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SUMMARY

The spatial distributions of neutrons slowing down from plutonium-beryllium (Pu-Be) sources as indicated by cadmium-covered indium foil activities were measured in water and in mixtures of metallic tungsten rods and water. The effects of the finite sizes of the sources on the shapes of the distributions were experimentally determined. The effects of the heterogeneity and finite size of the slowing-down media were also evaluated.

Experimental ages obtained with a 5-curie source corrected to a point source were 50.5±2 square centimeters in water and 46.8±3 and 40.6±3 square centimeters in mixtures of 15 tungsten - 85 water and 23.7 tungsten - 76.3 water percent by volume, respectively. An age of 53.0±3 square centimeters was determined for a 1-curie Pu-Be source in water. The measurements confirm a reduction in age due to tungsten with its large inelastic scattering cross sections. Calculated and measured ages agreed for water, but the calculated ages were an average of 15 percent lower than the measured ages for the tungsten-water mixtures. Possible reasons for the lower calculated ages are the uncertainties in high-energy tungsten cross sections and the use of the evaporation model to represent inelastic scattering above a neutron energy of 1.8 MeV.

INTRODUCTION

The large inelastic cross sections for tungsten (ref. 1) and the accompanying large energy losses for neutrons indicate that inelastic scattering processes are important in computations for reactors containing tungsten. Comparisons of calculations with measurements of neutron ages for tungsten-water media can serve as tests of available cross section data because of the sensitivity of ages to inelastic scattering in the slowing-down processes for tungsten-water mixtures.

Results for a large number of age measurements have been compiled (ref. 2). These measurements were made with various fast neutron sources and for several moderators and metal-moderator mixtures. Past disagreements between calculated and experimental

fission neutron ages in water have led to detailed study of the experimental methods used (refs. 3 and 4), and sources of systematic error have been investigated (refs. 5 and 6). The presently employed techniques must still use foils which are imperfect flux meters, and foil activity distributions must be corrected for effects of the finite source size. While these effects on measured ages are evaluated quantitatively, they reduce the precision with which experiments and calculations can be compared.

The measurements reported herein were made in a point-source point-detector geometry with cadmium-covered indium as a detector and plutonium-beryllium (α, n) neutron sources. These sources provide a broad distribution of fast neutrons with spectra that have been measured accurately above 1 MeV (refs. 7 and 8). The average source neutron energy is approximately 3 MeV, and the effects of uncertainties in source spectra on calculated ages were investigated.

METHOD OF MEASUREMENT

Ages were determined from measured cadmium-covered indium foil activity distributions about a point source (ref. 9) by evaluating the equation

$$\tau_{1.4eV} = \frac{1}{6} \frac{\int_0^\infty A_s r^2 4\pi r^2 \, dr}{\int_0^\infty A_s 4\pi r^2 \, dr} \tag{1}$$

where $\tau_{1.4eV}$ is the flux age to 1.4 electron volts and A_s is the averaged front-and-back counted foil activity proportional to the neutron flux at distance r from a point source located in an infinite medium. The Pu-Be sources used in the measurements are not point sources; however, the finite size of the sources is accounted for experimentally by extrapolating ages obtained with different-sized source configurations to an age for point sources. Effects associated with the use of cadmium-covered indium foils as flux detectors are more difficult to evaluate, but evidence in the literature (refs. 3 and 4) indicates that foil activation distributions correspond closely to flux distributions for the angular flux variations encountered in moderating media. The importance of this flux detector effect depends on the overall statistical accuracy of the age measurements and is discussed in the EXPERIMENTAL RESULTS AND DISCUSSION section of this report; effects relating to the finite size and heterogeneous composition of the tungsten-water media are also discussed in the EXPERIMENTAL RESULTS AND DISCUSSION section.

The integrals in equation (1) were evaluated numerically in the region of measure-

ment. At large values of r the following expression was used:

$$A_s r^2 = e^{-r/\lambda} \tag{2}$$

where the relaxation length λ was determined at values of r greater than 25 centimeters. In this region, the $A_s r^2$ distributions vary exponentially with r within the experimental accuracy.

The numerical integrations of equation (1), the determination of λ in expression (2), and the calculations of foil-saturated activities from observed count rates were performed with a computer program written for a digital computer (ref. 10). In the program, the integration of equation (1) was done primarily with closely spaced trapezoidal fits to the data; equivalent results were obtained with polynomial fits.

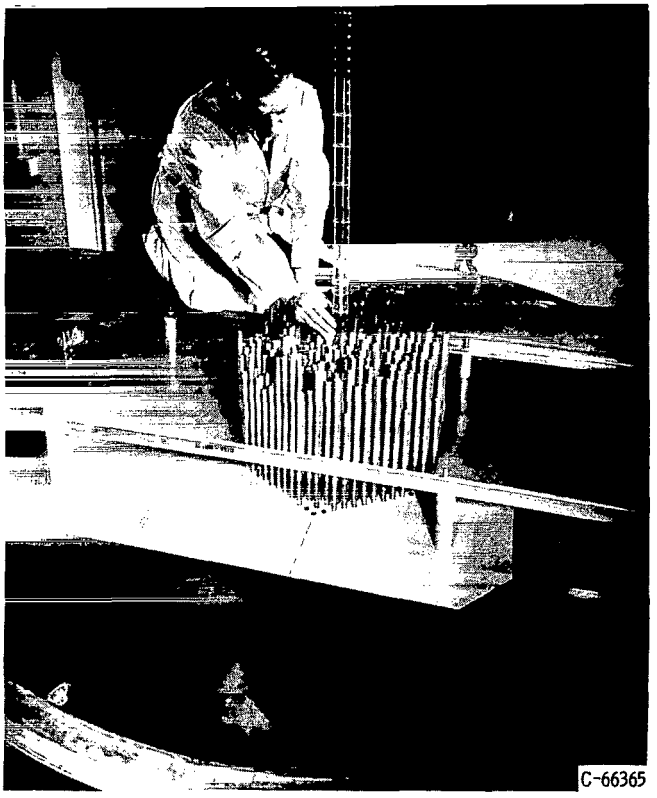


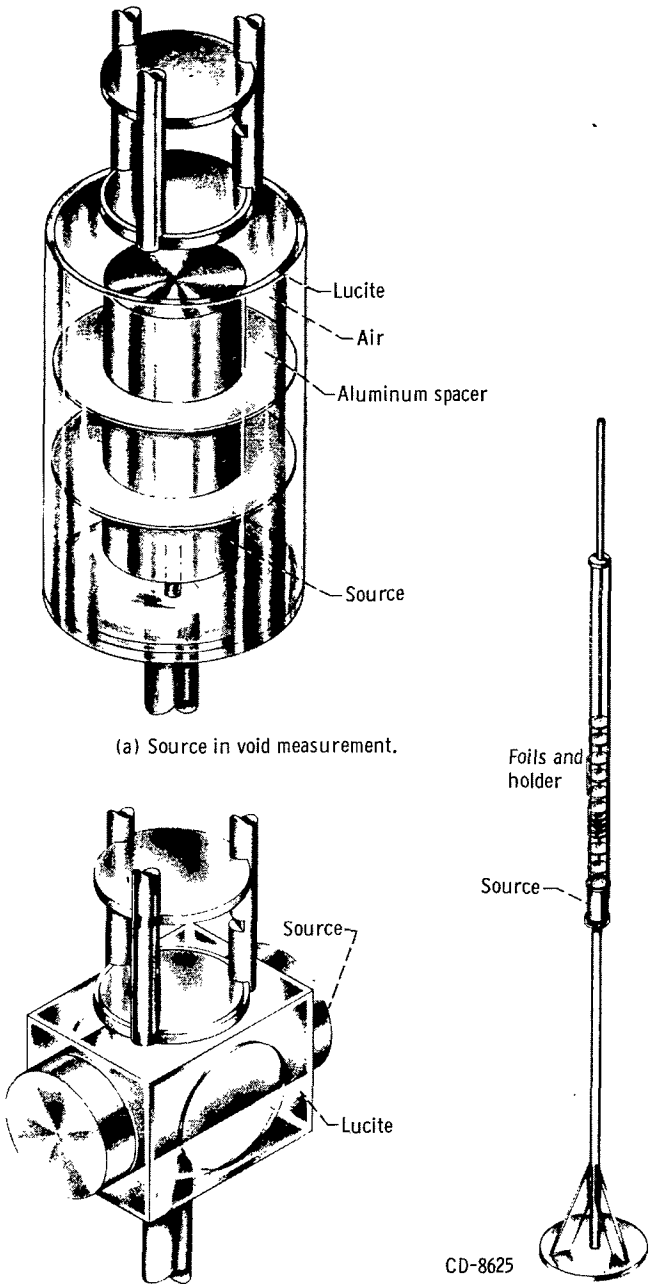
Figure 1. - Experimental geometry for age measurement for mixture of 23.7 tungsten - 76.3 water percent by volume.

EXPERIMENT

Geometry of Measurements

Spatial distributions of cadmium-covered indium foil activities were measured in water and in mixtures of 15 tungsten (W) - 85 water (H_2O), 23.7 W - 76.3 H_2O, and 26.7 W - 73.3 H_2O percent by volume. Measurements were made in a cylindrical tank 1.83 meters in diameter by 1.52 meters in height and also in a smaller tank that is 61 centimeters in diameter by 1.22 meters in height. These tanks contained demineralized water maintained at a resistivity of 200 000 ohm-centimeters or greater.

The large tank, which contained the 23.7 W - 76.3 H_2O mixture, is shown in figure 1. The tungsten used was in the form of metallic rods 1.19 centimeters in diameter and approximately 1.7 meters in length arranged in a hexagonal array with a 2.34-centimeter center-to-center rod spacing by the aluminum spacer grids



(a) Source in void measurement.

(b) Radial measurement.

(c) Measurement along source axis.

Figure 2. - Lucite foil and source holder used in water-age measurements.

shown. In the radial direction the medium consists of 30 centimeters of tungsten and water surrounded by 61 centimeters of water. The foil activation measurements were made in the axial direction along the central rod. The 5-curie Pu-Be source was positioned 60 centimeters from the bottom of the tank and supported by a section of the central tungsten rod. The indium foils were held by the Lucite holder shown in figure 2(c). The upper section of the central tungsten rod was cut into short lengths that were positioned between the foils, which were irradiated at a minimum spacing of 7.6 centimeters. The indium foils measured 0.127 millimeter in thickness by 3.18 centimeters in diameter and were contained in 0.89-millimeter-wall-thickness cadmium covers.

The same foils and holder were used for the age measurements in water. Foil activation distributions were measured in two tanks of different sizes. The size of the small tank was close to the size of the tungsten rod bundle in figure 1. The source was positioned about 60 centimeters from the bottom of the tanks by the Lucite pedestal shown in figure 2(c). Measurements in the large water tank were made in both radial and axial directions from the cylindrical source. A 1-curie as well as a 5-curie Pu-Be source was used, and, in addition, measurements were made with the sources enclosed in hollow Lucite cylinders. These

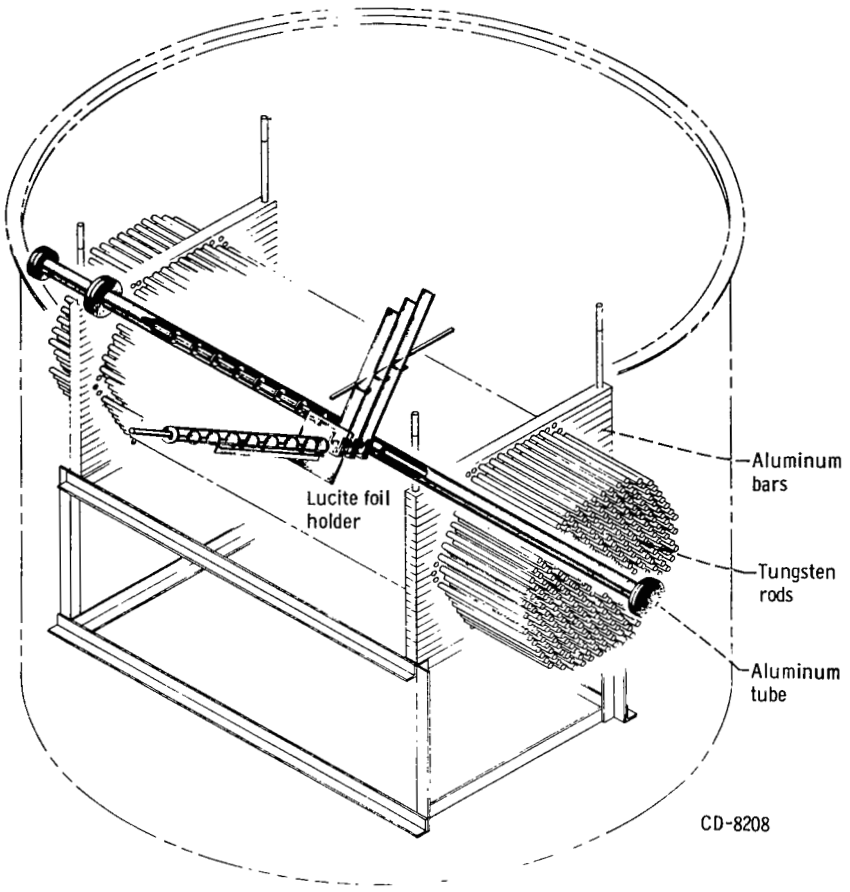


Figure 3. - Experimental geometry of age measurement in mixture of 15 tungsten - 85 water percent by volume.

measurements required several arrangements of the foil holder relative to the source, as illustrated in figure 2. In all cases the distance from the center of the source to the foil was measured to 0.5 millimeter or less.

Measurements with the mixtures of 15 W - 85 H_2O and 26.7 W - 73.3 H_2O were made in the geometry shown in figure 3. The hexagonal tungsten array was supported horizontally in the tank by slotted aluminum bars. An aluminum tube of 1.6-millimeter-wall thickness passes through the tungsten array between the central rod and the first hexagonal row of rods. To preserve symmetrical composition, the source and the foils were positioned in this tube by Lucite and tungsten spacers, and the remaining tube volume was filled with water. In addition, for the 15 W - 85 H_2O array, foil activations with 3.49-centimeter-diameter foils were made perpendicular to the rods with the Lucite holders shown in figure 3. The rod spacing for this array is 2.94 centimeters, and the tungsten-water medium free of supporting structure is 1.22 meters in length by 68.6 centimeters in diameter. The source was positioned 50 centimeters from the aluminum support bars.

The 26.7 W - 73.3 H_2O array was the most tightly spaced and differed from the other

arrays in that the first hexagonal row of rods had to be eliminated in the direction from the source opposite to that of the measurement. The foils used in this lattice were 2.54 centimeters in diameter, and the source was 50 centimeters from the aluminum bars.

Foil Calibration and Counting

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 by simultaneous irradiation on a rotating wheel in air with the NASA zero power thermal reactor as a neutron source. Relative foil efficiency factors obtained in this calibrating flux varied ±3 percent. Foils were front-and-back counted separately with several internal-flow 2π proportional counters. Counter plateaus were maintained to better than 1 percent per 100 volts, and a standard source was counted daily. Standard methods of computing foil-saturated activity from observed count rates and irradiation times were used.

The dominant foil activity of interest is an isotope of indium (In), namely 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 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. The 4.5-hour activity was observed to be a maximum of 2 percent of the 54-minute activity near the source. Another activity induced by capture in 4.3 percent abundant In^{113} is In^{114} that gradually builds up a 50-day activity with continued foil use. Corrections are required for those foils that are placed at large distances from the source following irradiation close to the source. An irradiation history for each foil was maintained.

EXPERIMENTAL RESULTS AND DISCUSSION

The experimental data obtained with the 5-curie Pu-Be source in water and in tungsten-water mixtures are presented from which finite source ages are determined directly. A number of measurements designed to furnish corrections of these finite source ages are then presented, and corrected point source ages are obtained. These point source ages are then compared with calculated ages.

Finite Source Ages

Foil activity data for water and for two tungsten-water mixtures are plotted in figure 4(a), in which the foil activity at position r has been multiplied by r^2. The water and 23.7 W - 76.3 H_2O media data at the top of the graph, which were measured with 3.18-centimeter-diameter foils, provide a direct comparison of the large differences in the foil activity distributions for these media. The 26.7 W - 73.3 H_2O medium distribution is lower than the 23.7 W - 76.3 H_2O medium distribution primarily because smaller foils were used in the 26.7 W - 73.3 H_2O medium distribution. The distributions for these two tungsten-water mixtures are similar, but small differences in shape may be noted from a detailed comparison.

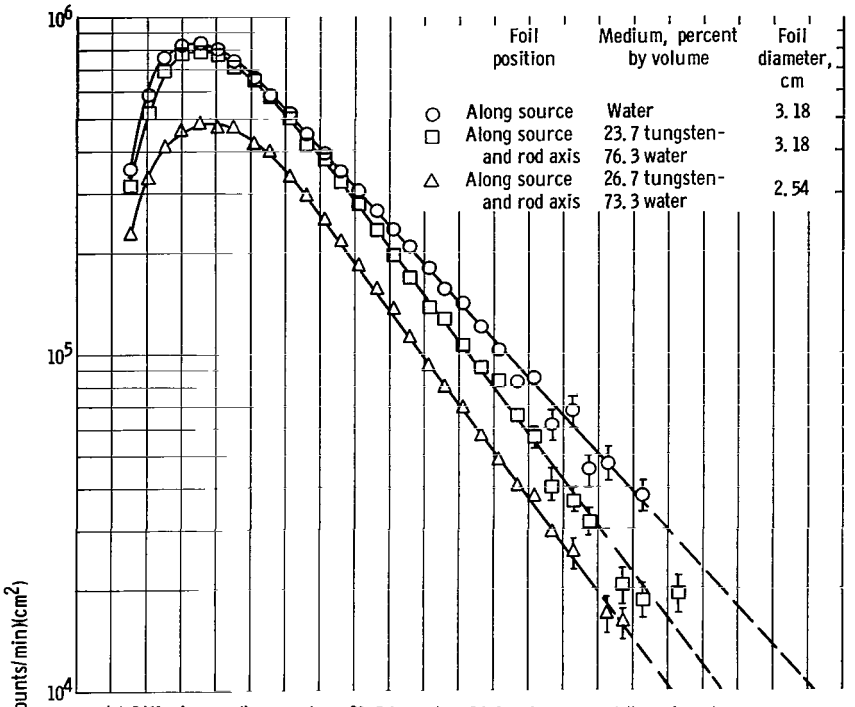
Foil activity data measured in two directions, parallel and perpendicular to the tungsten rods, for the 15 W - 85 H_2O mixture are shown in figure 4(b). The foils used for both measurements are 3.49 centimeters in diameter so that the magnitude as well as the shape of the curves can be compared. At values of r greater than 10 centimeters, the data perpendicular to the rods are 10 to 15 percent below the data parallel to the rods.

Values of ages obtained from the data in figures 4(a) and (b) are shown in table I. Included in the table are the percentages of the $A_s r^2$ and $A_s r^4$ integrals that were extrapolated and the estimated uncertainties in the measurements. For values of r for which A_s is actually measured, the uncertainty in the age is determined from the standard deviation of the foil count rates and their contribution to the total $A_s r^2$ and $A_s r^4$ integrals. The uncertainty due to the extrapolated part of the integrals is determined from the uncertainty in λ and the fractional contribution of this part of the integral to the total.

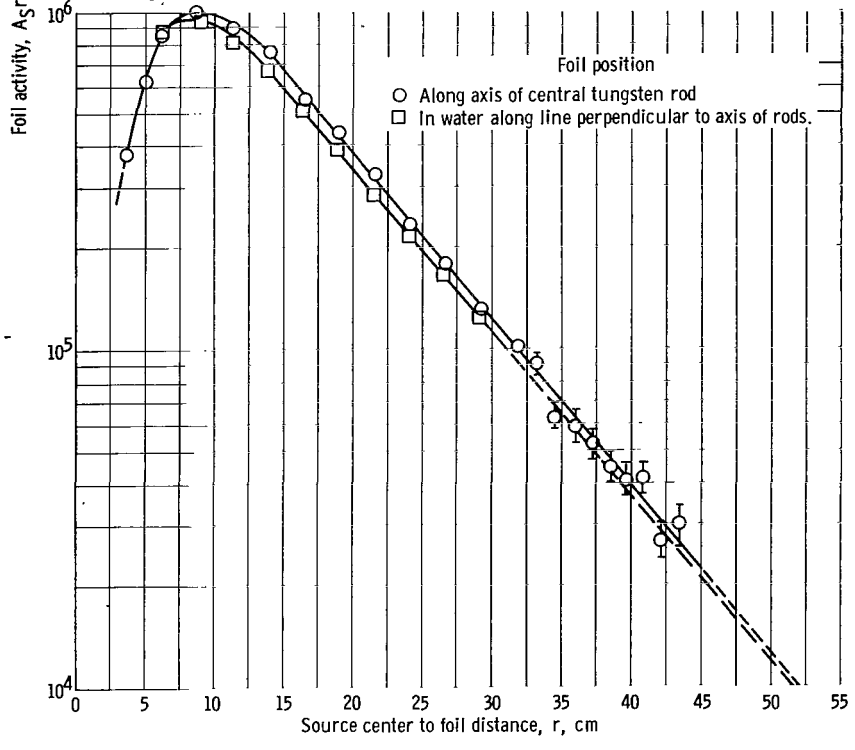
TABLE I. - FINITE 5-CURIE SOURCE AGES OBTAINED FROM FOIL ACTIVATION DISTRIBUTIONS

Slowing down medium, percent tungsten by volume	Age, τ, cm^2	Relaxation length, λ, cm	Extrapolation fraction, percent	
			$A_s r^2$	$A_s r^4$
100 water	53.4±2	9.5±0.4	1.5	15
15 tungsten - 85 water[a]	49.8±2	8.7±0.4	1.6	20
15 tungsten - 85 water[b]	49.5±3	9.0±0.5	18	60
23.7 tungsten - 76.3 water[a]	43.6±2	7.7±0.4	2	16
26.7 tungsten - 73.3 water[a]	45.2±2	7.9±0.4	3	22

[a]Parallel to tungsten rods.
[b]Perpendicular to tungsten rods.

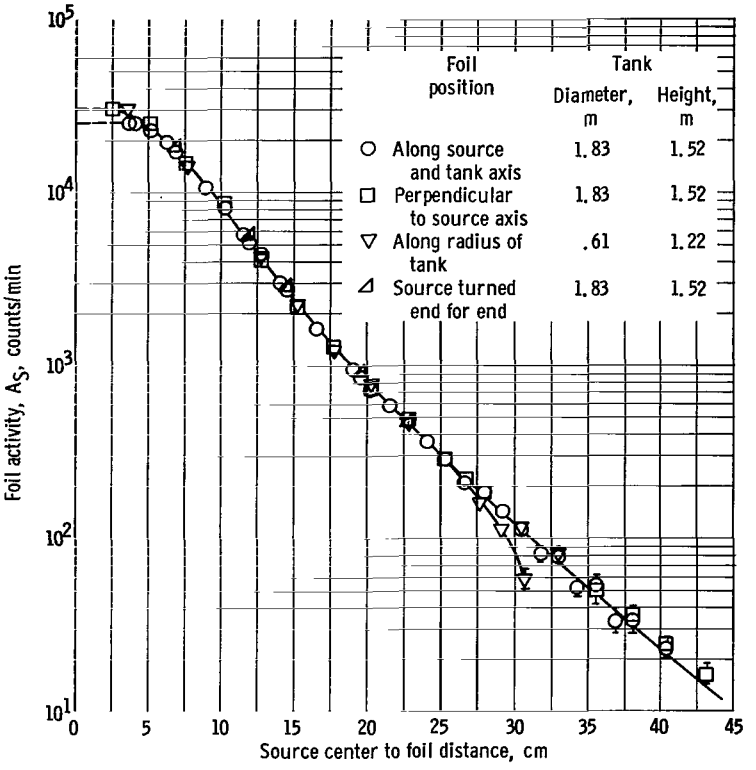


(a) Diffusion medium, water, 23.7 tungsten-76.3 water percent (by volume), and 26.7 tungsten-73.3 water percent (by volume); foil diameters, 3.18 and 2.54 centimeters.



(b) Diffusion medium, 15 tungsten-85 water percent (by volume); foil diameter, 3.49 centimeters.

Figure 4. - Foil activation data in water and tungsten-water mixtures for 5-curie plutonium-beryllium source.



(c) Diffusion medium, water; foil diameter, 3.18 centimeters.

Figure 4. - Concluded.

Point Source Ages

Finite source and finite medium corrections. - A number of indium foil activity distributions were measured in water to determine the effects of the finite source orientation and size and the finiteness of the diffusion medium on the measured distributions. A complete mapping of foil activation around the 5-curie Pu-Be source was made. The size and the composition of this source are given in table II. Foil activity distributions obtained with the 5-curie source and measured with 3.18-centimeter-diameter foils are plotted in figure 4(c). Foils were positioned along the axis of the tank, perpendicular to the source, and along the axis of the source, as indicated by figures 2(b) and (c). The distributions measured in the different directions from the source axis are similar with the exception of the data near the source. This similarity indicates that the large differences in the foil activity distributions observed for water and tungsten-water media (fig. 4(a)) are not caused by the source orientation.

Effects of a finite sized diffusion medium are indicated by the triangular data points in figure 4(c) that were obtained along the radius of the small water tank. These points indicate lowered foil activities in the vicinity of 5 centimeters or less from the tank wall.

TABLE II. - PLUTONIUM-BERYLLIUM SOURCE DATA

Source number	Neutron emission rate, March, 1962, neutrons/sec	Outside diameter, cm	Total length, cm	Composition by weight, g			
				Pu	Be	Ta	Stainless steel
M682	9.21×10^6	3.33	6.89	80.0	39.3	254	96
M683	1.68	1.96	5.34	16.0	7.9	90	40.6

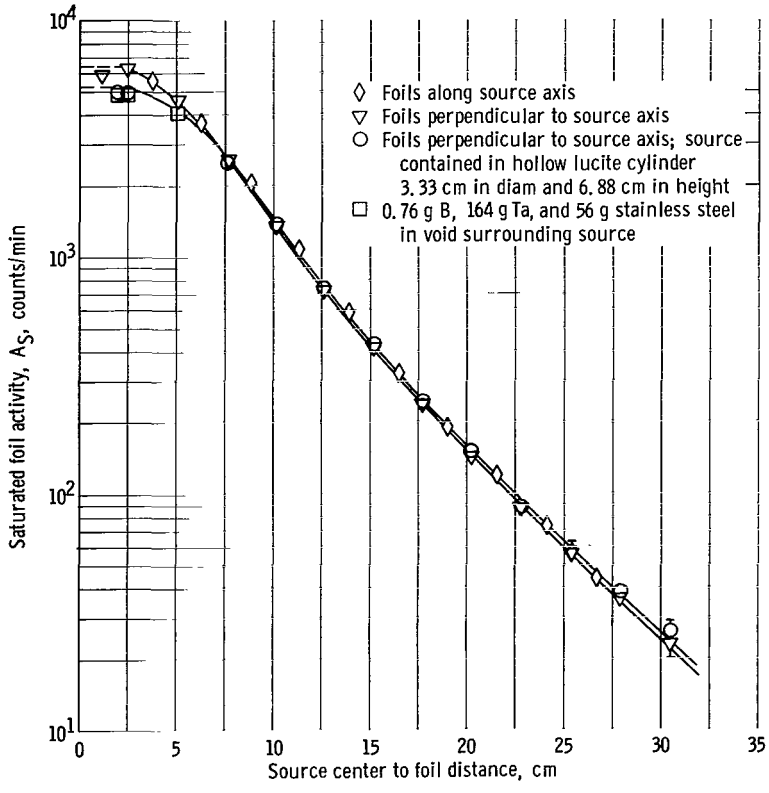


Figure 5. - Foil activation data in water for 1-curie plutonium-beryllium source.

If the data perpendicular to the rod axes shown in figure 4(b) are limited to the data 5 or more centimeters from the edge of the rod array, the measurements made in the 15 W - 85 H_2O mixture to a distance of 29 centimeters from the source should be unaffected by the water surrounding the rod bundle. This is confirmed by the data of figure 4(b).

Additional data taken along the axis of the smaller water tank are not shown in figure 4(c) because no differences between the small- and the large-tank data were observed. Inasmuch as the tungsten-water media with lower measured ages are the same size as the small water tank media, it is concluded that the measurements along the axes of the rods are also equivalent to infinite medium measurements.

In order to study effects of source size on measured ages, four distributions in water were also obtained, using a 1-curie source and 3.18-centimeter-diameter foils. The size and composition of this source are given in table II. The 1-curie source distributions shown in figure 5 indicate the essential symmetry of the foil activity distributions around the source at source-to-foil distances greater than 4 centimeters, as also indicated by the data for the 5-curie source. The remaining data in figure 5 were taken with the source centered in a hollow Lucite cylinder (fig. 2(a), p. 4). The inside dimensions of the hollow cylinder are the same as the outside dimensions of the 5-curie source. Three additional data points were taken with 0.76 gram of natural boron, 164 grams of tantalum, and 56 grams of stainless steel contained in the void surrounding the source. This material increased the macroscopic capture cross section of the 1-curie source for 1.4-electron-volt neutrons to approximately that of the 5-curie source. A reduction of 5 percent in foil activity resulted from the inclusion of boron in the void at distances less than 5 centimeters from the source. At greater distances, the effects of boron on the measured distributions were negligible.

Two additional activity distributions were measured in water with the 5-curie source placed in larger voids, as shown in figure 2(a). These distributions are shown in figure 6 along with the 5-curie source distribution previously shown in figure 4(a). The dashed curve in figure 6 was obtained by extrapolating cross plots of the foil activity data as a function of source void size and corresponds to a zero source size distribution. Reasonably accurate extrapolations were made by plotting the logarithm of foil activity, which varied linearly with source size expressed as the square of the radius of a sphere that displaced diffusion media equivalent to that of the combined source and void volumes.

Ages computed from the data in figures 4(c), 5, and 6 that pertain to source-size effects are plotted in figure 7. The source-size parameter used is the square of the radius of the equivalent sphere. Also shown in figure 7 is the age of polonium-beryllium (Po-Be) source neutrons in water, obtained as an average of measurements compiled in reference 2. The lines drawn through the 1-curie and the 5-curie source data are calculated by means of the expression

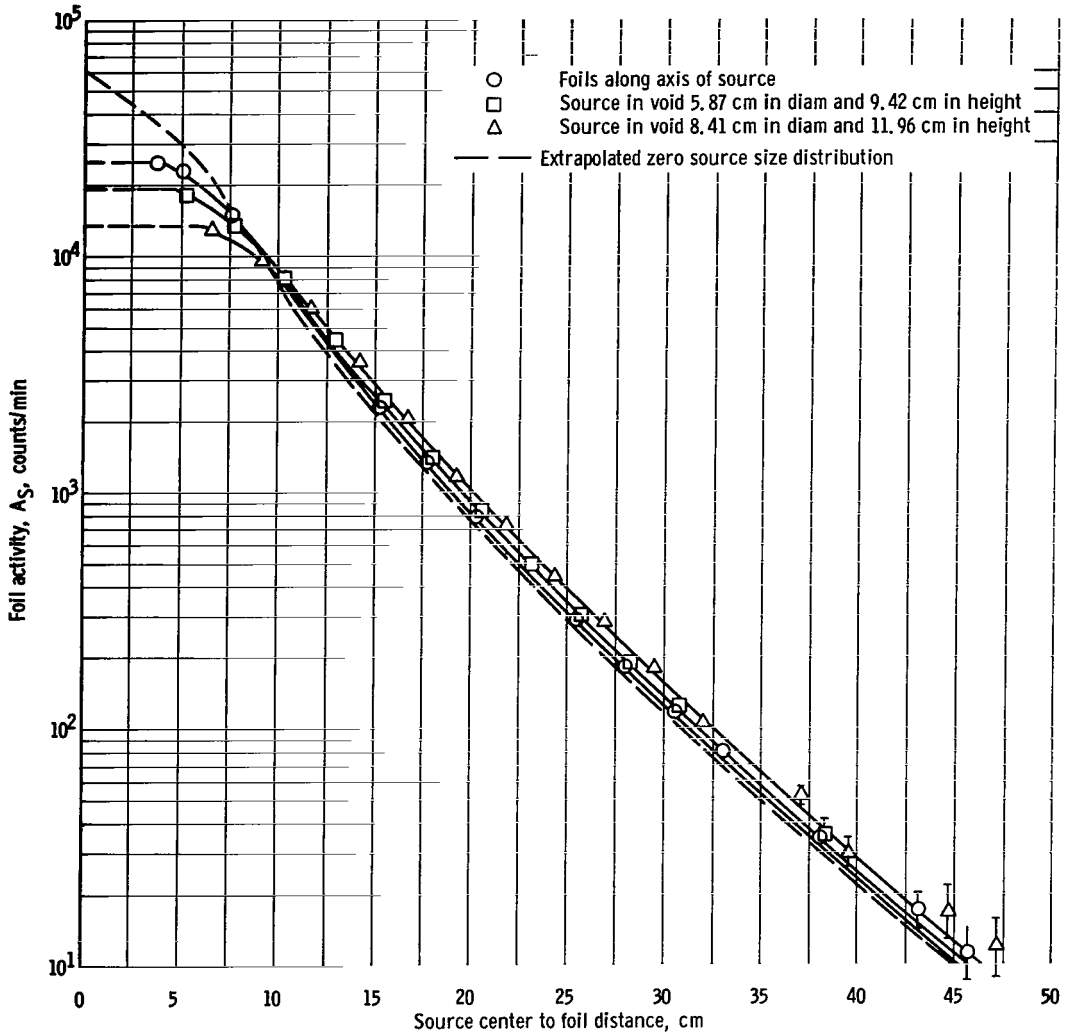


Figure 6. - Foil activation data in water for 5-curie plutonium-beryllium neutron source in cylindrical voids of various sizes.

$$\tau = \tau_{pt} + bR^2 \tag{3}$$

Equation (3) was derived by Mullin (ref. 11) for spherical shell sources of radius R. This approximate expression for the point source age τ_{pt} was derived for two extreme cases of air in the shell (b = 1/2) and water in the shell (b = 1/6). The value of τ_{pt} shown in figure 7 for the 5-curie source was obtained with b = 1/2 and was indicated to be higher, although in fair agreement with, the zero source radius data point obtained from the extrapolated distribution in figure 6.

With the exception of the ages for the larger voids shown in figure 7, the effects of source size and composition lie within the uncertainties of the measurements. However, there is an indication that the 5-curie Pu-Be age is smaller than the 1-curie Pu-Be and Po-Be ages. This can be explained by the softer neutron spectrum from the larger Pu-Be

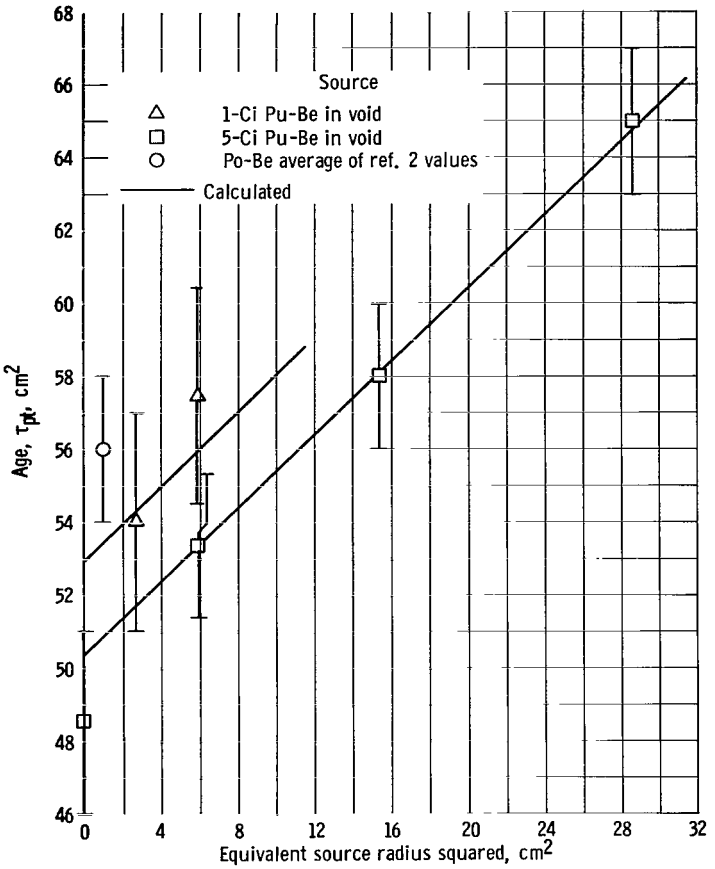


Figure 7. - Source size and source spectrum effects on point source age in water.

source (refs. 7, 12, and 13). If the measured ages are corrected from actual source-size to point-source ages, the spectral differences between the three sources are more apparent. A correction of 3 square centimeters is indicated; this correction is subtracted from the 5-curie source age data to obtain point-source ages. This correction is smaller than one obtained from the extrapolated distributions but larger than one obtained from equation (3) by using $1/2 < b > 1/6$ to account for the material in the source.

Foil detector corrections. - Since the foils used are finite in radii, the experimental foil activities are averages for the various source-to-detector distances for each unit area of the foils. An approximate method (ref. 14) that assumes the foils are flux detectors is used to correct for this effect. For the foil sizes used this correction reduces the measured ages by approximately 0. 2 square centimeter. A correction to the measured fission neutron age in water of 0. 5 square centimeter is computed in reference 3 with the assumption that the foils are black and therefore act as current detectors. A second cor-

rection of 0.6 square centimeter is computed to account for the variation of effective cadmium cutoff energy with neutron angular distribution. A study of foil counting efficiency as a function of incident neutron direction in reference 4 indicates some compensation for foil blackness due to the variation of beta-ray counting efficiency with incident neutron direction. A correction is also determined in reference 4 for foil blackness in a plane geometry age measurement. If the methods in reference 3 are applied to plane geometry, a larger correction than suggested by reference 4 is computed.

Investigations of the effects of foil captures at energies other than the 1.4-electron-volt resonance have been made in the past by shielding foils with indium as well as cadmium. The captures in the shielded foil, which occur primarily in the wings of the 1.4-electron-volt resonance, account for approximately 50 percent of the unshielded foil activity. In reference 6, no change in the shape of the measured spatial distribution was observed with shielded foils. For the tungsten-water media studied, corrections for foils used as flux detectors are difficult to measure and are computed to be small relative to the experimental statistical uncertainty of the present measurements and therefore are neglected.

Heterogeneous Effects

Possible deviations of the ages for homogeneous media from ages measured with the metallic tungsten rods are also difficult to evaluate. A truly homogeneous measurement may be desirable but is difficult to achieve because the concentrations of interest are beyond the solubility limits of tungsten salts in water. Although the foil activation distributions measured parallel and perpendicular to the tungsten rods are different, as indicated in figure 4(b), no significant difference in age is indicated for these directions with differing angular fluxes. Wade (ref. 15) has measured large differences in parallel and perpendicular ages for aluminum rod - 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, thereby permitting neutrons to remain in the rods for many collisions and in turn permitting neutron transport down an aluminum rod. The rod spacing was also large, thereby permitting 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 for 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 generally pass through tungsten and water in a quasi-homogeneous manner. Therefore, the measured tungsten-water ages are believed to be equivalent to homogeneous media ages.

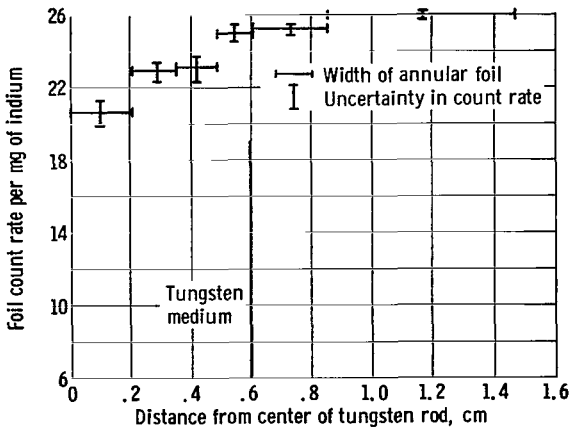


Figure 8. - Relative count rates of annular foils comprising cadmium-covered circular indium foil.

TABLE III. - CORRECTED EXPERIMENTAL AGES FOR PLUTONIUM-BERYLLIUM SOURCES

Source	Medium, percent by volume	Age, cm^2
1	100 H_2O	53.0±3
5	100 H_2O	50.5±2
	15 W - 85 H_2O[a]	46.8±3
	15 W - 85 H_2O[b]	46.5±4
	23.7 W - 76.3 H_2O[a]	40.6±3
	26.7 W - 73.3 H_2O[a]	42.2±3

[a]Parallel to tungsten rods.
[b]Perpendicular to tungsten rods.

Local Foil Activity Depression

Detailed foil activation data were obtained by counting individual annular sections of circular indium foils that extend across a tungsten rod and into the water surrounding the rod. The results (fig. 8) indicate significant local depression caused by the rods. This depression is explained by the large capture cross section of tungsten at neutron energies around 1.4 electron volts: the depression is not expected to affect the shape of the foil activity distributions measured for the tungsten-water media because the foil positions used maintained a constant local rod-to-foil distance. Neutron capture by tungsten, however, can explain the difference in the transverse and axial measurements of figure 4(b) (p. 8). Since tungsten capture processes occur primarily at neutron energies of less than 20 electron volts, these processes affect the magnitude but not the shape of the slowing-down distributions. At 20 electron volts and less, however, neutron mean free paths are small and media are consequently heterogeneous. From the tungsten-water media geometry and the data of figure 4(b), it is evident that the perpendicular currents of 1.4-electron-volt neutrons in tungsten should be reduced by capture more than the axial currents.

Corrected Point Source Ages

In the preceding review of possible differences between measured finite-source ages and point-source ages, corrections in water media for the size of the sources used were obtained. Since the corrections are small and the distributions in tungsten-water media are not too different from those in water, these corrections are applied also to the tungsten-water ages. These corrections may be slightly overestimated, since much of the source-material (see table III) is similar to the tungsten-water media. Other possible systematic errors are considered to be small relative to the assigned statistical uncer-

tainties of the ages. The corrected ages are shown in table III; the uncertainties shown are determined from foil counting statistics, and an additional uncertainty of ±1 square centimeter for source size effects is included for the tungsten-water ages.

Comparison of Experimental and Calculated Ages

Ages in water and tungsten-water mixtures were calculated with the GAM II computer code (ref. 16). The method has been used to calculate a number of ages measured by radioactive sources (ref. 17). In the calculation, the moments option was used and the effective resonance integrals of the natural tungsten rods were included. A measured rod density of 19. 3±0. 2 grams per cubic centimeter was used. Tungsten cross sections (ref. 18) were based on measured inelastic data for tungsten-184 and calculated partial inelastic cross sections for the other isotopes up to an energy of 1. 8 MeV. Above this energy, the measured total nonelastic cross sections were used in conjunction with the evaporation model in the GAM II energy transfer calculations.

The Anderson-Bond neutron spectrum (ref. 7), shown in figure 9, was used in the cal-

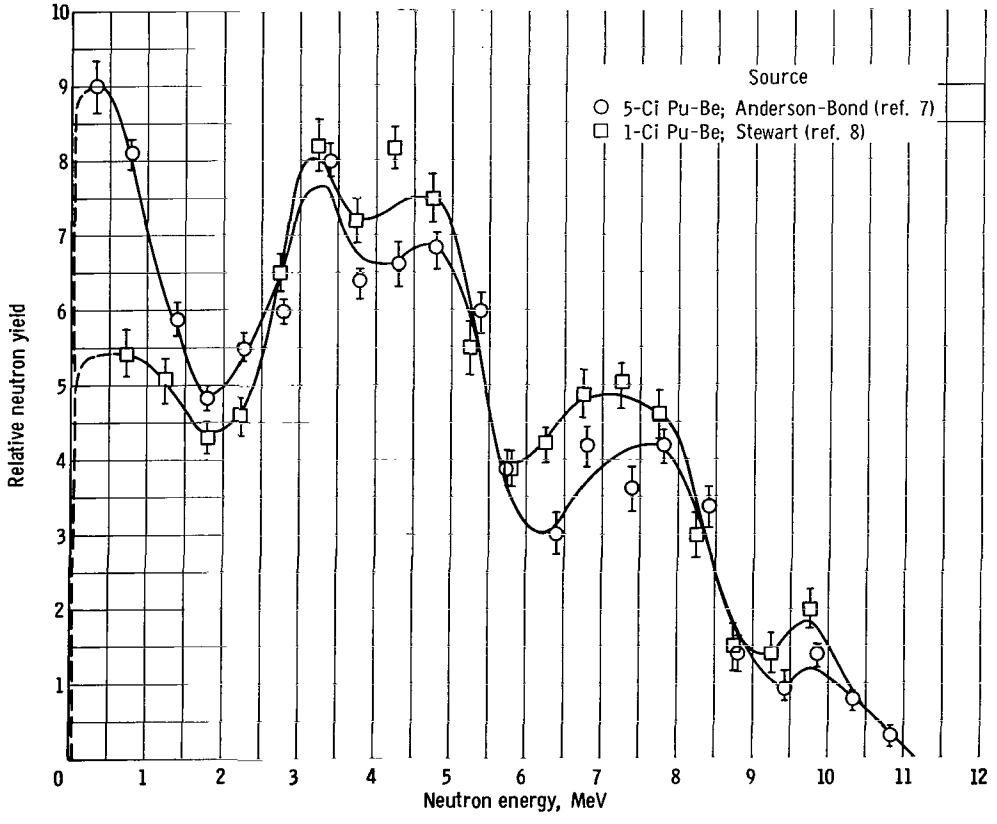


Figure 9. - Measured plutonium-beryllium source spectra.

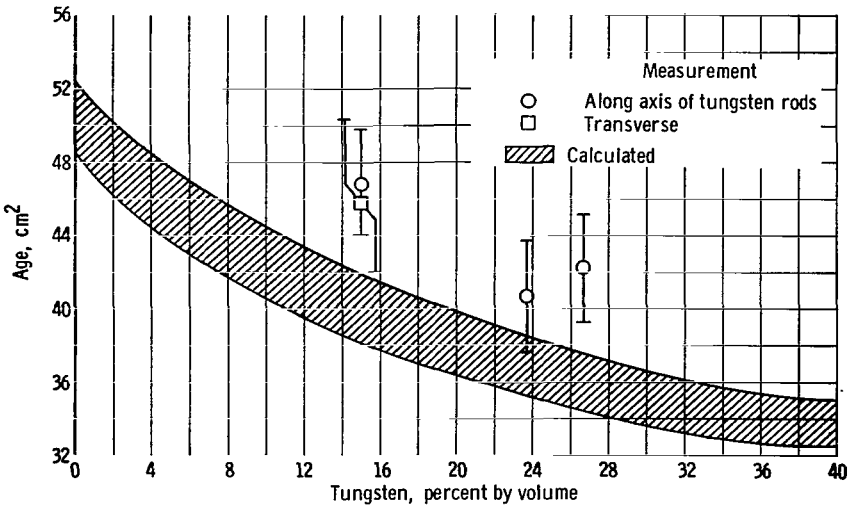


Figure 10. - Point source ages to indium resonance for 5-curie plutonium-beryllium neutron source in tungsten-water medium.

culations for neutron energies above 0. 4 MeV for the 5-curie source; below this energy no spectral data exist. However, neutron yields of the order of 25 percent for energies below 1 MeV have been measured (refs. 9 and 11); a yield of 21 percent below 1 MeV is indicated by the Anderson-Bond spectrum. The calculated ages are fairly insensitive to the exact energy distribution of these low-energy neutrons because of the small magnitude of ages for source energy below 0. 5 MeV. The 1-curie source spectra measured by Stewart (ref. 8), also shown in figure 9, is similar in shape to the 5-curie source above an energy of 2. 5 MeV. A similar spectra with a lower yield (below 2. 5 MeV) has been measured for small Po-Be sources (ref. 7).

The ages for water and tungsten-water media have been calculated from the Anderson-Bond spectra shown in figure 9. The results are shown in figure 10 with the calculated ages indicated by a band to account for uncertainties in the input neutron source spectrum. The Anderson-Bond spectrum calculation lies within the band, and the limits of the band are determined for a ±6 percent change in neutron yield below 1 MeV. Measured ages shown in figure 10 are obtained from table III. The calculated and the experimental data for water are closely in agreement within the uncertainties shown; however, for tungsten-water media, the measured ages averaged 15 percent above the calculated ages. Inclusion of the experimental uncertainties in the inelastic cross sections used in the calculations results in overlapping of the calculations and the experimental data.

A possible reason for the lower calculated ages in tungsten-water media lies in the validity of the evaporation model that is used to determine the energy distribution of the neutrons inelastically scattered by tungsten at high energies. Ages calculated with GAM II using the measured total inelastic cross section and the evaporation model are

lower than those calculated using the evaporation model in combination with measured partial inelastic cross sections below 1.8 MeV for tungsten-184 (ref. 19). Extension of the partial inelastic cross sections measured below 1.8 MeV to higher energies by the synthesis of partial inelastic cross sections for known inelastically excited levels above 1.8 MeV, such that the total inelastic cross section for natural tungsten is preserved, provides an estimate of the partial cross sections. The use of these estimated partial inelastic cross sections provides values of calculated ages that are in better agreement with the experimental values for the tungsten-water media.

SUMMARY OF RESULTS

The ages of plutonium-beryllium source neutrons were measured in water and in mixtures of tungsten-metallic rods and water. The data confirm the calculated reduction in age due to the displacement of water by tungsten with its large inelastic scattering cross sections.

The experimental ages obtained for a 5-curie source and corrected to point source geometry are 50.5±2 square centimeters in water and 46.8±3 and 40.6±3 square centimeters in mixtures of 15 tungsten - 85 water and 23.7 tungsten - 76.3 water percent by volume, respectively. An age of 53.0±3 square centimeters was determined for a 1-curie plutonium-beryllium source in water.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, July 28, 1966,
129-02-04-03-22.

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