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Delayed Neutrons from Fission of U^{235} *

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The periods, yields and energies of the delayed neutrons from fission of U^{235} have been measured with a pneumatic transfer apparatus ("rabbit") at the heavy water pile of the Argonne Laboratory. The following periods account for the saturated decay curve of delayed neutrons for times longer than 0.02 sec. after irradiation ceases:

Half-life	Energy	Yield (relative to total neutron emission)
55.6 sec.	250 kv	0.025%
22.0	560	0.166
4.51	430	0.213
1.52	620	0.241
0.43	420	0.085
0.05		0.025
		Total yield 0.755%

The application of the delayed neutron data to the constants of pile kinetics is discussed and the value of the inhour (the pile reactivity unit) is calculated.

I. INTRODUCTION

ABOUT one percent of the neutrons produced by the fission of uranium are not emitted instantaneously but are "delayed" several seconds on the average. Before the beginning of the Manhattan Project, a small amount of information had already been published on the subject of these delayed neutrons. Roberts, Meyer and Wang[1] had observed the emission of neutrons from uranium after fission in the uranium had ceased. Later Meyer and Wang[2] showed that these "delayed" neutrons were not simply the result of $(\gamma-n)$ reactions of γ's from the fission products but probably came directly from the fission products in some way. The delayed neutrons were observed to decay with a period of about 12 sec. Booth, Dunning and Slack[3] found two periods for the delayed neutrons of half-life 45 and 10–15 sec., and an initial intensity of roughly one delayed neutron per 60 fissions. The delayed neutrons have been studied intensively on the Manhattan Project because of their very important function in aiding pile stability. In fact, even with reactivities of several hundred "inhours" (see Section III G), a pile is above critical because of the contribution of delayed neutrons, and its period is of the order of seconds rather than tenths of a second as it would be if all the neutrons were emitted instantaneously.

Early studies both with the pile and cyclotron showed that the delayed neutrons were not emitted according to a single radioactive period but according to several periods ranging up to about one minute. The most accurate work in identifying the periods at the time the present experiments were begun was that of Snell, Nedzel and Ibser[4] using the cyclotron and of Redman and Saxon,[5] using the graphite Argonne pile. The results of the two groups of experiments agreed rather well in demonstrating the existence of delayed neutrons of half life about 55, 23 and 4.5 sec, but showed some disagreement on several shorter periods. Fermi[6] had estimated the

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[1] R. B. Roberts, R. C. Meyer, and P. Wang, Phys. Rev. **55**, 510 (1939).

[2] R. B. Roberts, L. R. Hafstad, R. C. Meyer, and P. Wang, Phys. Rev. **55**, 664 (1939).

[3] E. T. Booth, J. R. Dunning, and F. G. Slack, Phys. Rev. **55**, 876 (1939).

[4] Smyth Report, Rev. Mod. Phys. **17**, 459 (1945).

[5] Unpublished Manhattan Project Work (1943).

[6] Unpublished Manhattan Project Work (1943).

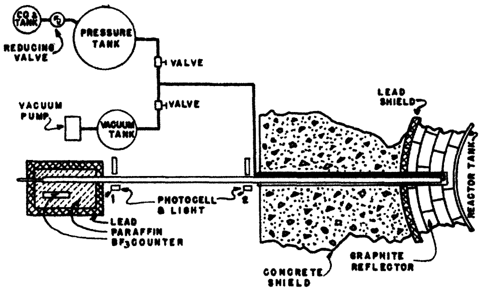

FIG. 1. The rapid transfer tube ("rabbit") and associated apparatus.

energy of the delayed neutrons by measuring their range in the graphite standard pile, and obtained 640 kv as an "average" energy which emphasized greatly the 23 sec. period.

Even though the knowledge of the delayed neutrons from U^{235} was thus in a rather satisfactory state, it was decided to extend the measurements, utilizing the Argonne heavy water pile. The decision was made on the following basis: (1) The available flux was higher than had been used in the previous work; (2) The recently constructed rapid transfer apparatus at the pile would simplify investigation of the region of short periods where most doubt existed; (3) A careful analysis of the periods and yields of U^{235} would serve as a standard of comparison for future work planned on the other fissionable isotopes.

II. APPARATUS

In order to analyze the delayed neutron periods, it is necessary to transfer a uranium sample from a region of high flux to a standard position near a well-shielded neutron counter in a fraction of a second, then to record the rapidly changing counting rate as a function of time in as detailed a manner as possible. The "rabbit" and associated apparatus fulfills these conditions in quite a satisfactory manner.

The rabbit is an electronically controlled pneumatic transfer device. It moves a sample which is to be irradiated to a position near the reactor tank of the pile and out again to a counter as rapidly as is practicable, using CO_2 as an operating medium. The device (Fig. 1) consists of the following pieces of equipment: CO_2 tank with reducing valve; pressure reservoir; two soloneoid-operated valves; vacuum reservoir; vacuum pump; a relay circuit to open and close the valves; two photo-cell units with appropriate circuits; BF_3 counter and circuits; electrocardiograph for recording counting rates, and the necessary piping including a properly shielded transfer tube.

The transfer tube is of aluminum, 3.5 cm inside diameter and 7 meters long, about half the length being enclosed in an 8 in. square plug which fits into the concrete shield of the pile. The plug is of paraffin and lead shot, and the transfer tube is bent from one corner of the plug to the diagonally opposite corner to prevent radiation leakage. The pressure tank is of about 150 liter capacity, while the vacuum tank is about 25 liters and is evacuated by a Megavac pump. All piping losses have been reduced as far is practicable in order to speed gas flow. The valves are pilot piston operated; i.e., the pressure differential does the actual opening and closing. The relay control circuit is designed in such a way that the valves may be opened at the touch of a button and close automatically at a time variable up to about one second later.

The cartridges containing the uranium samples (several grams of enriched oxide) are of lusteroid and fit very loosely in the transfer tube. Friction losses are small as are pressure losses past the cartridge. The cartridges are relatively light, of the order of 20 gm when full. The photo-cell units which are used to time the irradiation operate on the dark pulse caused when a light beam is interrupted by the passage of the sample. Holes cut in the pipe and covered with sheet plastic are used for the light beam. The sample, after irradiation, is blown out of the pile and comes to rest at the end of the tube where it is held in a fixed position by a catch. The end of the tube is buried in a paraffin block and a BF_3 counter is located in the paraffin at a variable distance from the sample. The delayed neutrons emitted by the sample are slowed in the paraffin and detected by the counter. The shielding of the pile itself and that around the paraffin geometry keeps the background down to about 12 counts per minute. The BF_3 counter is connected to a preamplifier located in the paraffin block, then to a fast amplifier and a scaler (scale of 512). The counter is operated at a voltage several hundred volts less than the usual operating potential (about 1600 v instead of 1850 v). It was found during this work that at the usual voltage the counter would respond to γ-rays, when suddenly subjected to them, for a period of some seconds after which it would cease to count the γ's. Such an effect would interfere seriously with recording the delayed neutrons, of course, but fortunately disappeared at the lower voltage.

The scaler pulses are recorded on an electrocardiograph tape. The electrocardiograph is a standard portable model, consisting of a light source, an Eindhoven string galvanometer (current sensitive), an optical system and a slit camera. Light passes through the galvanometer, and an image of the string (a gold plated quartz fiber), magnified 500$\times$, is focused on the slit, past which the sensitized paper travels at a constant rate of 2.5 cm/sec. The paper comes in rolls of 50-ft. length, 25 ft. of which are usually used in making a run (about $44\frac{1}{4}$ minutes running time). The paper has crosswise lines put on by a rotating marker every 25th of a second, and from these markings it is possible to interpolate to about 0.004 sec. in time. The following marks are applied to the paper: pulses when opening and closing the valves, when the cartridge passes each photo-cell, and the scaler kicks. The scaler pulse is a square wave form which is produced by the recorder driver tube output, properly attenuated. The galvanometer sensitivity is about 0.3μ amp. per cm (after magnification) and its period is 0.0015 sec. It can handle counting rates up to 2.5×10^6 cts/min. (40,000 c.p.s.) with a scale of 512. Figure 2 shows the initial portion of a typical tape containing the timing marks mentioned above.

It is desirable to use very high counting rates in order to get statistical accuracy for the short periods. The limitation, of course, lies in the "dead time" of the apparatus associated with the BF_3 counter, the counter itself having a negligible dead time. The dead time of the apparatus was made as low as possible by using a fast scaler and amplifier and mounting a preamplifier with the counter in the paraffin block. The dead time was measured by recording the gross decay curve of the delayed neutrons on a tape at a pile power such that the dead time correction would be small, then again at a power about ten times as great. The ratio of the observed counting rates for the two runs was plotted as a function of time. The ratio, which would, of course, be a constant (10) if there were no dead time correction, was less than 10 at the initial part of the curve and increased to 10 when the rates became low. The ratio actually showed a linear decrease with counting rate (Fig. 3), as is to be expected, and the rate of decrease (slope

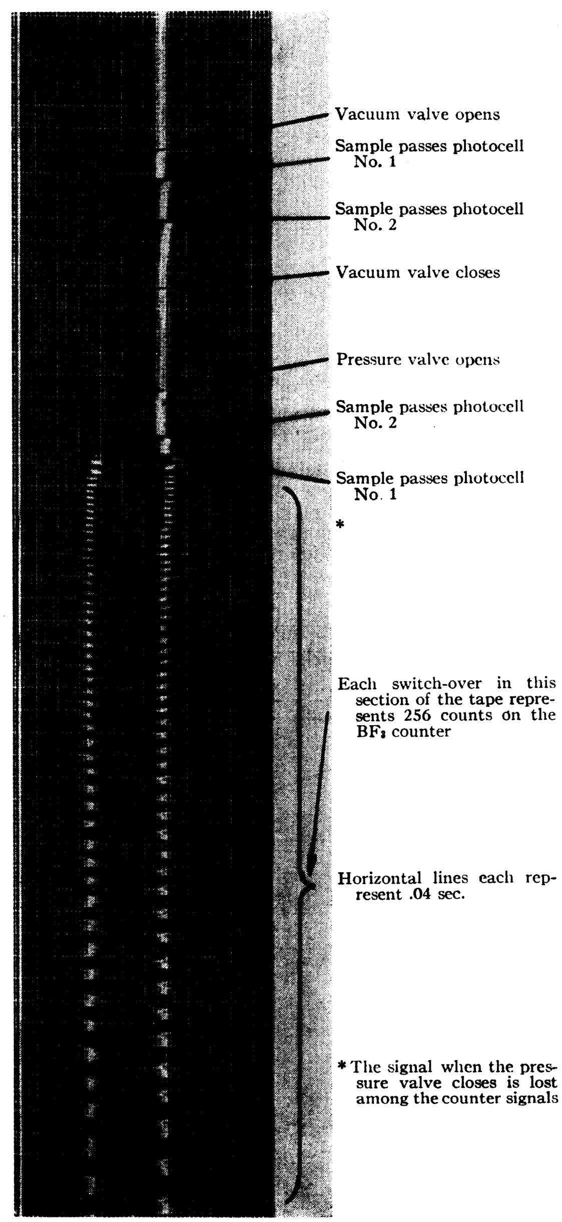

FIG. 2. Initial portion of a typical electrocardiograph tape showing timing marks and the beginning of the delayed neutron decay curve.

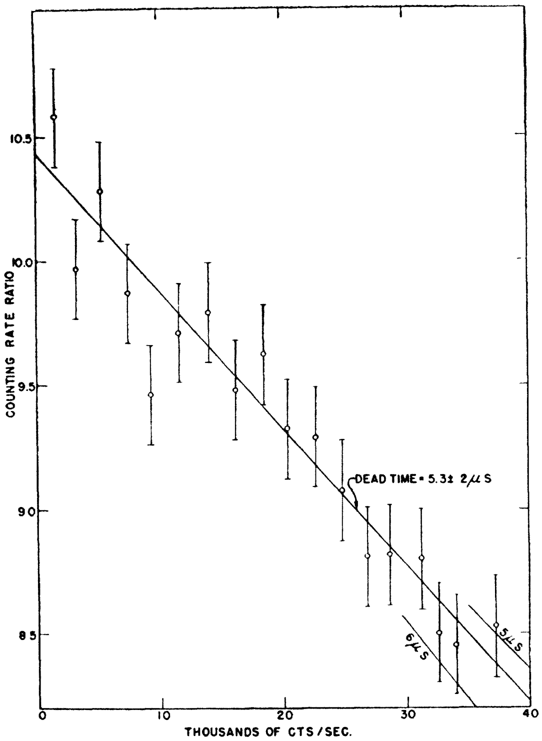

FIG. 3. Counting rate ratio for a high and low power run as a function of counting rate from which the dead time of the counting circuits is determined.

of the curve in Fig. 3) gives the dead time as 5.3 ± 0.2 microseconds. This value of the dead time means that the correction will become 10 percent at a rate of 19,000 c.p.s.

By assuming constant accelerations and using the length of time between photo-cell pulses, together with the known distances involved, it is possible to calculate the time that the cartridge arrived at, and left, the inner end of the transfer tube to an accuracy of about 0.02 or 0.03 sec. The transfer times which have been generally used are of the order of 0.6 sec. on the "in" transfer and 0.4 sec on the "out" transfer. This latter figure has been reduced on occasion to about 0.25 sec. by the use of higher pressure in the pressure reservoir.

III. MEASUREMENTS AND ANALYSIS

The various periods were studied by the usual method of determining the longest period first, then treating it as known in getting the next longest, etc., adjusting the time and intensity of irradiation to emphasize the desired period as much as possible. The discussion of the results will follow the same order.

A. The 55-Second Period

Here the method is simply to use full intensity, irradiate about 5 minutes then start counting only after the shorter lives have died out (about 5 minutes). A tape from such a run will then

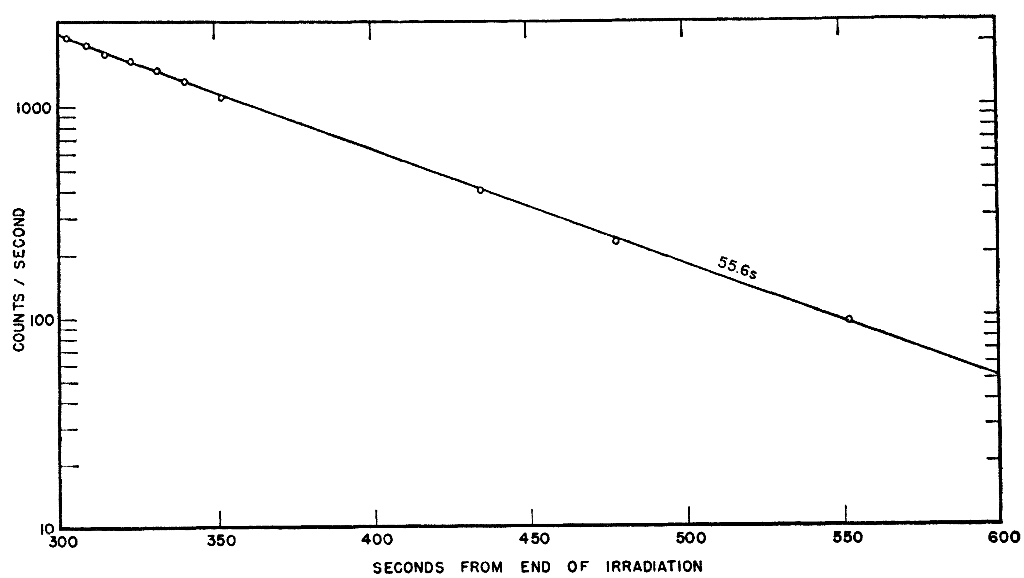

FIG. 4. Delayed neutron decay curve following a 5-min. irradiation.

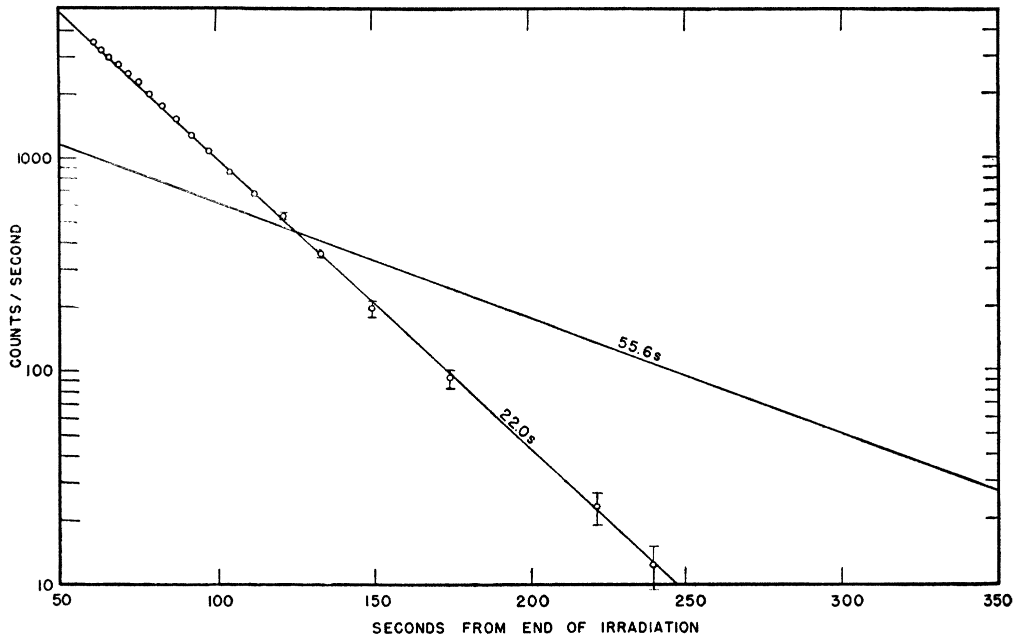

FIG. 5. Decay curve following a 30-sec. irradiation. The 55.6-sec. line shows the amount of that activity which has been subtracted.

cover the time from, say, 300 to 600 seconds after the end of the irradiation and contain a total of several hundred thousand counts. The tape is "scaled" by determining the *times* on the tape corresponding to the completion of a given number of counts, 10,240 in the present case (20 marks on tape). The number of counts divided by the time interval is then listed as the raw counting rate for the midpoint of the particular time interval. Each point has the same percent statistical error in spite of the decreasing counting rate.

Corrections to the raw counting rate are then applied in the following order, (1) for dead time as discussed under II, (2) for background, determined close to the time of irradiation because of changes caused by pile conditions, (3) for placement, because only for a time interval very short compared to the mean life would it be correct to plot the above *rate* at the center of the interval. The quantity actually measured is the number of counts divided by the time, $\Delta c/\Delta t$, whereas the correct rate at the midpoint would be

$$\frac{\Delta c e^{-\Delta t/2\tau}}{\tau(1-e^{-\Delta t/\tau})}$$

which is smaller than $\Delta c/\Delta t$. Hence, the measured rate is decreased by the difference between the above quantities. This correction, of course, assumes a knowledge of the period, τ, which is being investigated, but it is always known accurately enough for the purpose. The runs were made and scaled in such a way that all the above corrections were kept below a few percent.

Figure 4 shows the corrected data for a "55-second" run (5-min. irradiation). The period can be determined simply by drawing a straight line through the points and measuring its slope. However, it is difficult to determine what probable error to assign the result in such a case and difficult to prevent subjective errors in the process. For this reason and because errors in the long period would carry over into the work on the shorter periods, it was decided to determine the long period in a more quantitative manner, the graph showing quite convincingly that only one period is present after five minutes.

Theoretically, if only one period is present, one can determine the period most accurately from a given total number of counts by taking the ratio of the counts from t to infinity, to the total number of counts, where t is such that the ratio will be about $\frac{1}{5}$. This method was approximated by measuring the integral number of counts with

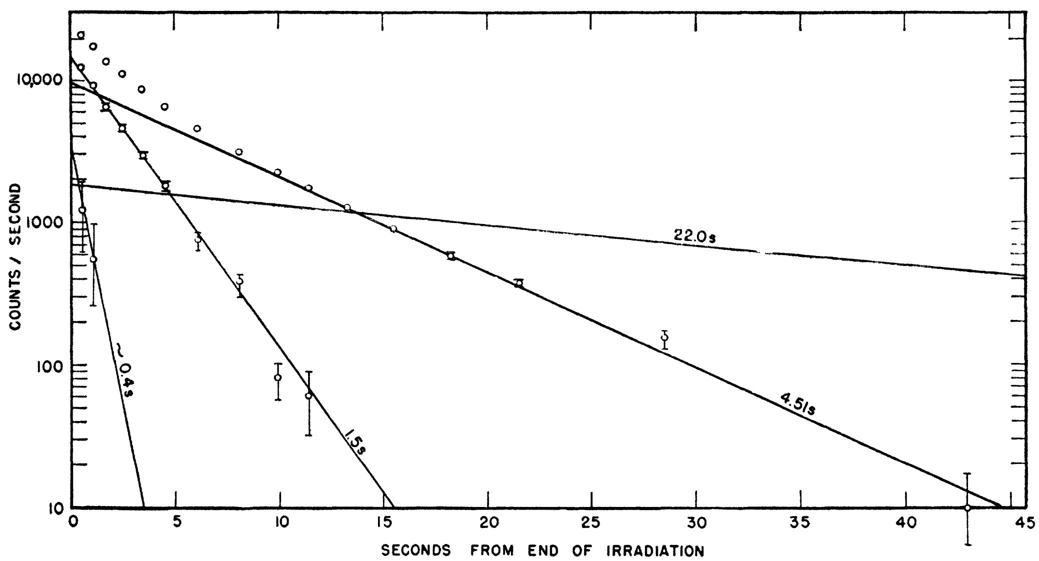

FIG. 6. A 6-sec. irradiation for the determination of the short periods with the 55.6- and 22.0-sec. periods subtracted.

a mechanical recorder (no tape being used) for two intervals, say 5–7 and 8–13 minutes, from the ratio of which the period can quickly be determined. The result of 19 such mechanical recorder runs gave 55.6±0.2 sec. for the half-life. The line shown in Fig. 1 is the one calculated from the above integral method, both for slope and magnitude, *for that particular run.* The correspondence between the line and the points scaled from the tape illustrates the agreement between the integral method and simple curve-fitting.

B. The 22-Second Period

An irradiation time of about 30 sec. at an intensity such that the counting rate is the maximum usable (about 15,000 c.p.s.) 50 sec. after irradiation (when the shorter periods have died out) gives the best conditions for determining the 22-sec. period. The longer period, taken as 55.6 sec., must be subtracted from the raw data as an additional correction in this case. However, there are not sufficient counts remaining after 300 sec. to give a 55 sec. curve with an accuracy sufficient for such correction. The amount of 55-sec. correction was actually determined by recording the *integral* number of counts occurring after 300 sec. with the mechanical counter—this number and an assumed period of 55.6 sec. gives the amount of 55.6 sec. activity to be subtracted from the earlier points. It was felt that this method was less subjective than subtraction of an amount of 55.6 activity adjusted to make the remainder lie on a straight line.

Figure 5 is a run analyzed in the above manner. The line labeled 55.6 shows the amount of this activity (as determined from the mechanical recorder count after 300 sec.) subtracted from the data to give the experimental points shown. Unlike Fig. 4, the experimental error now increases with time because although all original points have the same error, those at later times have a larger amount of 55.6 activity subtracted, leaving a larger relative error. The period shown by the 22.0 line in Fig. 2 was determined by a least-squares fit of the experimental points. This method was considered to be of somewhat better value than a graphical fit, the method used for the 55.6 period being inapplicable because the activity could not be followed over a sufficiently large number of half-lives. A series of five tapes, made under the same conditions as those of Fig. 2, was analyzed and the half-life determined by the least-squares fit for each run. The average of the results for the half-life is 22.0±0.2 sec.

The ratio of the saturated initial activity of the 55.6 sec. to the 22.0 sec. activity ("relative yield" of the former) can be obtained of course from the initial values of each activity given from curves as in Fig. 2. However, it is more accurate to determine the yield, after the 22.0 sec. half-life is known accurately, by measuring the integral number of counts (after a run of a special length) for two time intervals chosen such that the 22.0 sec. activity predominates during the first and the 55.6 sec. during the second interval. The relative yield is then a simple function of the ratio of the two integral counts (corrected of course for dead time and background). The mean result of six such mechanical recorder runs is

$$Y(55)=0.172\pm0.003.$$

C. The Short Periods

Irradiations of several seconds duration were made at low enough intensities so that the initial counting rate would be about the maximum usable value. The intensity was read from the tape and the 22.0 and 55.6 sec. activities subtracted, using the integral number of counts obtained for the time after the short periods had disappeared, together with the measured 55.6/22.0 yield to calculate the amounts to be subtracted. The method is the same as described in B except that the contributions of two periods were being treated here.

The intensity remaining after subtraction of the long periods was then simply plotted on log paper and analyzed into separate activities by graphical methods. The use of integral counts on the mechanical recorder to get yields was used only for one period (4.5/22.0 yield) as the times which would be involved for the shorter periods would be too short to handle. Five separate runs with different irradiation times were analyzed this way, giving essentially the same periods each time, so it was felt that the graphical method was satisfactory for these short periods. Figures 6 and 7 of about 6- and 1-sec. irradiation time, respectively, show the analysis of two of these runs. The latter run was designed to accentuate the shortest periods and does show quite clearly the presence of two periods shorter than the 4.5-sec. period, of 1.5- and 0.43-sec. half-life. The two short periods agree with the findings of Snell and indicate that the 1.1-sec. activity found by

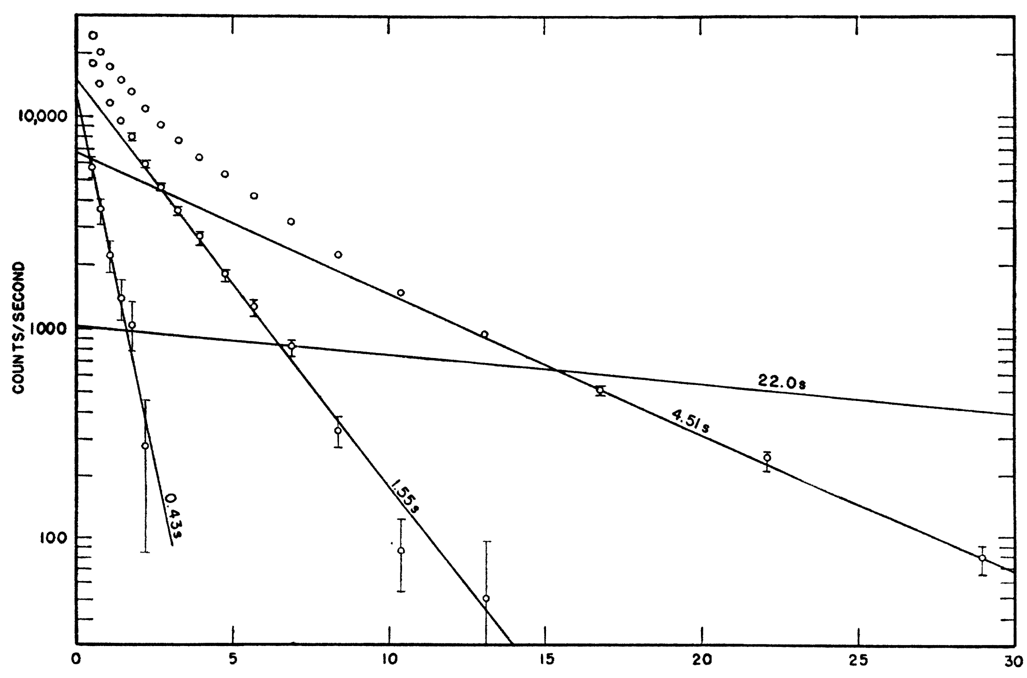

FIG. 7. A one-sec. irradiation for the determination of the shortest periods.

Redman and Saxon was really a combination of the above two activities.

The average of the five runs give the following values of the half-lives and relative yields for the short periods (again taking 22.0 sec. as the standard).

$T_{\frac{1}{2}}$	Yield
4.51±0.1 sec.	1.42±0.06
1.52±0.05	1.35±0.06
0.43±0.05	0.57±0.04

The periods were determined simply from the graphical analysis, and the yields from the extrapolation of the periods back to zero time. In addition, values for the yield of the 4.5 sec. activity obtained from mechanical counter integral values (as mentioned in the paragraph above) were used in obtaining the average value for the 4.5 sec. yield. The probable error given is only a reasonable estimate because of the subjective nature of the graphical analysis.

An over-all check of the period and yield values was made by calculating the total decay curve of all the delayed neutrons, after a saturated run, from the measured period and yield values. A saturated run was then made and the total decay curve plotted. The calculated curve and the experimental points (equated at $t=0$) are compared in Fig. 8, and it is seen that the five periods and yields represent the total curve quite well. Some runs were also made with extremely short irradiation times (about 0.1 sec.), and compared with curves calculated from the above periods, to investigate possible shorter periods. The results showed that for times greater than 0.25 sec. after the end of a saturated irradiation the periods and yields above completely accounted for the decay curve. This means that if any shorter periods are present, they die out within 0.25 sec. after irradiation. The detection of an extremely short period was carried out later by a different method which will be described in Section III G.

D. Energy of the Delayed Neutrons

It is possible that the yields measured above do not give the true relative numbers of the neutrons of the different periods. The detecting apparatus used probably has an efficiency that varies with neutron energy; hence, it would not

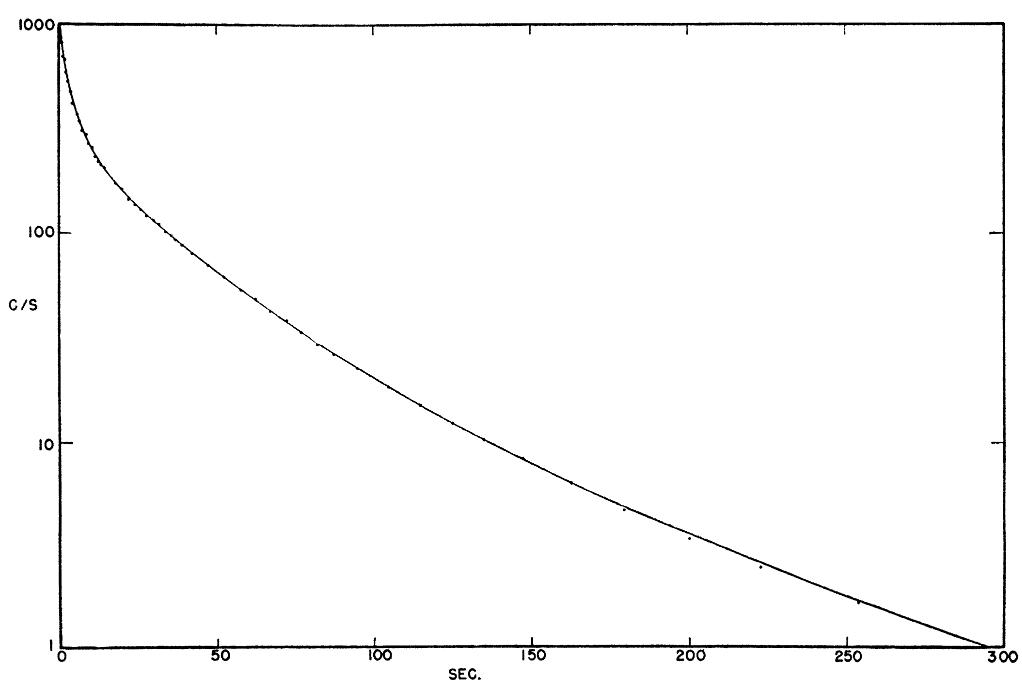

FIG. 8. The decay curve following a saturated irradiation (points) compared to the curve calculated from the periods and yields of Table I.

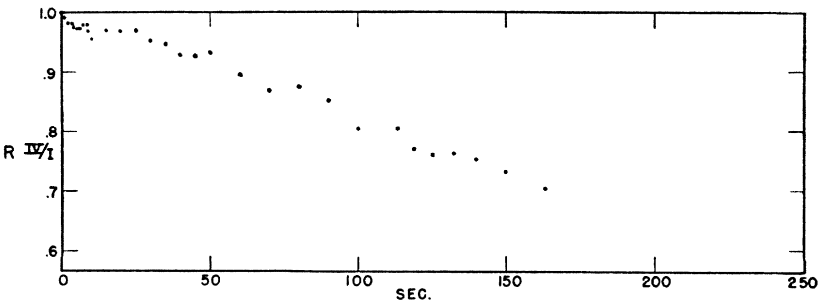

FIG. 9. Ratio of delayed neutron intensity at two different positions in the paraffin block as a function of time after saturated irradiation. The decrease in the ratio means a decrease in the average energy of the delayed neutrons as a function of time.

give true yields for periods made up of neutrons of different energies.

To investigate the possible difference in energy of the neutron periods, a saturated decay curve was obtained with the counter 20 cm from the sample in the paraffin block ("position IV") and compared with a similar curve obtained in the position 8 cm from the sample ("position I") which had been used for all the period and yield work. The two saturated curves, both set equal to unity at $t=0$ (actually the intensity was ~ 30 times greater in position I) were compared and the ratio IV/I is shown in Fig. 9. The ratio of the two curves is not constant but decreases with time showing that the energies of the different periods are not the same and, as the longer periods become more predominant, the decrease of intensity in going from I to IV becomes greater, i.e., the average energy becomes less.

The actual shape of the slowing down curve in the paraffin was obtained for the 55.6- and the 22.0-sec. periods by analyzing the decay curve into its components at four different positions in the paraffin. Figure 10 gives the results where I is the intensity of the period and r the distance from source to counter. The curves obtained with two photo-neutron sources (Na-Be, 920 kv and Na-D_2O, 280 kv) are also shown. The curves show that the 55.6 period is much less energetic than the 22.0 period and the photo-neutron sources allow an energy calibration of the curves, putting the former period at 250 kv and the latter at 560 kv.

One might expect from the curve of Fig. 9 (which showed that the *average* energy keeps dropping after $t=0$) that, for the shorter periods also, the energy would increase as the period decreases. The energy of the individual shorter periods was measured by analyzing runs made in position IV and obtaining the relative (taking 22.0 as 1.00 again) yields of the short periods in this position much as had been done in position I. It will then be true that a relative yield in IV *greater* than that in I means that the particular period has an energy *higher* than the 22-sec. energy. The ratio of the yields in IV to those in I are shown in Fig. 11 for all the periods. The observed ratios do not indicate any monotonic change of energy with half-life but merely a trend toward higher energy with shorter half-life. An energy scale based on the photo-neutron source measurements is shown in Fig. 9 also. Thus, the approximate energy values may be estimated as 430, 620 and 420 kev. for the 4.51, 1.52 and 0.43 periods, respectively, each with an error of about 60 kev.

The actual variation of energy values of the individual periods seems so great that it is sur-

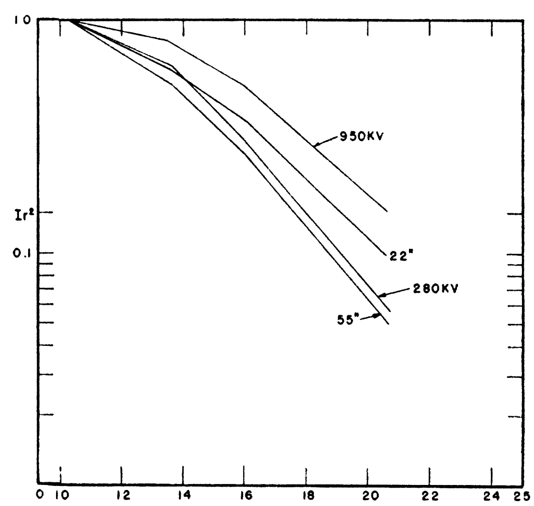

FIG. 10. Intensity of two delayed neutron periods and of two standard photo-neutron sources as a function of position in the paraffin block.

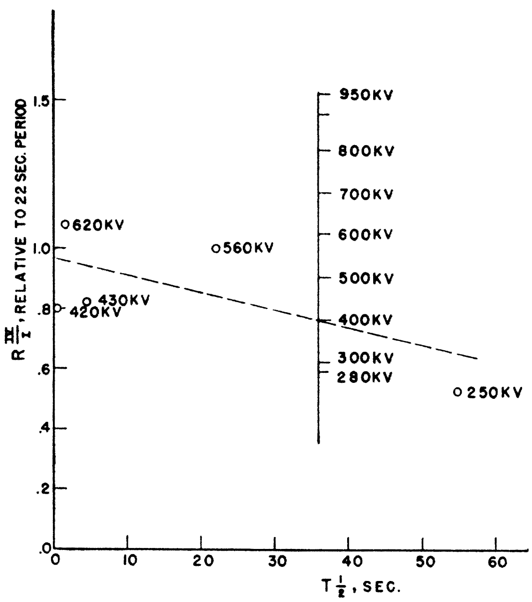

FIG. 11. Values of the intensity ratio at two positions in the paraffin block for the individual periods. The energy scale is based on the standard photo-neutron sources and gives the delayed neutron energy values shown.

prising that Fig. 9 shows such a continuous decrease in energy with time (i.e., decrease in ratio IV/I). To investigate any possible discrepancy, the value of R, the ratio IV/I, to be expected as a function of time after a saturated run, was calculated from the R's for each period given in Fig. 11. This was done by weighting the R for each period according to the amount of that period present at a given time after irradiation. The resulting ratio drops almost continuously from a value of 0.92 (at $t=0$) to 0.52 (when only the 55.6-sec. period is left) showing that the *average* energy at $t=0$ is slightly less than the 22-sec. period, say 510 kv, and drops (almost) continuously to a steady value of 250 kv. The calculated average ratio IV/I, set equal to unity at $t=0$, is shown in Fig. 12 compared with the experimental points of Fig. 9. The agreement between the calculated and experimental ratio shows that there is no discrepancy between the average energy and the individual period values. The approximate energy scale included in Fig. 12 gives the average energy of the delayed neutrons as a function of time after a saturated run.

E. Correction of the Measured Yields for Energy

It is certain that, because of the difference in energy of the periods, the yields measured in position I should be corrected for energy dependence. However, the magnitude of the correction, or even its sign, is difficult to calcuate. If a thermal detector is very close to a fast neutron source, it will favor the low energies, while if it is far from the source, it will favor the high energies. Because of the finite size of the paraffin block and the various gaps in it (the rabbit pipe, BF_3 counter, pre-amplifier, etc.), the actual distribution curve of thermal neutrons in the paraffin is impractical to calculate. What is needed, of course, for the true yield is the value of Ir^2 integrated from zero to infinity, whereas only the intensity at a fixed r was actually measured.

The correction was made experimentally by measuring the value of two of the relative yields with the "long counter" [7] which is very nearly energy-independent. For the long counter measurements, the sample was shot clear through the usual geometry out to a position (in the center

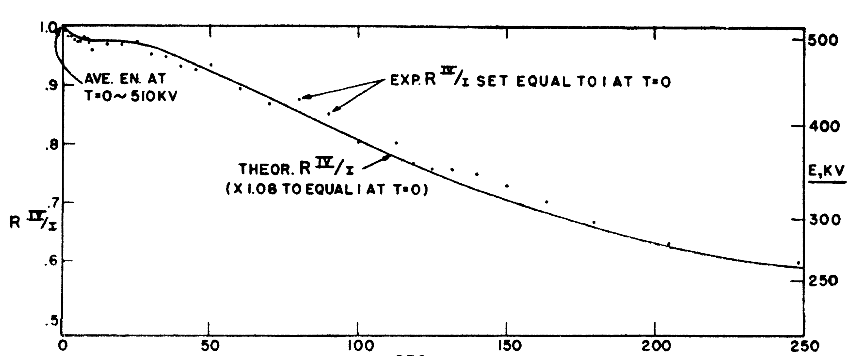

FIG. 12. Average value of delayed neutron energy after a saturated irradiation (right-hand scale) and the observed *vs.* calculated intensity ratio (left-hand scale).

[7] A. O. Hanson, Los Alamos Declassified Document No. 59.

TABLE I. Properties of delayed neutron periods.

Half-life	Energy	Relative yield, position I	Yield, corrected for energy
55.6 ±0.2 sec.	250±60 kv	0.172±0.003	0.153±0.004
22.0 ±0.2	560±60	1.000	1.000
4.51±0.1	430±60	1.42 ±0.06	1.28 ±0.08
1.52±0.05	620±60	1.35 ±0.06	1.45 ±0.08
0.43±0.05	420±60	0.57 ±0.04	0.51 ±0.05

TABLE II. Absolute yields of delayed neutron periods.

Half-life	Absolute yield
55.6 sec.	2.5×10^{-4}
22.0	16.6
4.51	21.3
1.52	24.1
0.43	8.5
	73.0×10^{-4}

of the room adjoining the pile) in front of the long counter. The yields of the 55.6- and the 4.5-sec. periods (relative to the 22.0) were determined by taking integral counts over appropriate time intervals in the same manner as these yields were measured in position I. In each measurement the back-scattering correction was made by use of a paraffin cone in front of the long counter; its amount was about 20 percent so the back-scattering in the room was not excessive.

The long counter relative yields for the 55.6- and the 4.5-sec. periods are both lower than the values measured in position I, which shows that, for position I, the low energies are emphasized (because the energy of the 22-sec. period is higher than that of the other two). It was not possible to measure the yields of the short periods with the long counter because of insufficient intensity, so the true relative yields for the short periods were obtained by comparison with the corrections for the 4.5- and 55.6-sec. corrections. The largest correction (for the 55.6 sec.) was only 12 percent, so the error in estimating the correction for the short periods by interpolation is probably not serious. The final values for the corrected yields,

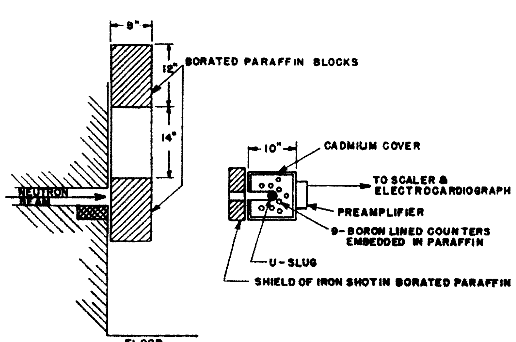

FIG. 13. Apparatus for the determination of absolute yield of delayed neutrons and of short period delayed neutrons.

together with the other petinent data, are listed together in Table I for convenience. The estimated errors are based partly on statistical error and partly on variation in results of successive runs.

The results given here cannot be compared very easily with those already published, for the energy dependence of the apparatus actually used for other measurements would have to be considered. However, in general, the yield values of Redman and Saxon agree quite well with the yields found here for the long periods (they did not resolve the two shortest periods). The half-life values agree reasonably well with Snell's and especially well for the short lives where, however, he obtained no yield values. Burgy *et al.*[8] have recently published energy values for the delayed neutrons, based on measurement of proton recoils in a cloud chamber, which correspond very well with those of Table I.

F. Absolute Yield of Delayed Neutrons and Applications to Pile Behavior

Nagle, Redman and Saxon[9] determined the absolute yield (the fraction of the total neutrons emitted which are delayed) by comparing the activation of indium foils in a graphite block by delayed neutrons with the activation by instantaneous neutrons. In making the comparison it was necessary to extrapolate back over a period of about 15 seconds, using the known periods, to obtain the initial intensity of the delayed neutrons. Use of their experimental data but the present periods and yields, corrected for energy (i.e., five periods instead of their four), raises the absolute yield from their calculated value of 0.0078 to 0.0081. The latter value, of course, refers only to those delayed neutron periods of

[8] M. Burgy, L. A. Pardue, H. B. Willard, and E. O. Wollan, Phys. Rev. **70**, 104A (1946).
[9] Unpublished Manhattan Project Work (1943).

0.43 sec. or longer—the presence of shorter periods would mean a larger absolute yield. Because the absolute yield value of 0.0081 seemed high compared to the yield obtained from actual pile behavior, the absolute yield was re-measured by an independent method.

The apparatus is shown diagrammatically in Fig. 13. When the "guillotine" is dropped from the position shown, it allows a 0.19 sec. irradiation of the uranium slug as the opening passes the beam of thermal neutrons. For the yield work, however, the guillotine was held in the open position to measure the total neutron omission from the metal slug and then dropped to give the delayed neutron decay curve. The decay curve was recorded on an electrocardiograph tape in the same manner as was used for the work at the rabbit. The initial intensity of the decay curve (which was 100 times background) compared to the intensity with the beam open then gives the absolute yield directly. Actually the open beam intensity was measured at a low pile power and converted to high power by means of a fission chamber monitor located inside the pile shield. The initial intensity of the decay curve was obtained by extrapolating the experimental points back from $t=1$ sec. to $t=0$ according to the five periods of Table I. This was done because of the presence of a hitherto unknown short period present at shorter times (see Section G).

The "neutron trap," designed primarily for high efficiency (about 1 percent), was intended to be somewhat independent of energy (through placement of counters) but, unfortunately, has a rather large energy dependence. Therefore, it is necessary to correct the observed yield for the difference in energy of fission neutrons and delayed neutrons (which have an average energy of about 500 kv at $t=0$). The energy sensitivity of the trap was measured, by comparison with the long counter, for several different neutron energies; for Ra-Be, Na-Be, 22-sec. delayed neutron period, 55-sec. period, and Na-D_2O neutrons. It was found from these standards that the sensitivity decreases smoothly with increasing energy and that the conversion factor between fission neutrons and 500 kv neutrons is 1.36 ± 0.06. The observed yield was $(0.99 \pm0.04$ percent) which then becomes $(0.73+0.05$ percent), when corrected for energy sensitivity. This yield, of course, does not include periods shorter than the five of Table I. The absolute

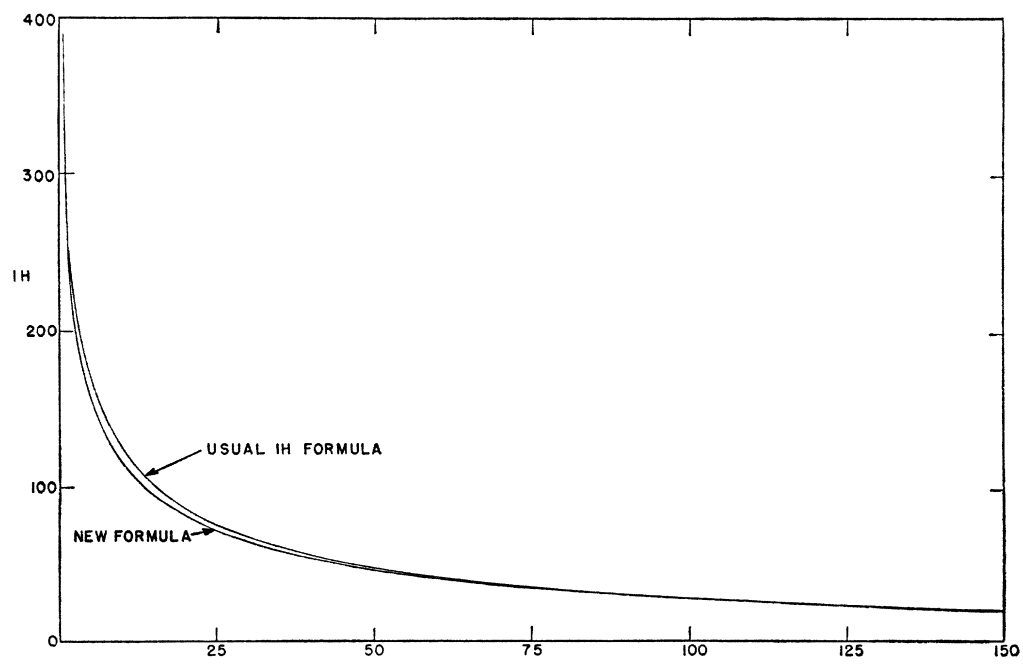

FIG. 14. The relationship between the excess reactivity of a pile and its period (the "inhour formula").

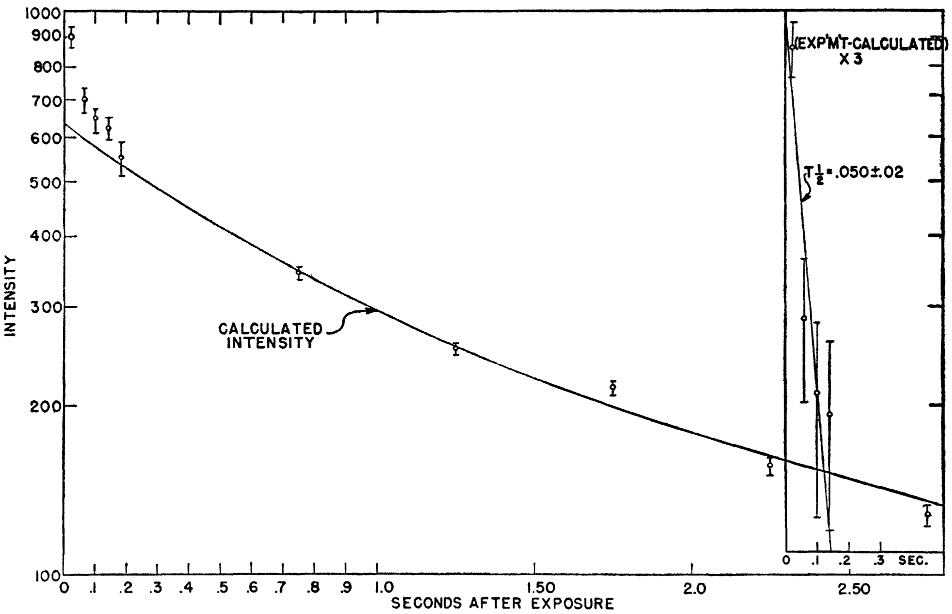

FIG. 15. Delayed neutron decay curve after a 0.19-sec. irradiation obtained with the apparatus of Fig. 13. The initial part of the curve (shown on larger scale also in right hand box) is evidence for an activity of 0.05-sec. half-life.

yield of 0.0073 can be combined with the relative yields of Table I to obtain the absolute yield values of the individual periods which are listed in Table II.

It is a simple matter to ascertain whether the absolute yields are consistent with observed pile behavior. Observations[10] with graphite-uranium piles have shown that the amount of reactivity ("excess k") which will give a pile period of one hour is $2.5\pm0.5\times10^{-5}$. This amount of reactivity is by definition one "inhour." The excess k corresponding to one inhour also follows directly[11] from the absolute yields:

$$(k-1)_{1\ ih}=\frac{t_0}{3600}+\sum_i \frac{y_i\tau_i}{3600+\tau_i},$$

where t_0 is the average lifetime of the neutrons in the pile and y_i is the absolute yield of the ith delayed neutron group of period τ_i (in seconds). The value of t_0 is about 1.5×10^{-3} sec.[12]; its exact value is unimportant. Substitution of numerical values gives

$$(k-1)_{1\ ih}=(2.6\pm0.2)\times10^{-5},$$

which is in good agreement with, and more accurate than, the value obtained directly from pile behavior.

The periods and yields reported here also make it possible to give a more accurate formulation of the relationship between the reactivity in inhours and the pile period (the "inhour formula") than that given in reference 10. Substitution of the new values into the formula given as Eq. 3 of reference 11 gives the following relationship:

$$ih \text{ of reactivity}=\frac{54}{T}+\frac{20.3}{T+0.62}+\frac{204}{T+2.19}+\frac{535}{T+6.5}+\frac{2036}{T+31.7}+\frac{787}{T+80.3}$$

and the two formulas (old and new) are compared in Fig. 14. It is to be noted that the present formula is adjusted to equal unity for $T=3600$ in accordance with the definition of the inhour, while the formula of reference 10 (aside from the older yield and period values) differ

[10] Anderson, Fermi, Wattenberg, Weil and Zinn, Phys. Rev. **72**, 16 (1947).

[11] L. W. Nordheim, Manhattan District Declassified Document No. 35, Eq. 3, June 14, 1946.

[12] E. Fermi, MDDC No. 74, June 18, 1946.

slightly in that the sum of the numerators is set equal to 3600 and, hence, the reactivity is slightly less than one inhour for a period of one hour.

G. New Short Period Delayed Neutron Activity

The guillotine of Fig. 13 was also used to investigate a possible short-period, delayed neutron activity whose existence seemed likely from some measurements made during the absolute yield work. A 0.19 sec. irradiation was obtained by dropping the guillotine past the beam and the resulting decay curve, recorded on the electrocardiograph tape, was compared with a theoretical curve made up of the five known periods (in amounts corrected for relative saturation and energy sensitivity of the neutron trap). The results are shown in Fig. 15 where the theoretical curve is equated to the experimental in the region 0.5–2.5 sec., the experimental points being the sum of the counts obtained on a number of runs. The presence of a short period is evident, and it turns out to have a half-life of 0.05 ± 0.02 sec. and a relative intensity (22 sec. period = 1.00) of approximately 0.15, which is about the same yield as the 55 sec. period. The reality of the period was checked by removing the uranium slug and cutting a hole in the Cd cover of the trap to obtain a high counting rate from the thermal neutrons when the beam was open. The experiment was repeated under these conditions and the rate dropped to background instantly when the beam was cut off, thus eliminating any spurious source of the short-lived activity (such as mechanical shock, bouncing, etc.). The guillotine actually shuts off the beam in about 1 millisecond and the decay curve can be measured immediately, limited only by the speed of the recording circuit and the available counting rate.

The absolute total yield value of 0.73 percent, which was described in Section F, does not include the 0.05 sec. period, of course. Inclusion of this period raises the yield to 0.755 percent, a change which is uncertain by a negligible amount because of the unknown energy of the 0.05 sec. period. The short period has very little effect in a saturated run, being only about 4 percent of the total initially and dropping to less than 1 percent within 0.2 sec. Because this period is much shorter than the usual pile periods, it also has no effect on the considerations of Section F concerning the value of the inhour or the inhour formula.

A separate experiment was performed in an attempt to determine if any periods shorter than 0.05 sec. exist. The set-up was the same as Fig. 13 with the addition of a rotating shutter in the beam before the uranium slug and a timing device, so that only those counts in a certain time interval after each burst of neutrons would be detected. The apparatus was actually the "chopper" velocity selector[13] used to detect short periods rather then neutron times-of-flight. The lower limit to the lifetimes which could be detected by this method was about one millisecond and was set by the time of flight of the neutrons plus the lifetime of the neutrons in the neutron trap.

Because of the high background inherent in such an adaptation of the chopper, the experimental uncertainty turned out to be quite high. However, the absolute yield obtained (by comparing the "instantaneous" neutrons with those delayed) for all periods greater than one millisecond is 0.0084 ± 0.0012 which agrees, within experimental error, with the value of 0.00755 for the six periods already discussed. Thus, no periods between one and 50 milliseconds were found, and any such periods, if present, must constitute only a small part of the total delayed neutron emission.

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[13] T. Brill and H. Lichtenberger, to be published.

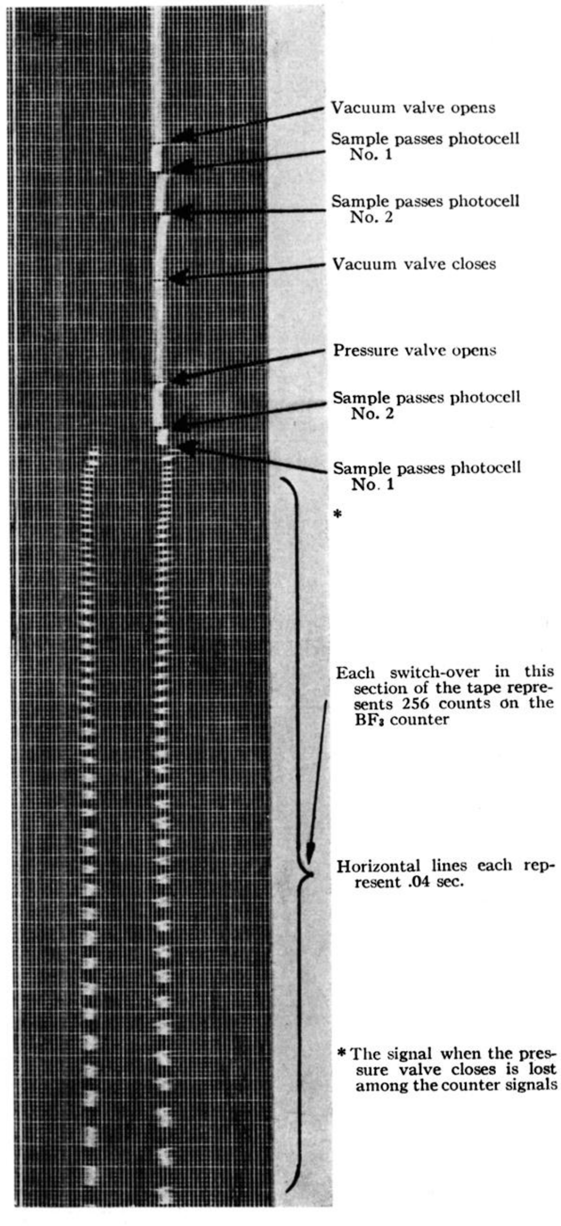

FIG. 2. Initial portion of a typical electrocardiograph tape showing timing marks and the beginning of the delayed neutron decay curve.