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Method for Measuring Neutron-Absorption Cross Sections by the Effect on the Reactivity of a Chain-Reacting Pile

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This paper describes a method for measuring neutron-absorption cross sections based on the following principle: Introduction of a neutron-absorbing substance into a pile decreases the reactivity and in order to keep the power level constant the control rods must be displaced. By proper calibration this displacement may be used as a precision measure of the absorption cross section.

1. INTRODUCTION

THE reactivity of a chain-reacting pile depends critically on the balance of neutron production, absorption, and leakage. A small change in the absorption of neutrons taking place in the pile produces a drift in the intensity at which the pile is operating. This effect has been utilized for measuring neutron-absorption cross sectons.

This method was particularly useful in the development of piles since it gives directly the effect of the neutron absorption of various materials in the operation of a pile. The method measures the absorption directly while effects of scattering usually enter in a minor way. This has an advantage over methods which obtain the absorption as the difference between the total and the scattering cross section, especially where the difference is small.

2. NEUTRON REPRODUCTION

In the first two chain-reacting piles which were constructed at the Metallurgical Project, neutrons were reproduced in a structure consisting of a lattice of uranium lumps embedded in a pile of graphite bricks. In this structure neutrons are reproduced in a cycle in which fast neutrons are slowed down to thermal energies by elastic collisions with carbon. Upon reaching thermal energies, the neutrons continue to diffuse without further loss in energy, on the average, until they are either absorbed in the pile or escape the pile by leakage. A fraction of the neutrons which are absorbed produce fission in uranium with the liberation of new fast neutrons. The average number of neutrons produced from one original neutron in such a cycle is called the reproduction factor, k. The value of k depends on the balance of neutron production, absorption, and leakage.

When the pile is operated at sufficiently high intensity, the neutron production is predominantly that from neutron-induced fission and the contribution from spontaneous fission (α, n) reactions, (γ, n) reactions, and cosmic rays becomes vanishingly small. The pile is said to be in the critical condition when the neutron intensity remains constant. The value of k is then just slightly less than unity, the deviation from unity measuring just the amount of neutron production which is contributed by other neutron sources than the neutron-induced fission. In the piles used in our work, the critical condition could be obtained by the adjustment of a cadmium control rod. Insertion of more or less cadmium in the pile served to increase or decrease the amount of neutron absorption with consequent decrease or increase in the value of k. In what follows, the neutron intensity at which the pile is operated will be taken to be high enough so that the value of k at the critical condition may be considered to be unity with sufficient accuracy.

When the value of k is slightly larger than unity, the neutron intensity will drift upwards, while with k slightly less than unity, the neutron intensity will drift downward. The reactivity is a measure of the excess of k over unity. For $k-1=2.5\times10^{-5}$, the neutron intensity will increase with a period of about 1 hour. For pile periods very long compared to the longest delayed neutron period (78 sec.), $(k-1)$ is inversely proportional to the period.

3. CONTROL ROD CALIBRATION

In this work, we have measured the effect of the insertion of an absorber in the pile by ob-

serving the displacement of the control rod which was required to return the pile to the critical condition. It was found, however, that for a given change in reactivity, the displacement required, if measured in centimeters, was not always the same but depended on the position of the control rod in the pile. It was convenient to introduce a new unit of rod position such that displacements measured in the new units would always be proportional to $(k-1)$. In order to provide a precise definition of such a unit, use was made of the property of the pile that its period is proportional to $1/(k-1)$ in the limit of long periods. Accordingly, the unit of rod position was given the name *inhour* (from "inverse hour," symbol: ih), with the significance that when the control rod is displaced from the critical position by 1 inhour, the pile will have a period of (very nearly) 1 hour. (See Appendix I.)

4. NEUTRON ABSORPTION

The introduction of a neutron-absorbing substance into a pile reduces the value of k. To compensate for this loss of k, it is necessary to move the control rod out of the pile. The change in the critical position of the rod measured in inhours is a measure of the absorption of the substance.

The absorption of two substances may be compared by comparing the change in critical position which they produce. However, the number of neutrons absorbed by the substance depends on the way in which its cross section varies with energy, and on the energy distribution of the neutrons in the pile. It is clear that our measurement is a measure of the average value of the cross section for the particular energy distribution which obtains in the pile used. In the graphite piles which were used for this work, the contribution of the thermal neutrons predominates except in a few instances for those substances which have strong, low lying resonance levels. For most substances, the effect of scattering on the value of the reproduction factor enters in a relatively minor way. In most cases, then, a comparison of the effect on k of two substances is a comparison mainly of their thermal-neutron-absorption cross section.

5. INTENSITY MEASUREMENT

The intensity of operation of the pile was measured by observing the ionization current produced in a large BF_3 ionization chamber connected to a high sensitivity galvanometer. Small drifts were observed with a differential galvanometer, which was connected so as to measure the difference between the ionization current and that provided by a battery and potentiometer. By adjusting the neutron intensity to give an ionization current of 10^{-5} ampere, it was easy to observe drifts of 1/1000 in intensity, using a differential galvanometer with a sensitivity of 10^{-9} ampere for 1-mm deflection at 1 meter. Thus a displacement of 0.01 inhour from criticality would produce a drift of 5 mm in 3 minutes. This was ample sensitivity for most measurements, as will be discussed later.

6. BORON STANDARD

A standard absorber was prepared using known amounts of boron, the cross section of which is accurately known. The value of the absorption cross section for boron has been measured[1] by the transmission method for slow neutrons using a mechanical velocity selector. Such a measurement gives an absolute and accurate measure of the absorption cross section, because in boron the scattering cross section is very small compared to the absorption cross section, and it is easy to analyze the results obtained at different neutron velocities in terms of a part proportional to $1/v$ which is caused by the absorption, and a constant part which is caused by the scattering. At 2200 meters per second, these authors give 703×10^{-24} cm^2 for the absorption cross section of boron.

In carrying out an absorption comparison, it is important that every atom of the sample have the same chance to capture a neutron; or failing this exactly, it is sufficient if the unknown and the standard samples are conditioned in such a way that the situation is the same for both. In order to minimize the effects of self-absorption and yet obtain an easily measured effect, an arrangement was used which distributed the absorber over a fairly wide area. In the case of the

[1] E. Bragdon, E. Fermi, J. Marshall, and L. Marshall, Phys. Rev. (to be published).

TABLE I. Standardization of absorption measurements.

Critical position in inhours		
Blank	Borax	Cadmium
105.127	99.806	98.926
105.144	99.806	98.902
105.163	99.821	
105.145	99.862	
105.190		
105.153	99.823	98.914

boron standard, in some measurements we used BF_3 gas, in others we used borax for which we provided a graphite holder, $10\times10\times120$ cm^3 which could contain 92 aluminum dishes for the borax about 1 inch in diameter each, and distributed inside the graphite. This holder could be reproducibly inserted near the center of the pile, in a position symmetrically disposed with respect to the neighboring uranium lumps. (See Appendix II.)

The boron standard was made by preparing a solution of borax and depositing one milliliter of this solution on a disk of filter paper in each of a set of 92 aluminum dishes. This solution, when evaporated, had the appearance of having distributed itself quite uniformly over the filter-paper disk. In making a comparison with an unknown absorber, equal filter-paper disks and equal aluminum dishes were always used to make the standard and the unknown identical in every respect except for the borax in the one and the material of the unknown in the other. The total absorption cross section of the borax for the average pile neutrons was about 9 cm^2; and since this was distributed over a total area of 460 cm^2, the effect of self-absorption was of the order of 2 percent. If the size of the unknown is adjusted to give the same absorption cross section over the same area, no error resulting from self-absorption occurs in the comparison. The error in the relative absorption cross section occurs as the difference in the self-absorption effects.

The borax solution was analyzed for boron by first standardizing a solution of sodium hydroxide with potassium hydrogen tartrate. The borax was converted to boric acid with HCl, using a methyl orange indicator, and a titration was then carried out with the NaOH in the presence of mannitol. The method is that given in Treadway and Hall, *Analytical Chemistry 2*, 502. Two sets of three measurements each were carried out in our borax solution, one by Mr. W. Sturm of the Argonne Laboratory, and the other, independently, by Mr. D. Revinson of the Analytical Chemistry Group of the Metallurgical Laboratory. The average of the first series gave 2.816×10^{-4} mole of boron per ml, and for the second set, 2.793×10^{-4} mole of boron per ml. The agreement was considered satisfactory and the average of these results, 2.804×10^{-4} mole per ml was used in determining the cross sections. To the cross section per atom of boron, which at 2200 meters per second is 703×10^{-24} cm^2, we added 1×10^{-24} cm^2 to take into account the contribution of the sodium and hydrogen, and used 704×10^{-24} cm^2 at 2200 meters/second for the atomic-absorption cross section of borax. The total cross section of 92 borax disks was thus 10.94 cm^2 at 2200 meters/second.

7. CRITICAL POSITION MEASUREMENTS

The effect of this boron standard on the reactivity of the pile was studied by comparing the critical position obtained with a blank set of aluminum dishes, and filter-paper disks with that obtained with the 92 borax absorbers. Since the absorption was distributed among 22 neighboring cells, only a minor perturbation in the neutron intensity distribution was produced. Measurements of the critical position were made by setting the control rod to produce first a slow drift in one direction and then in the other, and interpolating between the two settings in inverse proportion to the period of drift observed.

The critical position may be altered during the course of the measurement because of changes in temperature and barometric pressure which may take place. It is always necessary to make corrections for these effects during the course of a

TABLE II. Analysis of columbium pentoxide.

Spectrochemical analysis Sample No. (old sample)		Mfg. spectrochemical analysis Sample No. 2 (new sample)	
99→ Cb			
Ce	50 ppm	Ta_2O_5	None
Gd	10 ppm	TiO_2	Less than 0.001%
Hf	50 ppm	Fe_1S	None
Mo	20 ppm	ZnCuMg	Very weak
Sc	5 ppm	SiO_2	0.03%
Pr	5 ppm		
S	20 ppm		
Zr	100 ppm		

measurement. In the Argonne graphite pile, the temperature effect amounted to -0.814 ih/°C while the pressure effect, which was caused by the change in the amount of air nitrogen in the pile, amounted to -3.23 ih/cm Hg. There was also a humidity effect caused by the change in water content of the air on the pile which amounted to -2.85 ih/cm H_2O vapor. Of these, the most serious was the pressure effect, and it was always necessary to read the barometric pressure to 0.01 mm of Hg using a special mercury or aneroid barometer. Barometric pressure changes rapidly and in a spurious way, and over the short interval of time of such a change the pressure may not have had a chance to equilibrate over all the pile structure. The limiting sensitivity of the method is imposed by the pressure effect and amounts to ~ 0.01 ih.

The temperature effect is less troublesome because the temperature of the pile changed slowly and in a regular way, so that by arranging a series of measurements in a cyclic time sequence of the form *ABBA* the slow drift in critical position caused by temperature change would be automatically eliminated in the averages.

In Table I is listed a series of measurements of critical position expressed in inhours with, and without the borax standard. The effect of pressure has already been corrected for in these values.

From these data, the sensitivity of the method is seen to be 2.052 cm² (at 2200 m/s) per inhour of rod displacement, with a precision measure of about ± 0.03 cm².

As an example of the method, the measurement of the absorption cross section of columbium is of interest. Columbium has only one isotope, and it was to be expected that the absorption of a neutron would give rise to a radioactive isotope so that the absorption cross section could be measured by observing the *B* emissions. Early activation cross section measurements by L. Seren, H. Friedlander, and S. Turkel at the Argonne Laboratory gave an apparent result of about 0.02×10^{-24} cm².

A high purity sample of Cb_2O_5 was obtained from the Fansteel Company. A preliminary measurement showed an absorption cross section of 1.4×10^{-24} cm², almost 100 times larger than that found by the activation method. A new sample was then obtained from the Fansteel Company which was reported to have even higher purity than the first. Spectroscopic analyses made on the two samples are given in Table II.

TABLE III. Absorption of columbium.

	Critical position in inhours			
	Blank	Cb No. 1	Boron (std.)	Cb No. 2
Run A	117.66	115.14	115.39	115.14
Run B	117.67	115.17	115.39	115.15
			115.40	
	117.66	115.15	115.39	115.14

Change in critical position

Due to Cb No. 1 ih = 2.51
Cb No. 2 ih = 2.52
Boron std. ih = 2.27

Absorption cross section of Cb (referred to 2200 m/s) $= 1.44\times10^{-24}$ cm²

The Cb_2O_5 was pressed into pellets which were placed in the aluminum sample dishes covered with a disk of filter paper. In order to obtain approximately the same control-rod displacement, 46 of the standard boron dishes were used. These were uniformly distributed in the graphite holder. The no-absorber critical position was obtained with empty aluminum dishes and blank filter-paper disks. The first sample contained 931.45 grams of Cb_2O_5, the second sample 934.31 grams, while there was 0.1395 gram of boron in the standard. Measurements of critical position of the rod in inhours are given in Table III. Corrections for changes in pressure during the measurement are already included in the numbers given.

With very good agreement for both samples, the experiment yielded for the ratio of the average absorption cross section, for pile neutrons, of columbium to that of boron the value 0.00204. On the assumption that the absorption cross section obeys the same law of variation with neutron velocity as does the boron (the $1/v$ law) the columbium-absorption cross section may be given the value of 1.4×10^{-24} cm² at 2200 m/s.

8. CADMIUM STANDARD ABSORBER

In a large part of the work it was found convenient to use cadmium as a standard absorber rather than boron. A wire of cadmium has the property that practically all neutrons with energy less than about 0.3 ev which strike it will be

TABLE IV. Measurement of the beryllium cross section.

Sample	Change in inhours
7296 grams Be	−0.11
12960 grams C	0.00
8 cm² Cd	−3.80

absorbed. Since most of the neutrons in the pile are below 0.3 ev, cadmium serves as a convenient standard absorber, whose neutron cross section may be obtained from its geometrical dimensions.

Cylindrical cadmium wires of diameter D and length l have a geometrical cross section for isotropically distributed neutrons

$$A = \tfrac{1}{4}\pi Dl$$

neglecting end effects.

In comparing the effect of cadmium to that of the standard borax absorbers, we used wires which had an average diameter of 0.1006 cm and a total length of 128.25 cm, giving a neutron cross section of 10.14 cm². These wires were distributed uniformly over the graphite holder together with blank aluminum dishes and blank filter-paper disks. Control-rod displacements resulting from the cadmium and compared to the borax are given in inhours in Table I. The effect of the cadmium is seen to be 6.239 ih or 1.625 cm²/ih.

The neutron cross section of cadmium may be converted to that of a $1/v$ absorber at 2200 meters per second by multiplying by the factor $2.052/1.625 = 1.26$.

9. TEMPERATURE OF PILE NEUTRONS

Since the boron absorption of neutrons varies according to the $1/v$ law, the number of neutrons which are absorbed by thin absorbers is proportional to the neutron density, and is independent of the neutron velocity distribution. Thick cadmium, however, captures every thermal neutron which strikes it, hence the absorption by cadmium depends also on the average velocity of neutrons.

A comparison of the effect of the absorption of these two substances gives information about the average velocity of pile neutrons. In making the comparison it is necessary to subtract that part of the effect of boron which is caused by absorption of neutrons above the cadmium limit. This was done by means of a BF_3 counter placed above a hole extending into the center of the pile. Using boron carbide collimation, the counter could not see neutrons which might be reflected by the pile shield, but only those emerging directly from near the bottom of the hole. Such neutrons have a distribution quite close to that which is present inside the pile. With no cadmium in the beam we observed 5200 counts per minute; with cadmium, 112 counts per minute; and with 3 inches of B_4C powder in the beam, 4 counts per minute. The contribution of the neutrons above the cadmium limit is thus 2.08 percent. Thus, an absorber whose cross section is 2.095 cm² at 2200 m/s, and which absorbs according to the $1/v$ law up to the cadmium limit and not at all above, changes the critical position by 1 inhour. For an absorber which absorbs all neutrons up to the cadmium limit with equal probability the same change in critical position is produced by 1.625 cm² of cross section. It follows that the average velocity of the neutrons which are in the center of the pile and below the cadmium limit is 2836 meters per second. This corresponds to a neutron temperature of 383° Kelvin.

10. EFFECT OF SCATTERING

A neutron scatterer may affect the reactivity of a pile either by altering the spatial, or the energy distribution of neutrons in the pile. A scatterer placed near a uranium lump may reduce the number of neutrons which can diffuse into the lump and thereby diminish the reactivity. An increase in the reactivity may be obtained if the scatterer is placed near the edge of the pile so that the neutron leakage is reduced. A pure scatterer can, however, produce no change in the spatial distribution if it is placed in a region where the gradient of the neutron density is zero. For this reason, absorption measurements are always made with the sample symmetrically disposed with respect to the uranium lump, and near the center of the pile.

With a scatterer in this position, its effect on the energy distribution does alter the reactivity of the pile in a non-negligible way. By increasing the slowing-down power of the moderator, the resonance absorption in uranium is decreased and the result is an increase in the reactivity.

11. ABSORPTION CROSS SECTION OF BERYLLIUM

For certain light elements with very small neutron absorption, the increase in the reactivity due to slowing down (see Appendix III) may be comparable to the decrease due to absorption and must be taken into account. We describe, as an example, a determination of the absorption cross section of beryllium. Beryllium metal blocks were placed in the Argonne pile distributed in 16 cells, 456 grams per cell. The results of the inhour measurements are given in Table IV.

The measurement with cadmium wires standardizes the geometry used for absorption. As discussed above, the cadmium standardization may be reduced to that of a $1/v$ absorber at 2200 meters per second by multiplying its cross section by the factor 1.26. Thus the cadmium standardization gives: $3.80/8\times1.26=0.377$ ih/cm^2.

The measurement with graphite shows that the effect of slowing down on the reactivity of the graphite we used is equal to the effect of its absorption. The absorption cross section of our graphite as measured by a diffusion method was known to be 0.0049×10^{-24} cm^2 at 2200 m/s. The effect of the slowing down is proportional to $\sigma_s\xi$, where σ_s is the cross section for scattering for resonance neutrons, and ξ is the average logarithmic loss of energy per collision (see Appendix III). For graphite $\sigma_s=4.8\times10^{-24}$ cm^2 per atom and $\xi=0.158$ while for beryllium $\sigma_s=6.1\times10^{-24}$ cm^2 per atom and $\xi=0.202$ so the effect of slowing down in beryllium is:

$$\frac{6.1\times0.202}{4.8\times0.158}\times0.377\times4.9\times10^{-27}\times\frac{7296}{9}\times6.02\xi\times10^{23}=1.46 \text{ ih}.$$

Subtracting this from the total effect -0.11 ih we have for the effect of absorption -1.57 ih. Thus, the absorption cross section of beryllium at 2200 m/s is:

$$\frac{1.57}{0.377}\frac{9}{7296\times6.02\times10^{23}}=8.5\times10^{-27} \text{ cm}^2/\text{atom}.$$

Since an accurate chemical analysis for the beryllium blocks we used was not available this result represents an upper limit of the capture cross section of beryllium. We have reason to believe, however, that the material was of high purity.

TABLE V. Calibration of control rod of Argonne pile.

x cm	$di n/dx$	ih
0	.000	0
50	.023	.7
100	.067	2.7
150	.158	8.2
200	.299	19.5
250	.418	37.8
300	.492	60.7
350	.520	86.0
400	.490	111.5
450	.402	133.7
500	.281	151.2
550	.142	161.3

APPENDIX I

The Inhour

The inhour is proportional to $k-1$, thus,

$$\text{ih}=C(k-1)$$

where the value of C is given by

$$C=\lim_{k\to1}\frac{1}{T(k-1)},$$

and T is the period of the pile in hours.

The relation between the displacement from criticality in inhours and the period of the pile may be obtained from the intensities and periods of the delayed neutron emission. For the uranium-graphite pile, the following formula has been used in our work:

$$\text{ih(crit)}-\text{ih}=\frac{64}{T}+\frac{245}{T+3.57}+\frac{688}{T+10.1}+\frac{1938}{T+34.5}+\frac{665}{T+83},$$

where T is the period of the pile in seconds. The numbers in the denominators are the periods of the various delayed neutron emissions in seconds. The contribution of some shorter periods has been disregarded. It is to be noted that because of the way in which the inhour has been defined, the accuracy with which this formula gives the period becomes greater and greater for larger and larger values of the period. According to the above formula, the pile has a period of 1 hour when

$$\text{ih(crit)}-\text{ih}=0.990.$$

Calibrations of the control rod may always be effected with the use of this formula by observing the period of the pile for a given displacement of the control rod from the critical position. The value of the inhour is measured from its zero value corresponding to control rod out of the pile. Table V gives the sensitivity of the control rod $di h/dx$ as a function of the position of the rod in the pile in centimeters. The integral of this curve is also given.

The inhour is useful as a measure of rod displacement

because it is a measure of pile reactivity which is independent of the position of the control rod, so that linear interpolations are accurate in comparing the effects of different absorbers. Moreover, its value has an almost unambiguous significance for all graphite-uranium piles.

The value of the constant C is known for uranium-graphite piles to be

$$C=2.5\times10^{-5}\ \text{hours}^{-1}$$

with an accuracy of about 20 percent.

APPENDIX II

Effect of Position

The effect of a given absorber on the reproduction factor depends on its position in the pile. Because of the inhomogeneous character of the structure the general variation of neutron density has superimposed on it a strong local variation. Thus the density n of neutrons at the position x, y, z may be represented by

$$n(x, y, z)=\alpha(x, y, z)\beta(x, y, z),$$

where α is a smooth function, and β has the same periodicity as the cells and describes the local variations of intensity. For small absorbers which do not perturb the neutron distribution appreciably, the effect on the reactivity is proportional to the square of α and depends also in a complicated way on the position of the absorber within the cell.

In order to minimize the variations caused by this last factor it is preferable to place the absorbers not too close to the uranium lumps. For the graphite-uranium piles, the variation of α may be obtained with sufficient accuracy from the solutions of the diffusion equation

$$\nabla^2\alpha+B^2\alpha=0$$

subject to appropriate boundary conditions. In a uniform cubic structure of side a, α may be expected to vanish near the boundary so that the solution is

$$\alpha(x, y, z)=\alpha(0, 0, 0)\cos(\pi x/a)\cos(\pi y/a)\cos(\pi z/a),$$

in which the origin of the coordinates is taken at the center of the pile. Thus, the effect on k of an absorber added to the central cell is 8 times greater than if it were added to the average cell. The number of neutrons which it absorbs is only $\pi^3/8$ times greater.

In the Argonne pile used in this work, the design of the cell was such that an absorber having a cross section for pile neutrons of 1 cm² placed midway between two lumps would absorb about 1/28 of the neutrons absorbed by the cell itself. Thus, inappreciable perturbations of the neutron distribution would be caused in general if the amount of absorber added per cell had less than 1 cm² of absorption.

APPENDIX III

Energy Distribution of Pile Neutrons

It is convenient to distinguish two groups of neutrons in the pile, in consideration of the property of cadmium, in quite thin sheets, which absorbs completely one of these with only a minor effect on the other. Cadmium has a fairly sharp absorption limit between 0.3 and 0.5 ev depending on its thickness. Neutrons whose energy is below this limit are cadmium-absorbable and sometimes are termed C-neutrons. The neutrons of higher energy are not appreciably absorbed by cadmium and are sometimes termed epicadmium neutrons.

Because of the nature of the slowing-down process, the number of neutrons in a logarithmic energy interval is proportional to dE/E. Since the distance for slowing down is large compared with the spacing of the uranium lumps, but small compared with the dimensions of the pile, the distribution of sources may be taken to be uniform and the loss by leakage and absorption (which amounts to about 10 percent down to 1 ev) may be neglected in general. It is thus appropriate to speak of the slowing-down density $q(E)$ which is the number of neutrons per cm³ which is slowed from above to below the energy E within one second. This quantity is conserved in the pile except for losses caused by leakage and absorption, as mentioned. The relation to the density of neutrons $n(E)$ per unit energy interval is generally

$$n(E)=Q(E)\frac{1}{vE}\frac{1}{\xi_s\sigma_s}.$$

Here v is the neutron velocity, and σ_s is the reciprocal mean free path for collision with the moderator (carbon), and ξ_s is the average logarithmic loss of energy per collision.

The value of ξ for elastic collisions and isotropic scattering for a moderator of mass M of atomic weight A is:

$$\xi=1-\frac{(A-1)^2}{2A}\log\frac{A-1}{A-1},$$

which for not too small A reduces to $\xi\approx2/A$. For carbon ξ has the value 0.158, for oxygen it is 0.121, while for hydrogen its value is unity. The product $\xi_s\sigma_s$ is the slowing-down power per cm³ of the moderator.

Once the neutrons fall below the cadmium limit, the mechanism of the slowing down is greatly altered. The neutron energy becomes comparable to the energy of crystal binding of the atoms with which they collide, and to the energy of thermal agitation. The slowing down proceeds more slowly, and indeed, because of the preferential absorption of neutrons having lower energies, thermal equilibrium is never established exactly. For most purposes, it is sufficiently accurate to consider the C-neutrons in the pile as a group of neutrons having a Maxwellian energy distribution with a temperature somewhat higher than the true temperature of the pile, as discussed in the text.

Neglecting the variation of $q(E)$ and σ_s with neutron energy, the number of epicadmium neutrons which are absorbed per second by a substance with absorption cross section $\sigma_a(E)$ is

$$A_{\text{res}}=\int_{E_{\text{Cd}}}^{\infty}\sigma_a(E)n(E)v\,dE=\frac{q}{\xi\sigma_s}\int_{E_{\text{Cd}}}^{\infty}\sigma_a(E)\frac{dE}{E},$$

where the upper limit has been extended to infinity because the contribution to the absorption at high energies is usually quite small. The integral has been called the resonance-absorption integral, and in general its principal contributions come from the low energy neutrons.

Below the cadmium threshold, the neutrons have approximately the Maxwellian distribution as was pointed out above. This is a rather narrow energy range and the chance that a resonance occurs in it is fairly rare. Except for those cases where a resonance below 0.3 ev is known to occur, it is reasonable to suppose that the absorption has a $1/v$ dependence so that the thermal activation is given by:

$$A_{th}=n\bar{v}\sigma(\bar{v}).$$

Here $\bar{v}$ is the average velocity of the C-neutrons, and n is their density. The ratio of the activations is given by:

$$\frac{A_{\text{res}}}{A_{th}}=\frac{q}{n\bar{v}}\int_{E_{\text{Cd}}}^{\infty}\sigma_a(E)\frac{dE}{E}\Big/\xi\sigma_s\sigma(\bar{v}).$$

The quantity $(q/nv)\cdot(1/\xi\sigma_s)$ can be determined from the measurements described above in which a BF_3 counter was exposed to the neutrons from a hole in the pile. These data gave

$$\left(\frac{A_{th}}{A_{\text{res}}}\right)(\text{boron})=47.1.$$

Since the boron absorption follows the $1/v$ law, we have

$$\sigma(\bar{v})\Big/\int_{E_{\text{Cd}}}^{\infty}\sigma(\bar{v})\left(\frac{E(\bar{v})}{E}\right)^{\frac{1}{2}}\frac{dE}{E}\left(\frac{E_{\text{Cd}}}{2E(\bar{v})}\right)^{\frac{1}{2}}$$

for 0.90 gm/cm² of Cd we may take $E_{\text{Cd}}=0.4$ ev, while for $E(\bar{v})$ we take 0.042 ev and obtain, thereby, the general expression

$$\frac{A_{\text{res}}}{A_{th}}=\frac{0.045}{\sigma(\bar{v})}\int_{E_{\text{Cd}}}^{\infty}\sigma(E)\frac{dE}{E}$$

with an uncertainty of about 10 percent resulting from the uncertainty in E_{Cd}. The coefficient 0.045 is in good agreement with the value obtained from an independent method of obtaining this number based on the use of a calibration of indium foils in a "standard graphite pile" which is described elsewhere. This relation is useful in determining the value of $\int\sigma_a(E)dE/E$ from a comparison of the activations induced in a substance with and without cadmium protection.

The work reported here was done in 1943–44. It was carried out under contract between the University of Chicago and the Manhattan District Corps of Engineers, War Department.

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Evidence for, and Cross Section of 115 Day Se^{75} *

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Evidence has been given to show that the 115-day activity produced in selenium by thermal neutrons is due to Se^{75} which decays by K electron capture to As^{75}, accompanied by a 0.4 Mev γ-ray. A value for the cross section of Se^{74} for radiative capture of a thermal neutron has been given.

SEABORG'S tables[1] report as a K-capture process a 48-day and a 160-day activity for Se^{75} produced from As^{75} by a (p, n) and $(d, 2n)$ reaction, respectively. However, we have found a K-capture activity with a half-life of 115 ± 5 days produced by an (n, γ) reaction on selenium irradiated in the Argonne pile. The remainder of this paper will give evidence for this activity and for a value of the activation cross section for its production from Se^{74}.

The 115-day activity was established by counting samples mounted on scotch tape foils with an aluminum-walled cylindrical Geiger counter. One sample was counted for over six months.

Possibility of an arsenic activity produced by an (n, p) reaction on the selenium was ruled out by chemical separations from the selenium using an arsenic carrier. No activity was found in the arsenic fractions. The chemical separation was checked by adding 27-hour As^{76} to non-activated selenium and separating the two elements. No arsenic activity was found in the selenium por-

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[1] G. T. Seaborg, Rev. Mod. Phys. 16, 1 (1944).