-duct diameter, cm	Relaxation length, L, cm	Distance measured, R, cm	Extrapolated fraction, percent		Foil distribution age, cm <sup>2</sup>	Foil detector correction, cm <sup>2</sup>	Duct correction, cm <sup>2</sup>	Experimental point-source age, cm <sup>2</sup>
							$\int_R^\infty A_S r^4 dr$	$\int_R^\infty A_S r^2 dr$				
D-D	0	2.84	100 H <sub>2</sub> O	3	5.9	42	4.4	0.4	39.1±2.0	0.5	-1.6±0.8	38.0±2.3
D-D	90	2.47	100 H <sub>2</sub> O	3	6.1	38	5.7	.6	33.7±2.4	.5	-3.2±1.0	31.0±2.6
D-D	0	2.84	100 H <sub>2</sub> O	6	6.4	46	3.9	.4	44.3±0.7	.4	<sup>a</sup> -6.7±2.4	38.0±2.3
D-D	90	2.47	100 H <sub>2</sub> O	6	5.7	43	2.7	.3	38.2±1.4	.4	<sup>a</sup> -7.6±3.0	31.0±2.6
D-D	0	2.84	15 W - 85 H <sub>2</sub> O	6	5.6	46	3.3	.3	42.0±0.5	.4	-6.7±2.4	35.7±2.5
D-D	90	2.47	15 W - 85 H <sub>2</sub> O	6	5.6	27	24.2	5.0	37.9±2.5	.4	-7.6±3.0	30.7±3.9
D-D	0	2.84	26.7 W - 73.3 H <sub>2</sub> O	6	6.1	36	10.3	1.5	41.9±1.2	.5	-6.7±2.4	35.7±2.7
D-T	0	14.68	100 H <sub>2</sub> O	6	15.9	74	18.8	2.4	175.4±5.0	---	-----	-----
D-T	90	14.06	100 H <sub>2</sub> O	6	14.6	75	14.5	1.7	161.9±5.0	---	-----	-----
D-T	0	14.68	15 W - 85 H <sub>2</sub> O	6	12.8	60	17.7	2.2	112.7±5.0	---	-----	-----

<sup>a</sup>The duct corrections in D-D 100-percent water measurements with a 6-cm duct have been chosen so that experimental point-source ages will agree with 3-cm duct results.

the detailed distribution (ref. 4), they overlay the 3.49-centimeter-foil data. The conclusion made from these results is that the foil activity depression encountered in the measurements has no effect on the age.

Heterogeneous effects. - Possible deviations of the ages for homogeneous media from ages measured with the metallic tungsten rods are difficult to evaluate. A truly homogeneous measurement is difficult to achieve because the concentrations of interest are beyond the solubility limits of tungsten salts in water. Wade (ref. 12) has measured large differences in parallel and perpendicular ages for aluminum rods and heavy water media. The rods used by Wade, however, were of the order of 2 mean free paths in diameter, even in the MeV neutron energy region, which permitted neutrons to remain in the rods for many collisions and, in turn, permitted neutron transport down an aluminum rod. The rod spacing was also large, and thereby allowed neutrons to remain in heavy water for many collisions. The tungsten rods used herein are only about 0.5 mean free path in diameter, so that the probability of neutrons colliding in the rod and escaping into the water is high: the tungsten rod spacings are small, and the escape probability from water into the tungsten rods is therefore large. Consequently, in the present tungsten-water media, neutrons pass through tungsten and water in a quasi-homogeneous manner.

Beam-duct correction. - The size of the beam duct used has a significant effect on the measured D-D age, as shown by the foil distribution ages of the 3- and 6-centimeter-diameter ducts in water (table I). Measurements were not made with smaller ducts; however, Cooper (ref. 5) has computed the effect of small ducts by using Monte Carlo age calculations for 200-keV D-D neutrons in water. From these calculations can be obtained a correction of  $1.6 \pm 1$  square centimeters at  $0^\circ$  and  $3.2 \pm 1$  square centimeters at  $90^\circ$  for the 3-centimeter duct. The corrections have large uncertainties due to the Monte Carlo statistics, but the magnitudes of the corrections are small, particularly at  $0^\circ$ . The correction for the 6-centimeter-diameter duct is obtained as the Monte Carlo correction for the 3-centimeter-diameter duct plus the difference between the present foil-detector-corrected 6- and 3-centimeter-duct measurements. This duct correction is used for the tungsten-water mixture D-D measurements made with the 6-centimeter duct.

The quantitative effect of the duct on the D-T age measurements has not been evaluated, inasmuch as Monte Carlo calculations comparable with those made for the D-D sources are not available. However, qualitatively, the beam-duct correction is expected to be a smaller percentage of the measured age for D-T sources than that for D-D sources. This expectation follows from the considerations that the mean free path in water is 10 centimeters for uncollided D-T neutrons and 5 centimeters for uncollided D-D neutrons and that the slowing-down lengths for D-T neutrons are correspondingly larger. Therefore, a beam duct of a given size constitutes a smaller perturbation for a D-T than for a D-D slowing-down distribution.

Slowing-down medium size. - The slowing-down medium presented in figure 1 is the

same as that used in reference 4, where it was shown that the medium was infinite for Pu-Be source ages of the order of 50 square centimeters; thus, the medium is also infinite for the D-D ages of the order of 30 to 40 square centimeters measured herein. The required medium size for a D-T measurement was investigated in reference 13. Perpendicular to the direction of measurement, the medium used herein is adequate; however, in the direction of measurement, the medium is smaller than that of reference 13, but constitutes about four mean slowing-down distances.

Comparison with previous measurements for water. - The results obtained for D-D neutrons in water (table I) may be compared with the results of Spiegel, et al. (ref. 6), who used a deuteron beam of 250 keV incident on a thick target providing an average deuteron energy of 207 keV. They obtained measured ages of  $43.5 \pm 1.8$  square centimeters at a beam angle of  $0^\circ$  and  $33.1 \pm 1.3$  square centimeters at a beam angle of  $90^\circ$ . These values (when corrected for the presence of the 1.3-cm-diam beam duct with the Monte Carlo results of ref. 5) provide ages of  $42.6 \pm 2.0$  square centimeters at  $0^\circ$  and  $31.5 \pm 1.5$  square centimeters at  $90^\circ$ . Further corrections to account for differences in nominal neutron energies and the angular distribution of Spiegel's measurement from the present 135 keV deuteron source change these values of age to  $41.3 \pm 2.0$  square centimeters at  $0^\circ$  and  $32.0 \pm 1.5$  square centimeters at  $90^\circ$ . The present experimental age of  $38.0 \pm 2.3$  square centimeters at  $0^\circ$  (table I) is significantly lower; however, the present age of  $31.0 \pm 2.6$  square centimeters at  $90^\circ$  is in good agreement with Spiegel's results. The present experiment therefore provides the possible explanation that the disagreement between the results of Cooper (ref. 5) and Spiegel (ref. 6) in the  $0^\circ$  direction may be experimental in origin.

The present results for D-T neutrons in water (table I) may be compared with the results of Caswell, et al. (ref. 13) whose measurements were made only at  $90^\circ$  to the deuteron beam. They obtained an age of  $150 \pm 6$  square centimeters with a 2.5-centimeter-diameter beam tube. This result is significantly lower than the present experimental age of  $161.9 \pm 5.0$  square centimeters with a 6-centimeter-diameter beam tube. The present experimental age would be reduced if suitable beam-duct corrections were available.

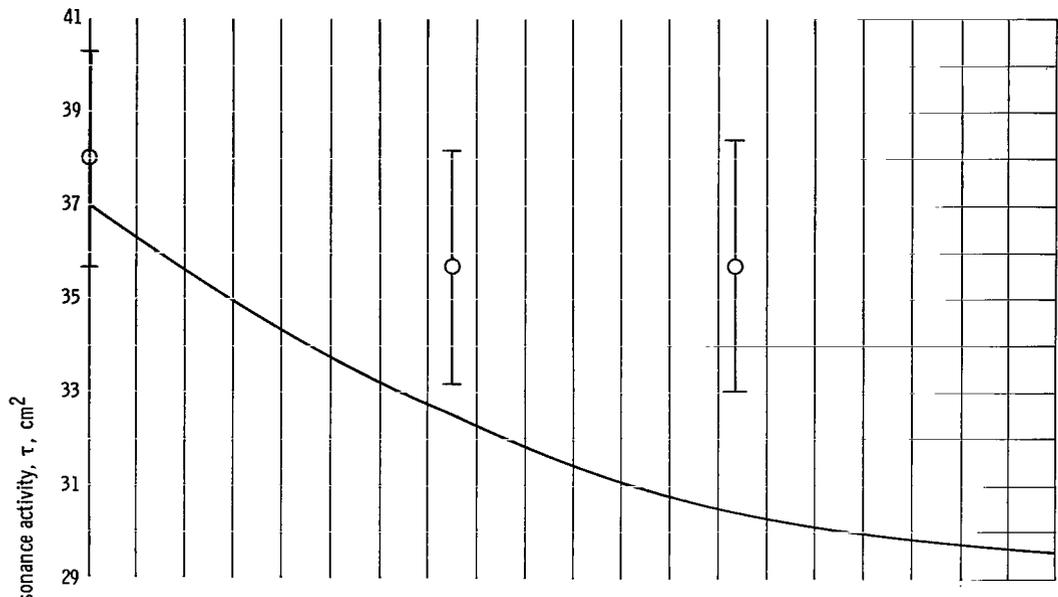
Calculated ages. - The calculated ages were obtained with the moments calculation option of the GAM II computer code (ref. 7). The GAM II code contains a library of nuclide cross sections for 99 energy groups covering the range from 0.414 eV to 14.9 MeV. The library used includes evaluated cross sections for inelastic scattering and (n, 2n) processes for the individual isotopes of tungsten and for water that were available as of the end of 1964. Inelastic scattering matrices for the isotopes of tungsten were generated by optical model fits to measured partial inelastic cross sections for  $W^{184}$  up to an energy of 1.5 MeV based on the parameters obtained in reference 14. Similar calculations were made for the other tungsten isotopes with the use of their known energy-level schemes. The isotopic cross sections used in GAM II are discussed in reference 15.

Above 1.5 MeV, the nonelastic cross section was assumed to be the same for each isotope and obtained from reference 1 for natural tungsten. Inelastic cross sections for each isotope were computed by subtracting the capture and the (n, 2n) cross sections from the nonelastic cross section. The emission spectrum for inelastically scattered neutrons above 1.5 MeV was computed from measured nuclear temperatures, with the same temperatures for all isotopes being used. Since this GAM II compilation was made, partial inelastic cross sections for  $W^{182}$ ,  $W^{184}$ , and  $W^{186}$  have been measured to 1.5 MeV at Argonne National Laboratory and have been analyzed by the optical model by Dunford (ref. 16). However, the GAM II cross sections used herein have not incorporated these recent data.

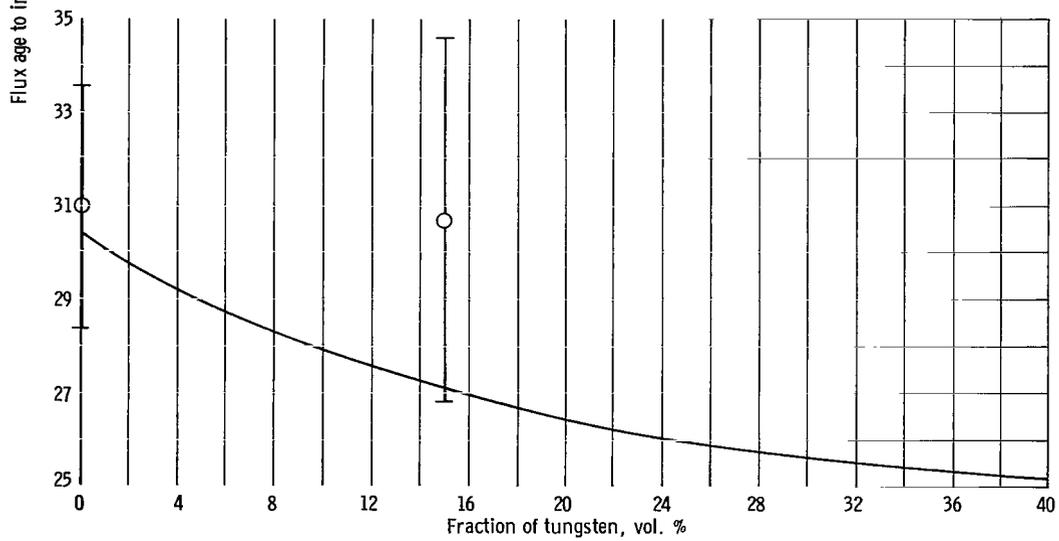
The source anisotropy effects were calculated for D-D sources by Cooper (ref. 5). The calculations of Cooper are used to obtain a (D-D) source correction for the monoenergetic point-isotropic source calculated by GAM II. This correction is obtained as the difference between the GAM II calculation for water at the nominal energy shown in table I and the Cooper calculation of the age in the direction of measurement corresponding to the same energy. Cooper's calculations were for somewhat higher energy neutrons than those used in the present experiment. The source intensity and anisotropy was also greater, so Cooper's correction was reduced by the ratio of the anisotropies in the two experiments. The corrections for the calculated GAM II ages are  $+0.5 \pm 0.2$  square centimeter at  $0^\circ$  and  $-2.5 \pm 0.7$  square centimeter at  $90^\circ$ . For comparison with the D-T measurements, no comparable corrections were made to the GAM II calculations for the D-T neutron sources.

Comparison of calculated and experimental ages. - The calculated ages and experimental ages for the D-D and D-T sources at two angles to the deuteron beam are shown in table I and in figures 7 and 8, respectively. Good agreement is seen between the experimental age ( $38.0 \pm 2.3 \text{ cm}^2$ ) and the calculated age ( $37.1 \text{ cm}^2$ ) for the  $0^\circ$  D-D measurement in water and for the  $90^\circ$  D-D measurement in water, where the experimental and calculated ages were  $31.0 \pm 2.6$  and  $30.6$  square centimeters, respectively. The difference between the experiment and the calculation increases with the tungsten fraction. In the forward direction, the measured age of  $35.7 \pm 2.5$  square centimeters for the 15 W - 85  $H_2O$  measurement is significantly larger than the calculated  $32.5$  square centimeters. The difference in the 26.7 W - 73.3  $H_2O$  measurement is even larger; the experimental age is  $35.7 \pm 2.6$  square centimeters, and the calculated age is  $30.5$  square centimeters. The  $90^\circ$  15 W - 85  $H_2O$  measurement of  $30.7 \pm 3.9$  square centimeters is higher than the calculated  $27.3$  square centimeters.

The uncorrected D-T measurements are higher than the calculations for both water ( $175.4 \pm 5.0 \text{ cm}^2$  as compared with  $166.0 \text{ cm}^2$ ) and the tungsten-water mixture ( $112.7 \pm 5.0 \text{ cm}^2$  as compared with  $91.6 \text{ cm}^2$ ), but the disagreement is greater for the tungsten-water mixture. A correction to the experiment for the beam duct is expected to be the same



(a) Angle of measurement to deuteron beam,  $0^\circ$ .



(b) Angle of measurement to deuteron beam,  $90^\circ$ .

Figure 7. - Comparison of calculated and corrected experimental D-D neutron ages.

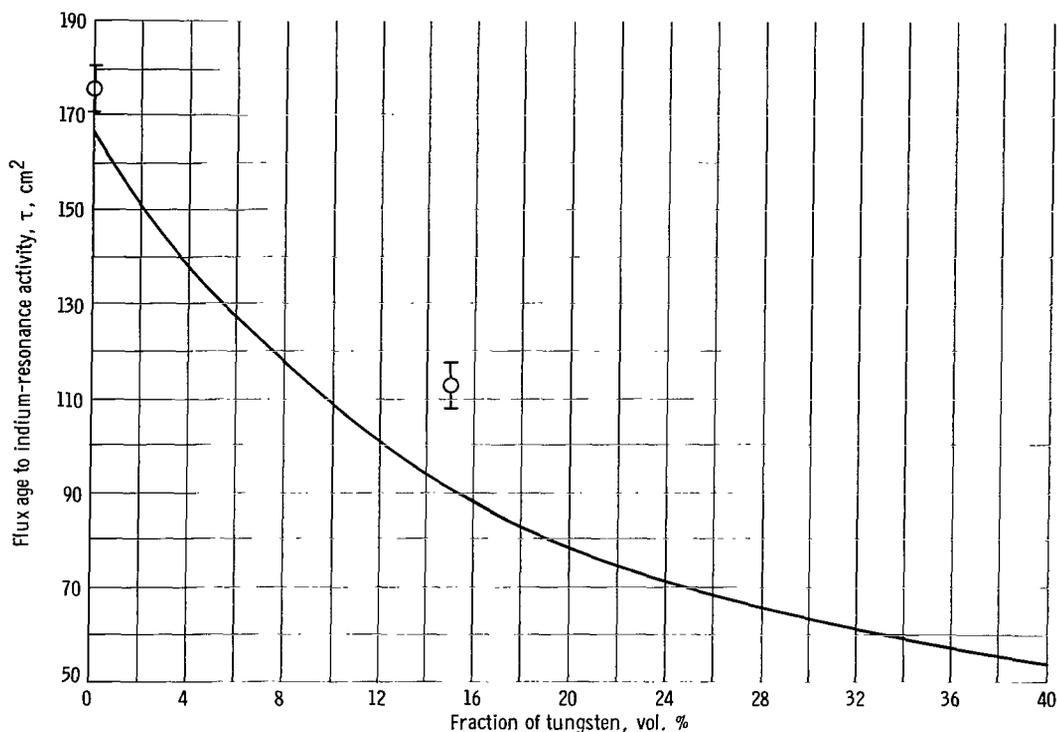


Figure 8. - Comparison of calculated and corrected experimental D-T ages. Angle of measurement to deuteron beam,  $0^\circ$ .

for both media and would lower both experimental ages. The resulting larger differences between experimental and calculated ages for D-T neutrons are indications that the tungsten-water age calculations are too low, as observed for D-D neutrons in tungsten-water media.

## CONCLUSIONS

Monoenergetic ages were determined from indium-resonance spatial distributions in water and tungsten-water media. Neutron sources were the  $D(d, n)He^3$  or the  $T(d, n)He^4$  reaction, and distributions were measured at  $0^\circ$  and  $90^\circ$  to the deuteron beam. The following conclusions are drawn:

1. The experimental ages for tungsten-water mixtures are smaller than the experimental ages for water because of the large inelastic scattering effects of tungsten.
2. The experimental ages for water with the  $D(d, n)He^3$  source are in good agreement with calculated ages. However, experimental ages for these nominally 2.5-MeV source neutrons in tungsten-water mixtures are larger than calculated ages that use the GAM II cross-section compilation. This discrepancy suggests that the partial inelastic cross

sections of the tungsten isotopes listed in GAM II are incomplete and that the evaporation model used to represent inelastic scattering for tungsten above 1.5 MeV probably overestimates down-scattering effects.

3. A published experimental age for  $D(d,n)He^3$  neutrons at  $0^0$  in water of  $43.5 \pm 1.8$  square centimeters (Spiegel, Oliver, and Caswell) is corrected to a value of  $41.3 \pm 2.0$  square centimeters for the presence of the beam duct and for small differences in source energy and angular distribution for direct comparison with the present experimental results. This corrected value significantly exceeds the present experimental age of  $38.0 \pm 2.3$  square centimeters at  $0^0$ . Inasmuch as the experimental ages at  $90^0$  are in agreement, and the present ages at  $0^0$  and  $90^0$  agree with calculations, the present results suggest that the age reported by Spiegel for the  $0^0$  direction may be too large.

4. The experimental ages obtained with the  $T(d,n)He^4$  source providing nominally 14-MeV neutrons also illustrated the large inelastic scattering effects of tungsten. Precise comparison of experimental and calculated ages is difficult because corrections for the beam duct for 14-MeV neutrons are not available. However, the beam duct corrections are expected to be similar for water and the tungsten-water mixture studied. Therefore, the 21-square-centimeter difference between the measured and calculated ages in the tungsten-water mixture compared with the difference of only 9 square centimeters in water is contributory evidence supporting the result that the evaporation model used in the GAM II cross-section set overestimates down scattering of the tungsten isotopes.

Lewis Research Center,  
National Aeronautics and Space Administration,  
Cleveland, Ohio, February 7, 1968,  
129-02-04-03-22.

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