Experimental Production of a Divergent Chain Reaction

E. Fermi
Institute for Nuclear Studies, University of Chicago 37, Illinois
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Except for minor revisions this paper is the reproduction of a report written for the Metallurgical Laboratory of the University of Chicago almost ten years ago, after the experimental production of a divergent chain reaction. This report has now been declassified and can be published.

The present first part of the report contains a general description of the first pile and of its operation. The details of the construction preparation, and testing of the materials and of the instrumentation are given by the members of the groups responsible for the work in Appendices I and II.

The pile had approximately the shape of a flattened of graphite having 388-cm equatorial radius and 309-cm polar radius. The uranium was distributed through the graphite mass in lumps partly of metal and partly of oxide arranged in a cubic lattice array with about 21-cm cell side. The experimental procedure followed in approaching the critical dimensions and in the actual operation of the pile is described. The observed critical dimensions are compared with the expectation from the tests on the various components of the structure.

This report gives a description of the construction and operation of a chain reacting pile. The pile was constructed in the West Stands Laboratory during the months of October and November 1942 and was operated for the first time on December 2, 1942.

It will appear from its description that an experiment of this kind required the collaboration of a large number of physicists.

The two groups of Zinn and Anderson took charge of the preparation of the materials and of the actual construction of the pile; the group of Wilson prepared the measuring equipment and the automatic controls. The details of this work are given by the members of the two groups in the appendices.

A large shape of the credit for the experiment goes also to all the services of the Metallurgical Laboratory and in particular to the groups responsible for the development of the production and the testing of the materials. The exceptionally high purity requirements of graphite and uranium which were needed in very large amounts probably made the procurement of suitable materials the greatest single difficulty in all the development.

General Description of the Pile

The pile consists essentially of a lattice of lumps, partly of uranium metal and partly of uranium oxide imbedded in graphite. Except for a small fraction near the surface of the pile the lattice cell is a cube of 8.25 inches side.

Since only a relatively small amount of metal (about six tons) was available and since our graphite was of various brands of different purity it had been planned originally to construct the pile in an approximately spherical shape, putting the best materials as near as possible to the center. It happened actually that the critical conditions were reached before the sphere was completed and construction was interrupted about one layer above the critical dimensions. For the same reason the top layers of the pile were made appreciably smaller than would correspond to the spherical shape originally planned. The present structure may be roughly described as a flatted rotational ellipsoid having the polar radius 309 cm and the equatorial radius 388 cm. (See Fig. 1.)

The graphite is supported on a wooden structure and rests on the floor on its lowest point.

The original plan foresaw the possibility that it might have been necessary to evacuate the structure in order to reach the critical conditions. For this reason the pile was constructed inside a tent of rubberized balloon fabric that in case of need could have been sealed and evacuated.

Since the amount of metal available was only about 6 tons, the metal-bearing part of the lattice was designed for best utilization factor. The metal lumps used weighed 6 pounds and consisted of metals of various origins (Westinghouse, Metal Hydrides and Ames). An exponential experiment performed on the metal lattice had given for it a reproduction factor of 1.067 and $\bigtriangledown^2 = 101.7 \times 10^{-6}$ cm^{-2}.[1] The use of heavier metal lumps of seven or

[1] The neutron density n varies approximately according to the equation $\bigtriangledown^2 n = an$, where a is a constant depending on the physical and geometrical structure of the lattice. The value of a called the Laplacian of the lattice and is denoted by $\bigtriangledown^2$. Larger values of

eight pounds would have given a better reproduction factor. Since, however, heavier metal lumps would have reduced the volume of the metal-bearing part of the lattice, it was deemed advisable to use lumps somewhat undersize.

The greatest part of the volume was occupied by a lattice having the same cell side of 8 $^1/_4$ inches with lumps of pressed UO_2 weighing about 2140 g. The reproduction factor for this lattice had been measured in a previous exponential experiment and had been found to be 1.039 with a $\bigtriangledown^2 = 59 \times 10^{-6}$ cm^{-2}.

Measurements performed during the construction

A series of measurements was performed while the pile was being assembled in order to make sure that the critical dimensions could not be reached inadvertently without taking the proper

Table I. Measurements of the pile during construction

Layer		R_{eff} УН	R^2_{eff}/A
15	42	128	390
19	78	158	320
23	119	187	294
25	148	200	270
29	221	225	229
33	345	248	178
36	470	265	149
41	350	288	98
45	1360	308	70
47	1940	317	52
51	4400	332	25
54	12400	344	9.5
57	divergent	356	—

$\bigtriangledown^2$ correspond to a better structure.

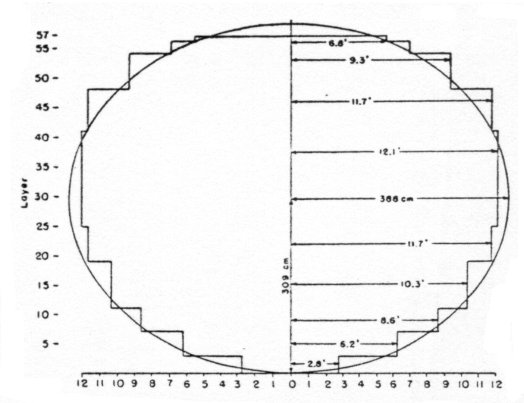

Рис. 1: Vartical cross section of the pile, showing the equivalent ellipsoid.

precautions. These measurements had also the purpose of checking the neutron multiplication properties of the structure while it was being assembled so as to permit the determination of the critical point before actually reaching it.

The measurements were performed using two types of detectors. A BF_3 counter was inserted in a slot about 43 inches from the ground and its reading were taken at frequent intervals of time. In addition an indium foil was irradiated every night in a position as close as possible to the effective center of the structure and its induced activity was measured the following morning and compared with the reading of the BF_3 counter. For these measurements the natural neutrons spontaneously emitted by uranium are a perfectly adequate source and no other source of neutrons was added.

Typical results of these measurements are collected in Table I. The first column indicates the height of the structure expressed in number of layer 9 each layer approximate 4 $^1/_8$ in.) The second column gives the intensity A expressed in counts per minute of a standard indium foil, induced by the natural neutrons when the foil is placed at a central place inside the structure where the neutron intensity is a maximum. Actually, the foils were placed as close as possible to the best position and a small correction was applied in order to account for the fact that the foil was not exactly at the optimal position.

In a spherical structure having the reproduction factor 1 for infinite dimensions the activation of a detector placed at the center due to the natural neutrons is proportional to the square of the radius. For an ellipsoid a similar property holds, the intensity at the center being proportional to the square of an effective radius R_{eff} given by the formula

$$\frac{3}{R_{\text{eff}}^2} = \frac{1}{a^2} + \frac{1}{b^2} + \frac{1}{c^2}, \tag{1}$$

where a, b and c are semi-axes of the ellipsoid. For the case of spherical sectors such as were the spares of our structure at various stages of its constructions, it clearly would be a major mathematical task to determine exactly R_{eff}. It proves, however, rather easy and not too arbitrary to determine graphically for any height of the spherical sector an equivalent flattened ellipsoid. (See Fig. 1.) The effective radius can then be calculated with formula (1). The values listed in the third column of Table I are calculated in this way.

If the reproduction factor were 1 for our lattice the expression given in the fourth column of the table should be a constant. It is seen instead that the values listed in column four decrease steadily and converge to zero at about the 56th layer. This is the point where the critical conditions are attained where the intensity due to the natural neutrons would become infinitely large. The values of R_{eff}^2/A are plotted in Fig. 2. The critical layer is at the intersection of the curve with x axis.

During the construction as a matter of precaution, appreciably before reaching this critical layer, some cadmium strips were inserted in suitable slots. They were removed once every day with the proper precautions in order to check

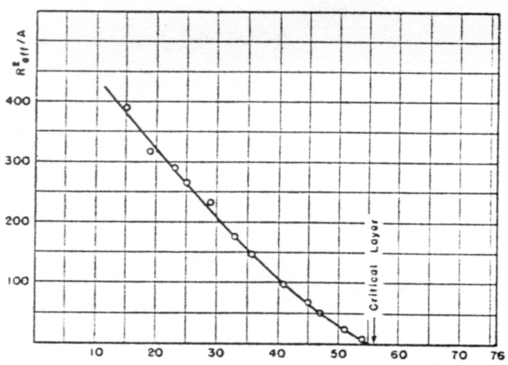

Рис. 2: Plot showing the approach to the critical size during construction.

The approach to the critical conditions. The actual construction was carried in this way to the 57th layer, about one beyond the critical dimensions.

When all the cadmium is removed the effective reproduction factor of the structure is about 1.0006.

Measuring Equipment and Controls

Any detector of neutrons or of gamma-radiation can be used for measuring the intensity of the reaction. Neutron detectors are somewhat preferable since they give a more immediate response to the intensity of the reaction and are not affected by the radiations emitted by the fission products after shut-down of the reaction. Actually used for determining the intensity of the reaction were several such neutron detectors, namely, two BF_3 proportional counters placed on the outside of the pile and several ionization chambers filled with BF_3 and placed near one of the walls of the pile. These chambers were connected to suitable amplifying system, and the amplified current was used to operate recording instruments and the automatic controls and safety devices.

The controlling of the reaction was obtained by inserting in the pile some strips of neutron absorbing materials (cadmium and, in one case, boron steel).

When the pile is not in operation, several such cadmium strips are inserted in a number of slots so as to bring the effective reproduction factor considerably below 1. It was actually found that any one of the cadmium strips is alone sufficient to bring the pile below the critical conditions. Besides a number of cadmium strips that can be used for manual operation of the pile, the pile is provided also with two safety rods and one automatic control rod. The safety rods are normally out of the pile during operation. They are kept outside of the pile by catch operated by a magnet and they are connected to a suitable system of weights so that they are drawn inside the pile by the weights if the catch is released. The magnets are energized by an amplifying system in such a way that they are automatically released if the intensity of the neutrons emitted by the pile rises above a specified limit.

The automatic control rod may be pushed inside and outside the pile by two electrons motors and may be operated either by hand or by an amplifying system in such a way that the rod is pushed inside if the intensity of the reaction increases above the desired level, and is pulled outside if the intensity is below the desired level. The detailed description of the control and measuring devices is given in Appendix II.

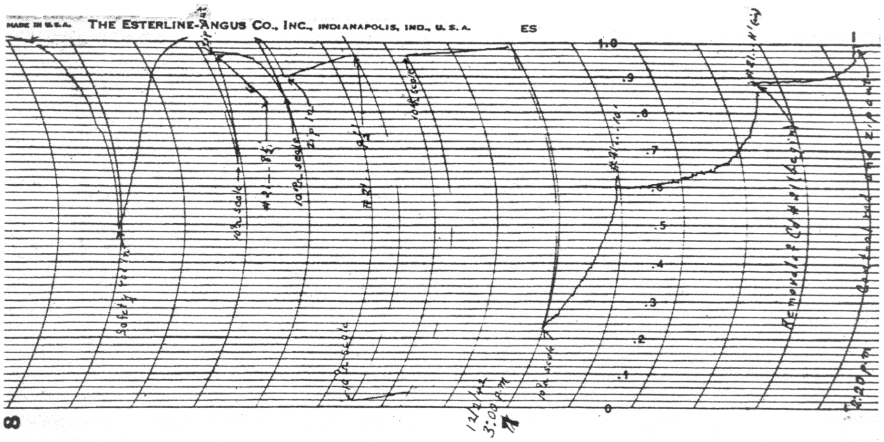

Рис. 3: First operation of the pile. Automatic record of the reaction intensity.

Operation of the Pile

In order to operate the pile, all the cadmium strips except one are first taken out of the pile. The last rod is then slowly pulled out of the pile. As the critical conditions are approached, the intensity of the neutrons emitted by the pile begins to increase rapidly. It should be noticed, however, that when this last strip of cadmium is so far inside the pile that the effective reproduction factor is just below 1, it takes a rather long time for the intensity to reach the saturation value. In a similar way, if the cadmium strip is so far outside of the pile that the reproduction factor is greater than 1, the intensity rises at a rather slow rate. Indeed, for our pile, when all the cadmium is completely outside of the pile, the intensity rises approximately at the rate of a factor of 2 every minute. When the cadmium strip is close to the critical position, these relaxation times become exceedingly long. It has been found, for example, that for one of our controlling strips, the relaxation time is given by: 230 minutes/x, where x is the distance of the rod from the critical position expressed in cm. This means that if the rod is only 1 cm off the critical position, the relaxation time is about 4 hours. For the automatic control rod the corresponding constant is 180 minutes. These long relaxation times which are due to the existence of a small percentage of delayed neutrons emitted in the fission process make it rather easy to keep the pile operating at a constant level of intensity even without the use of automatic regulation. Indeed, to operate the pile at the described level of intensity, one can usually proceed as follows:

First, the last strip of cadmium is pulled completely outside of the pile and the intensity as indicated by the various measuring devices begins to rise slowly. Since in these conditions, the relaxation time is about two minutes, the described level of intensity is usually reached in a few minutes. As soon as the meters indicate that the described level has been attained, the rod is pushed inside the pile to about the critical position. The measuring instruments indicate immediately a steadying of the intensity at about the described level. In order to keep the level constant, it is sufficient to push the rod one or two cm in or out every once in a while so as to compensate small variations in the reproduction

Table II. Radiation survey in the vicinity of the pile

	Milliroentgen per minute	Counts per minute of a standard indium foil at saturation
Near pile	50	$8 \cdot 10^6$
Inside pile room far from pile	6	10^6
Corridors on side of pile room	2	$2 \cdot 10^5$
Tower room	0.0005	negligible
Sidewalk of Ellis Street nearest to pile	0.05	6 000
Sidewalk of Ellis Street farther from pile	0.01	2 700
Control	0.001	–

factor due primarily to changes of atmospheric pressure. The diagram in Fig. 3 was taken by the automatic intensity recorder during the first operation of the pile.The exponential rise of the intensity is clearly noticeable on the diagram. The intensity was permitted to increase up to a value corresponding to an energy production of about $^1/_2$ watt. At this point, the automatic safety device operated, and the safety rods were pulled inside the pile and interrupted the reaction as evidenced on the diagram by the sudden drop in intensity.

A higher intensity test was made on December 12 when the pile was operated to an energy production of approximately 200 watts. The test was not run to a higher intensity on account of the limitations imposed by the necessity of keeping the radiation outside of the building well below the physiological tolerance dose. During the operation at high intensity which lasted about 45 minutes, some records of the intensity in various rooms inside the building and on the street outside were taken with standard R-meters and with BF_3 counters and indium foils to detect the neutron intensity. Typical values obtained in this survey are shown in Table II.

Comparison of Expected and Observed Critical Dimensions

In spite of the fact that the shape of the pile and its internal structure are far from regular, some conclusions may be obtained as to the actual reproduction factors of the various lattices used in the pile and their comparison with the reproduction factors expected from the results of exponential experiments.

We have already indicated (see Fig. 1) that the outline of the structure is not far from that of a flattened rotation ellipsoid with a polar semi-axis of 309 cm and an equatorial semi-axis of 388 cm. Formula (1) gives then as effective radius of the structure,

$$R = 355 \text{ cm}.$$

This value of the radius corresponds to a $\bigtriangledown^2$ of 78.3×10^{-6} cm^{-2} and to an average reproduction factor of about 1.054.

Since various lattices have been used at various places inside the structure, such values are only mean values for the various lattices used, and they can be compared with the individual values only if the statistical weight pertaining to each kind of lattice is known.

One can prove easily that the statistical weight of each component lattice is in first approximation proportional to its volume multiplied by the mean square density of neutrons over the volume occupied by the given lattice type. An attempt has been made to calculate in this way the statistical weight of the various lattices represented in our structure. The results of this calculation are given in Table III.

The first column of the table gives the type of lattice. For the sake of simplicity, lattice types having presumably a rather similar reproduction factor have been grouped together under the denomination of Speer. The second column gives the statistical weight of each kind of lattice expressed in percent. The third column gives the values of $\bigtriangledown^2$ as obtained from exponential experiments. The weighted average of $\bigtriangledown^2$ is 73.4 instead of the value of 78.3 as estimated from the critical dimensions.

This is an indication that the values of $\bigtriangledown^2$ and of the reproduction factors as calculated from exponential experiments have been slightly

Table III. Statistical Weight of Various Lattices in the Pile

Type of lattice	Statistical weight	$\bigtriangledown^2 \cdot 10^6$ from exponential experiments
Metal	39.2	+102
AGOT Brown AGOT	53.5	+59
Speer	6.6	+45
U.S. Live	0.5	−10
Dead	0.2	−520
	Weighted average	73.4

underestimated, the correct values being probably about 0.003 or 0.004 higher than the published values.

Energy Emitted by the Pile

The number of neutrons emitted by the pile, the number of fissions the energy produced can be estimated in terms of the activity of standard indium foils placed inside the pile. The standardization of these indium foils has indicated that the following relationship exists between the resonance activity, A_{Res} expressed in counts/minute at saturation with the foil screened by cadmium, and the slowing down density of neutrons in graphite

$$q = 0.00156 \times A_{\mathrm{Res}}. \tag{2}$$

The cadmium ratio in the greatest fraction of the volume of our structure is about 6.6; this means that if an activity of A counts/minute at saturation is recorded when the indium foil is not screened by cadmium, the activity with cadmium would be

$$A_{\mathrm{Res}} = A/6.6$$

and consequently,

$$q = 0.00156 \times A/6.6 = 0.000236 \times A.$$

The total number of neutrons that are slowed down inside the pile from above to below indium resonance energy is given, therefore, by:

$$0.000236 \times \bar{A}\ V,$$

where, $\bar{A}$ is the mean value of activity and V is the volume of the pile. We have assumed

$$V = 1.95 \times 10^8 \text{ cc.}$$

On the other hand, one can estimate that $\bar{A}$ is equal to about $0.3\times$ the activity A_0 at the center of the pile. It follows that the total number of neutrons slowed down in the pile from above to below indium resonance is

$$1.4 \times 10^4 \times A_0.$$

The total number of neutrons produced in the pile is about 13 percent higher, since some of the fast neutrons produced are absorbed at resonance before reaching indium resonance energy and a small fraction escapes from the pile. The total number of neutrons produced is given, therefore, by

$$1.6 \times 10^4 \times A_0. \tag{3}$$

If we assume that 2.2 neutrons per fission are emitted, we obtain from this the number of fissions per second expressed by the formula

$$F = 7200 A_0.$$

Assuming that the energy produced per fission is 200 MeV, equivalent to 3.2×10^{-4} erg, the power output of the pile is given by

$$2.3 A_0 \text{ erg/sec} = 2.3 \times 10^{-7} \times A_0 \text{ watts.}$$

This formula has been used in the estimates of the power output already given.

Appendix I. Construction of the Chain Reacting Pile

H.L. Anderson, A.C. Graves, P.G. Koontz, L. Seren, A. Wattenberg G.L. Weil, and W.H. Zinn[2]

In the previous sections of this report some discussion of the general structural features of the chain-reacting pile is given. In this section the detailed plan of the graphite-uranium system is set forth, together with a brief description of the preparation and testing of the special materials. This work, which occupied a period of three months, required that very careful physical measurements be made on rather large quantities of material. Our

[2]Present addresses:
H.L. Anderson,
institute for Nuclear studies,
University of Chicago,
Chicago, Illinois.

A.C. Graves,
Los Alamos scientific laboratory,
P.O. Box 1663,
Los Alamos, New Mexico.

P.G. Koontz,
College of Wooster,
Wooster, Ohio.

Leo Seren,
Betatron Section, Code 3116,
Nucleonics Division,
Naval Research Laboratory,
Washington, D.C.

Albert Wattenberg,
Laboratory for Nuclear Science and Engineering,
Massachusetts Institute of Technology,
Cambridge, Massachusetts.

G.L. Weil, Consultant,
Suite 603,
1025 Connecticut Avenue, N. W.,
Washington 6, D. C.

W.H. Zinn,
Argonne National Laboratory,
P. O. Box 299,
Lemont, Illinois.

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Two types of measurements on the materials with which it is proposed to build a chain reaction must be made. first, the reproduction factor for the particular graphite-uranium system being used must be determined and, secondly, reasonably large samples of the actual materials of construction must be checked in order to insure that the reproduction factor will not be lowered by the introduction of inferior batches of uranium or graphite. In this instance the problem was somewhat complicated by the fact that in the first chain reacting pile three different types of graphite-uranium systems had to be used.

Determination of the Reproduction Factor

The exponential pile experiment is designed to determine the reproduction factor k of an infinite lattice of uranium lumps in graphite without the necessary of constructing piles of very large dimensions. From such pile experiments the optimum cell constants have been determined for pressed UO_2 (density = 6.1 g/ cm^3) and cast uranium metal (density = 18 g/cm^3), together with the values of k associated with these optimum lattices in graphite of poorer quality than that available for the chain-reacting pile. For the purpose of designing the chain-reacting pile it was necessary to determine the value of k for the three components (cast uranium metal in AGOT graphite-pressed UO_2 in AGOT graphite- pressed UO_2 in Speer graphite) of its structure. The measurements and results of the exponential piles which were constructed to test these components will be given in this section.

Briefly, the theory of exponential pile measurements is as follows:

If one considers a uranium-graphite lattice structure of square cross section with side equal to a, and semi-infinite height, with a source of fast neutrons at the center of the base, then, at points sufficiently far removed from the source, the neutron intensity will be given an equation of the from

$$n = \sum_{ij} B_{ij} \; e^{-x/b_{ij}} \; cos \; \frac{i\pi y}{a} \cdot \cos \frac{j\pi z}{a}, \tag{1a}$$

where the x axis is taken along the vertical axis of the pile, and the $x = 0$

plane coinciding with the base of the pile. Thus, for points on the axis, each harmonic of the neutron intensity decreases exponentially,

$$n = B_{ij}\ \exp(-x/b_{ij}), \qquad (2a),$$

with a relaxation distance equal to b_{ij}. At a sufficiently large distance from the source the first harmonic only is important. The relaxation length $b(b_{11})$ is related to the reproduction factor k through the following equation:

$$K = \left[1 - \frac{\lambda\Lambda}{3} \cdot \left(\frac{1}{b^2} - \frac{2\pi^2}{a^2}\right) \times \exp\left\{\frac{r_0^2}{4} \cdot \left(\frac{1}{b^2} - \frac{2\pi^2}{a^2}\right)\right\}\right], \qquad (3a)$$

where λ = mean free path of thermal neutrons in graphite, A = mean free path for absorption collision, and $r_0^2/4$ = the age of nascent thermal neutrons. The quantity

$$\left(\frac{1}{b^2} - \frac{2\pi^2}{a^2}\right) = \frac{1}{c^2},$$

where c is the diffusion length. For the case that k is close to unity, c is very large and $1/c^2$ small so that one can write

$$K = \left[1 - \left(\frac{\lambda\Lambda}{3} + \frac{r_0^2}{4}\right) \cdot \left(\frac{1}{b^2} - \frac{2\pi^2}{a^2}\right)\right] \qquad (4a)$$

or

$$K = \left(1 - \frac{L^2}{c^2}\right), \quad \text{where} \quad \mathrm{L}^2 = \left(\frac{\lambda\Lambda}{3} + \frac{\mathrm{r}_0^2}{4}\right). \qquad (5a)$$

Thus, if L, the migration length, is known, a measurement of the relaxation distance b, associated with the first harmonic of the neutron intensity, will determine the reproduction factor corresponding to a lattice of infinite dimensions similar to the one being tested.

Because of the finite height (124 in.) of an actual exponential pile, two corrections must be applied to the neutron intensity measurements. First, a " harmonic correction" due to the presence of higher harmonics at point near the source; and second, an "end-correction" due to the proximity of the top of a pile to the measuring positions.

To determine the relaxation distance b, indium foils (0.0924 g/cm^2) are placed at positions along the axis of the pile, and the induced 54-minute activity measured on G-M counters. For these measurements the foil is held in a nickel holder; thus, the activation (A_{ni}) is due to both thermal and indium resonance neutrons. (All measurements are corrected to give the activities that would be observed for infinite times of irradiation.) The emission of neutrons by spontaneous fission of the uranium in the pile produces a "background" which must be subtracted from the intensity measurements. Finally, after making the harmonic and end corrections, one calculates b from the relation

$$b = \frac{D}{\ln\{(A_{ni})2/(A_{ni})1\}}, \tag{6a}$$

where D is the distance between the two positions at which (A_{ni}) is measured.

The length of a side a to be used in calculating k from Eq.(4a) must be that value for which the neutron intensity actually becomes equal to 0. (Because of the finite length of the mean free path λ compared to the dimensions of the pile, the effective side is large than the physical side.) From neutron intensity measurements near the edge of the pile one can estimate the effective value of a.

The migration length L (Eq.(5a)) can be calculated from the graphite density and the cadmium ratio. The cadmium ratio $(A_{ni})/(A_{cd})$ is the ratio of the activity of a foil with nickel holder (A_{ni}) and the activity (A_{cd}) at the same position when the foil is covered with cadmium. Activation in the latter case is due only to indium resonance neutrons.

The three piles with which we are concerned had the following general features in common. A pile was constructed on a base (AGX graphite), 16 in. high, in the top layer of which a source channel was placed. Four (Ra + Be) fast neutron sources, each of approximately 0.5 g, were used and these were divided into two closely equivalent 1 g sources. Each was placed in the channel at positions approximately halfway from the center to the edges of the pile. This arrangement, through cancellation of odd harmonics of the neutron intensity at points along the pile axis, considerably reduced the harmonic correction to be applied to the measurements. The lattice structure measured 99 in. × in. × 123 $^3/_4$ in., and consisted of 15 layers (each 4 $^1/_8$ in. high) of graphite bearing uranium, alternating with 15 layers of solid graphite. Measuring slots extending to the center of the pile were inserted in horizontal sections corresponding to the even-numbered graphite layers.

In order to eliminate errors caused by slow neutrons being scattered back into pile from the surroundings, the top and sides of the piles were covered with cadmium sheet.

In specifying the positions at which measurements were made, the following coordinate system and unit of length are used. The origin is taken at the center of the base of the lattice; the x coordinate along the pile axis, the

y coordinate in the direction of the line joining the sources, and the z coordinate in the direction of the measuring slots. the fundamental lattice constant (also equal to the distance between two layers of the pile) is taken as the unit of length, and in the piles to be described, is equal to 8.25 in.

Pile No. 18

The structure of this pile consisted of a cubic lattice of pressed UO_2 (Mallinckrodt ether purified) pseudo-spheres (average weight 2143 g) in Speer graphite. The lattice spacing was 8.25 inches, and the ratio of the weight of graphite to that of uranium per cell was 6.4.

A summary of the measurements is given in Table I.

In Table II are given the correction factors and corrected intensities together with a least square analysis of the results.

With the distance between positions 4 and 10 equal to 125.8 cm, we obtain for the exponential relaxation distance (Eq.(6a)) $b = 62.74$ cm. The effective side of the pile was estimated to be $a = 256.9$ cm. with this value and that for b, we

Table I. Measurements on Pile No. 18.

	Average intensities			
Position	With sources		Without source	Net intensity
x, y, z	A_{ni}	A_{cd}	A_{ni}	A_{ni}
4, 0, 0	33569		75	33494
6, 0, 0	17373	2747	82	17291
10, 0, 0	4513		70	4443

* Counts per minute

calculate

$$\frac{1}{c^2} = \frac{2\pi^2}{a^2} - \frac{1}{b^2} = 45 \times 10^{-6} \quad \mathrm{cm}^{-2}$$

and $c = 149$ cm.

From Table I we obtain a cadmium ratio equal to 6.32. The value of the migration length, L (Eq. (5a)), can be estimated knowing the graphite density (1.54) and the cadmium ratio. For this pile $L^2 = 7.2$ cm^2.

From Eq. (5a) we obtain for the reproduction factor

$$k = 1.032.$$

Pile No. 27

This pile was identical with No. 18 with the exception that AGOT graphite was used throughout in place of Speer. Tables III and IV give summaries of the measurements and corrected intensities.

From these results we calculate $b = 64.52$ cm, $1/c^2 = 58.9 \times 10^{-6}$ cm^{-2}, and $c = 130$ cm.

For AGOT graphite, density 1.62 g/cc, and a cadmium ratio from Table I equal to 6.67, L^2 is estimated to be $L^2 = 666$ cm^2. From these values we obtain for the reproduction factor $k = 1.039$. Thus, we use of AGOT in place of Speer graphite gives an increase in the reproduction factor of 0.7 percent.

Pile No. 29

Since the amount of case uranium metal available for testing was insufficient to fill a

Table II. Analysis of results of measurements upon Pile No. 18.

Position x, y, z	Net intensity from Table I	Hadronic correction	End correction	Corrected intensities	Log I	Least square value $5.11350-0.14525x$
4,0,0	33494	1.0193	1.0006	34161	4.5445	4.5325
6,0,0	17291	1.0039	1.0022	17396	4.2403	4.2420
10,0,0	4443	1.0002	1.0323	4587	3.6615	3.6610

Table III. Measurements on Pile No. 27.

	Average intensities			
Position	With sources		Without source	Net intensity
x, y, z	A_{ni}	A_{cd}	A_{ni}	A_{ni}
4, 0, 0	34261		84	34177
6, 0, 0	18158	2726	91	8067
10, 0, 0	4881		80	4801

complete lattice of the usual size, the pile was constructed in the form of a sandwich in which four oxide bearing layers (at the planes $x - 6, 7, 8, 9$) of Pile No. 27 were replaced with four metal-bearing layers in the same lattice. In addition, the AGOT graphite in this same region was replaced with AGOT (Lots Nos. 10, 11), which lots showed the lowest absorption cross section. The uranium metal (from Metal Hydrides) was in the form of cast cylinders, 2 $/_4$-in. diameter, weighting approximately 2.7 kg each. The graphite-to-uranium ratio was 5.1.

The determination of the exponential relaxation distance for the metal lattice of the sandwich pile is based essentially upon a comparison of the ratio of the neutron intensity below and above the metal lattice with the ratio of the intensities at the same positions in Pile No. 27. Since, however, Pile No. 29 was built at a different location than that of Pile No. 27, it was necessary to repeat Pile No. 27 at the new location. The results of this Pile (No. 28) agreed with those obtained for the identical Pile No. 27. Pile No. 28 was, therefore, used as the control for Pile No. 29.

If R_0 and R_m are, respectively, the ratios of the intensities at positions below and above the position of the metal lattice in the oxide and oxide-metal-oxide piles, b_0 and b_m the exponential relaxation distance associated with the oxide and metal lattices, and A the height of the metal lattice in the sandwich pile, then:

$$\ln \frac{R_0}{R_m} = \frac{A}{b_0} - \frac{A}{b_m}. \tag{7a}$$

Table IV. Analysis of results of measurements upon Pile No. 27.

Position x, y, z	Net intensity from Table I	Hadronic correction	End correction	Corrected intensities	Log I	Least square value $5.11350-0.14525x$
4,0,0	34177	1.0193	1.0006	35144	4.5445	4.5444
6,0,0	18067	1.0039	1.0022	18183	4.2596	4.2617
10,0,0	4801	1.0002	1.0323	4977.7	3.6970	3.6963

The measurements on Piles Nos. 28 and 29 are given in Table V.

$$\text{For Pile No.28}: \ R_0 = I_4/I_{10} = 7.021;$$

$$\text{For Pile No.29}: \ R_m = I_4/I_{10} = 6.219.$$

Since $A = 83.82$ cm, and b_0 for Pile No. 28, 64.472 cm, we obtain from Eq. (7a)

$$\ln \frac{7.021}{6.219} = \frac{83.82}{64.472} - \frac{83.82}{b_m} \tag{8a}$$

or

$$b_m = 71.10 \text{ cm}.$$

Table V. Measurements on Piles Nos. 28 and 29.

	Pile No. 28		Pile No. 29	
Position	Observed intensities		Observed intensities	
x, y, z	A_{ni}	A_{cd}	A_{ni}	A_{cd}
4, 0, 0	36680		37320	
6, 0, 0	19530	2865	20980	3200
10, 0, 0	5212		6001	

This gives an improvement of 42.8×10^{-6} cm^{-2} in the value of $\bigtriangledown^2$ compared to Pile No. 28, or an increase in the reproduction factor for metal over dioxide (L^2 estimated to be 700 cm^2) of

$$700 \times 42.8 \times 10^{-6} = 0.03$$

Therefore, k for the results for the three piles discussed is given in Table VI.

Table VI. Results of measurements upon test piles.

Pile No.	From Of U	Graphite	$\frac{\text{Graphite}}{\text{Uranium}}$	Cd-ratio	Thermal utilization factor	b (cm)	$\frac{10^6}{c^2}$ (cm^{-2})	L^2 (cm^2)	k
18	UO_2	Speer	6.4	6.32	0.866	62.74	45	712	1.032
27	UO_2	AGOT	6.4	6.67	0.869	64.52	58.9	666	1.039
29	Metal	AGOT (Lot Nos. 10, 11)	5.1	6.56	0.871	71.10	101.2	700	1.07

Graphite Cross-section Measurements

Accurate determination of the neutron capture cross section of the graphite to be used in a reacting pile is necessary for two reasons. First, if there is too much absorption in the graphite a chain reaction may be impossible or may require dimensions too large to be practical, and secondary, since the effect of the absorption is proportional to the square of neutron density the use of low cross-section material near the center will reduce the size of the structure. For these reasons cross-section measurements were made on each brand of graphite used in the structure. These were AGX (National Carbon Company), US (U.S. Graphite Company), Speer (Speer Graphite Company), and nine different lots of AGOT (National Carbon Company) graphite. Fir these measurements a series of σ cross-section piles, described in the following section, were constructed.

Description of σ-piles

Most of these piles were built on a base of Speer graphite approximately 5 $times$5 ft and about 3 ft high. A source slot through the center of the center layer of this base parallel to one edge measured about 10×10 cm. $^1/_4 \times\ ^1/_4$–in graphite strips were fastened to the top of this base in parallel rows 12 in. apart. On these strips a layer of Speer or AGX graphite was laid leaving a $^1/_4$–in. gap into which cadmium could be inserted. In general, this layer was different from the graphite being measured and was used only because pieces were available to bridge the $^1/_4$-in. gap. Above this layer 15 layers of the material to be tested were laid with detector slots at the top of layers 3, 6, and 9. These slots, numbered 1, 2, and 3, respectively, passed through the vertical axis of the pile perpendicular to the source slot in order that small inaccuracies in placing the foils would have a minimum effect on the measurement and in order to reduce as much as possible the radiation absorbed by operators handing the foils. The entire pile above the gap was covered with cadmium in order to reduce to a minimum the number of thermal neutrons entering the pile from the room.

In those piles built to measure σ for AGX, US, and Speer 1 graphite the dimensions of this top portion were very nearly $5 \times 5 \times 5$ ft. The remaining Speer piles and the AGOT piles were about 168×157 cm and 157 cm high.

Theory

The thermal neutron density n in a graphite structure containing a source is described by the following differential equation:

$$D \cdot \Delta n - (1/t) \cdot n + q = 0, \qquad (1b)$$

where D is the diffusion coefficient $= \lambda V/3$, λ is the mean free path for scattering, V is the neutron velocity, t is the mean life of a thermal neutron, and q is the nascent thermal density. If measurements are made with cadmium in the gap and without cadmium in the gap we will have two such equations for the two neutron densities n_1 and n_2. Subtracting these two equations and writing $n = n_2 - n_1$, we have

$$D \cdot \Delta n - (1/t) \cdot n = 0, \tag{2b}$$

or

$$L^2 \Delta n - n = 0,$$

where L is the diffusion length $(= Dt)$.

We will give the solution of this equation for a rectangular pile whose sides are $(a - 2\lambda/\sqrt{3})$, $(b - 2\lambda/\sqrt{3})$, and $(Z - \lambda/\sqrt{3})$ parallel to the x, y and z axis respectively. For boundary conditions we will assume that $n = 0$ when $x = \pm a/2$, $Y = \pm b/2$ and $z = Z$. The solution is

$$n = \sum_{lm} B_{lm}\ cos\ \frac{l\pi x}{a} \cdot cos\ \frac{m\pi y}{b} \cdot \left(e^{-z/b_{lm}} - e^{-2Z-z)/b_{lm}} \right). \tag{3b}$$

Here b_{lm}, the distance for the intensity of the lm harmonic to decrease by a factor of $1/e$ in a pile of infinite length is related to L by the following equation:

$$\frac{1}{L^2} = \frac{1}{b_{lm^2}} - \pi^2 \cdot \left(\frac{l^2}{a^2} + \frac{m^2}{b^2} \right). \tag{4b}$$

Along the vertical axis of the pile the first harmonic of neutron density is proportional to

$$e^{-z/b_{11}} - e^{-(2Z-z)/b_{11}}.$$

The second term of this expression is a reflection from the top of the pile and would not be present in an infinitely tall pile. Hence to correct for the finite height of a pile all intensities along the axis are multiplied by

$$\frac{1}{1 - e^{-2(Z-z)/b_{11}}}, \tag{5b}$$

the so-called end correction.

Equation (4b) gives a means of determining L.

One either measured b_{11} far from the source where the higher harmonic are small or corrects the measured intensities for these harmonics and obtains b_{11} closer to the source where the intensity is easier to measure.

This is done as follows: Assuming a value of L, Eq. (4b) permits a calculation of the relaxation length of each harmonic. Writing Eq. (3b) for the z axis we have

$$n = \sum_{lm} B_{lm} \cdot \left(e^{-z/b_{lm}} - e^{-(2Z-z)/b_{lm}} \right).$$

If two equal sources are used at $x = \pm a/4$, two such solutions must be added and a factor of $\cos lp/4$ appears. This causes the 1,3 harmonic to cancel the 3,1 harmonic and the 1,5 to cancel the 5,1 along the Z axis. The 3,3 harmonic is the first to appear and is negative.

to a good approximation we can write

$$n = B_{11} \cdot \left(e^{-z/b_{11}} - e^{2Z-z)/b_{11}} \right) - B_{33} \cdot \left(e^{-z/b_{33}} - e^{-(2Z-z)/b_{33}} \right) + \ldots.$$

The harmonic correction factor is therefore

$$\frac{B_{11}}{n} \cdot (e^{-z/b_{11}} - e^{-(2Z-z)/b_{11}}).$$

For σ-piles used in determining cross sections of AGOT graphite, the total harmonic and end correction factors were 1.0056 for slot 1 and 1.0131 for slot 3.

Measurements

Measurements were made with indium foils of 26 cm^2 area weighting 92.4 mg/ cm^{-2}. Two counters were used and each determined the activity of three foils from each of the three slots when there was cadmium in the slot and again when the slot was empty. Irradiation times were adjusted to keep the initial counting rates below 1500 counts per minute. The count was started three minutes after the foils were removed from the pile and continued for most measurements until more than 20 000 counts had been recorded. Assuming a half-life of 54 minutes for indium the initial activity after infinite irradiation was calculated. since the sensitivities of the two counters were not the same , the activities measured on one counter were multiplied by the ratio of sensitivities as determined from measurements on a number of piles. The mean activities at slots 1 and 3 were corrected for harmonics and end effects as explained in the preceding section. Then if these corrected activities are called I_1 and I_3, respectively, b_{11} was obtained from the formula

$$b_{11} = Z_{13}/(\ln_e I_1/I_3),$$

where Z_{13} is the distance between slots 1 and 3. Equation (4b) of the preceding section was used to calculate the diffusion length. These values are given in Table VII, Column 2, for each of the graphites measured. Column 1 gives the name of the graphite as stamped on each piece. GX 2 refers to the shipment of AGX cut to $4 \times 4 \times 30$ in. SP 1 refers to the shipment of Speer graphite cut to $4\ ^1/_8 \times 4\ ^1/_8 \times 4\ ^1/_2$ in. The prime denotes graphite taken from the ends of the furnace. This graphite was not stamped. TO 1 refers to the 1st lot of AGOT graphite; TO 2 refers to the second lot, and similarly for other lots up to lot 15. Column 3 gives the diffusion length corrected to a density of 1.600 grams/cc, and Column 4 gives the cross section calculated from the formula

$$\sigma_a = \frac{12.8 \times 10^{-24}}{L_{1.6^2}}.$$

It will be noted that the best graphites measured were T 10 and T 11. These lots and some T 14 were used for the core of the pile. The rest of the AGOT formed a rough sphere around this. SP 2 and SP 2′ graphite was placed outside this. At the very outside of the pile US and GX 2 graphite was used interchangeably.

Pressing of Uranium Oxide

The greater part of the pile constants uranium dioxide lumps which were fabricated by compressing loose dry UO_2 powder in a die with a hydraulic press. The chief problem here was the design of the die. Figure 4 gives the details of the dies which were used to press the $3\ ^1/_4$–in. pseudospheres. It is essential that the die be made of a good quality tool steel, hardened and

Table VII. Diffusion length and cross sections for various graphites.

Graphite	L	$L_{1.6}$	$\sigma_a \times 10^{24}$
SP 1	40.53	48.35	0.00549
SP 2	49.77	47.93	0.00563
SP 2′	50.53	48.63	0.00541
TO 0, 2, 3, 4, 5, 6	48.95	49.71	0.00518
TO 8, 9, 13	49.74	50.49	0.00502
T 10	50.83	51.40	0.00484
T 111	51.16	51.70	0.00479
T 12	49.86	50.42	0.00504
T 14	50.14	50.67	0.00499
T 15	49.71	50.96	0.00493
AGX	43.25	43.79	0.00668
U.S.	44.57	44.79	0.00638

ground and polished since the power has a considerable abrasive action. The force used in making the briquettes was in the range of 150 to 175 tons. Lubrication of the die proved to be important and it was found that a dilute solution (0.5 percent by weight) of stearic acid in acetone was quite satisfactory. A small amount of a wetting agent (ethylene glycol) was added to the lubricant so that when it was brushed on the polished surface of the die it would spread evenly. After some experience in handling the dies had been obtained it was possible to fabricate with one press 400 to 500 briquettes in an 8-hour working day.

Machining of Graphite

The graphite is received from the manufacturer in bars of 4 $^1/_4 \times 4\ ^1/_4$–in. cross section and in lengths from 17 in. to 50 in. The surfaces are quite rough and therefore it is necessary that they be made smooth and that bricks of a standard length be cut.

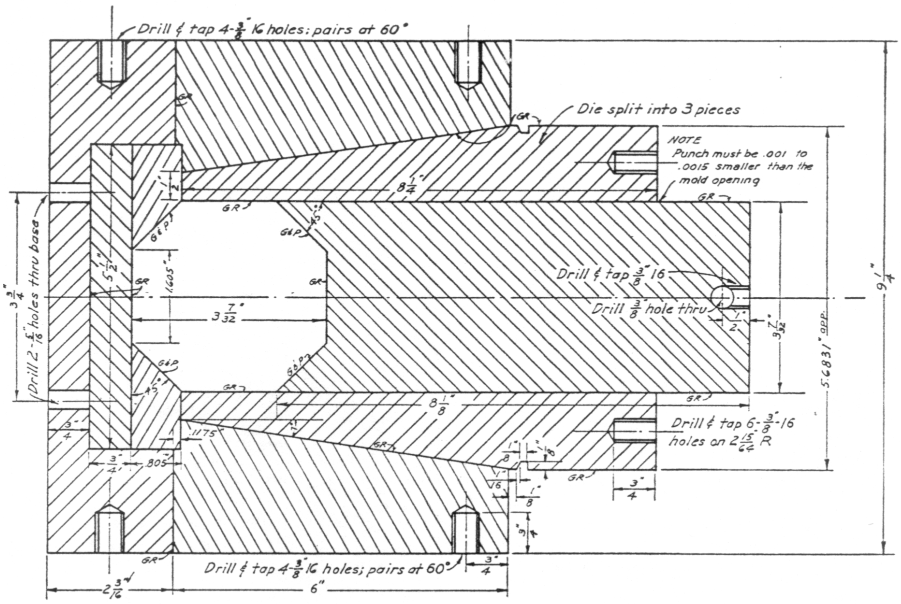

Рис. 4: Die for pressing uranium oxide “pseudospheres.”

For this work ordinary wood-working machines were used. Two surfaces are first made plane and accurately perpendicular to each other in a joiner and the remaining two surface are finished by a planer. A swing-saw was used for cutting to length. The surfaces were held to ± 0.005 inch and the length to ± 0.020 inch. The only departure from this was a slight rippling which appeared occasionally as the result of dull blades or improper manipulation of the work on the machines. Molybdenum steel cutting blades were used in these machines and resharpening, although a constant chore, was not so frequent as to cause any real difficulty. About 14 tons of material could be prepared in this way per 8-hour working day. In all 40 000 bricks were required. A further graphite machining operation was the drilling of the $3\ ^1/_4$–in. diameter holes with shaped bottoms, which were required to permit the insertion of the UO_2 briquettes into the graphite. these holes were drilled in a single operation by mounting a spade bit in the head stock of a heavy lathe and forcing the brick up to the tool with the lathe carriage. Due care had to be given to the design of the cutting tool, and to the alignment and centering of the bit.

These tools required frequent resharpening and, in fact, this proved to be the only difficulty in this operation. Carballoy bits showed the longest life but were rejected because of the greater effort required in preparing them Bits ground from old files proved to be most satisfactory; about 60 holes could be drilled without resharpening. Actual drilling of the hole required about 20 seconds and from 60 to 100 holes per hour was the usual rate the whole operation. A total of 22 000 holes were drilled.

Construction of the Pile

The unit cell of the graphite-uranium lattice has a side of 8 $^1/_4$ in. and a volume of 0.324 cu ft. In order to achieve this lattice the graphite bricks were machined to a cross section of 4 $^1/_8 \times 4$ $^1/_8$ in. and were cut to a length of 16 $^1/_2$ in. The structure was planned as a sphere of maximum radius of 13 ft; the choice of a sphere being necessary because of the fact that probably not sufficient material would be available for any other shape which would be chain reacting. The decision to build a sphere necessitated two important additions to the structure. The first of these was a wooden framework in which the sphere was inscribed, and secondly, a graphite pier which supports side of the the sphere through which the control rods pass. It was believed to be entirely possible that after the structure was erected that the wood might warp or shrink and cause some displacement of the graphite above it. Since this would be undesirable from the point of view of passing control rods into the pile, that part of the pile through which the rods pass is entirely supported by this graphite pier. Originally it had been intended to evacuate the pile and, therefore, considerable pains were taken to see that the wooden framework fitted the graphite securely and that it presented a smooth continuous surface to the surrounding balloon cloth envelope. It turned out, however, that evacuation was not necessary and, therefore, these details are unimportant.

The cube in which the sphere is inscribed has a side of 24 ft 2 in. From this it follows that a part of the 26-ft diameter sphere is cut off the sides; these parts represent a rather small percentage of the total volume of the sphere. As planned the sphere was to have a shell 1 in. thick on the outside made up of graphite without uranium or so-called dead graphite. The graphite- uranium lattice was expected to occupy a sphere of 12-ft radius and have a total volume of 7200 cu ft and hence about 22.300 cells were expected to be included in the structure.

As has been indicated either not all of the material available was of uniform quality and in order to use this material most efficiently that of highest quality was placed at the center with the less reactive types arranged in concentric shells; the quality decreasing outward from the center. The 26-ft diameter sphere would have required that about 75 layers of the 4 $^1/_8$–in. thick bricks would be piled up; however, the chain-reacting condition was reached at the 57-th layer.

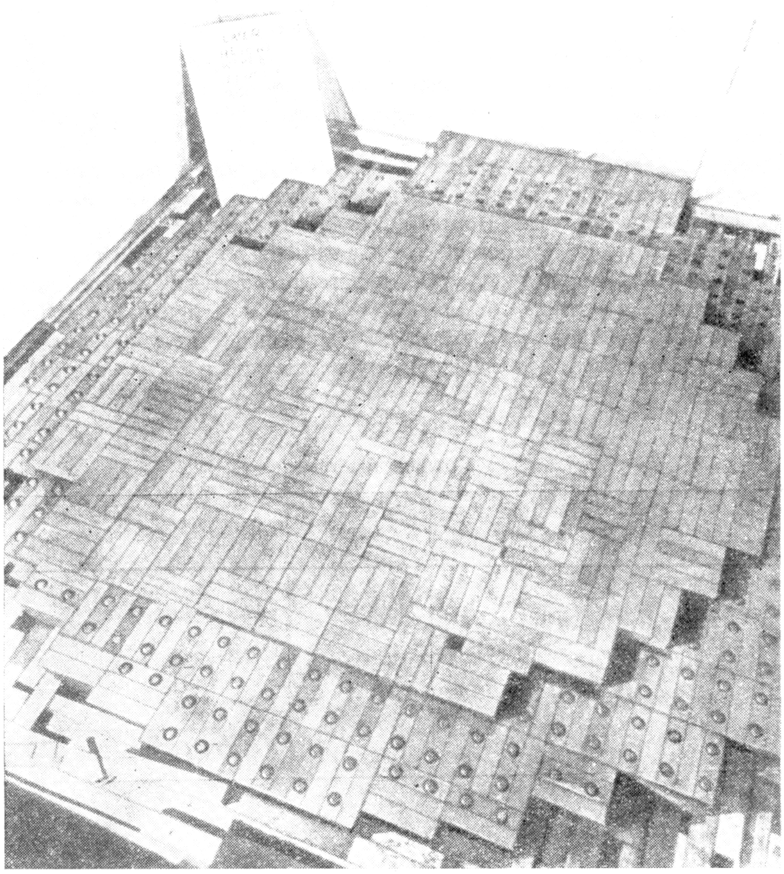

Рис. 5: A layer of the pile.

The actual amount of graphite in the pile is indicated in Table VIII in which also the amounts of each brand are given.

The US and AGX brands had dimensions somewhat different than the majority of the graphite and since they are of lower quality they were mostly used in the other shell of dead graphite.

In Table IX the details of the uranium lumps are given. Column 1 gives the geometrical form of the lump.

The designation 3 $^{1}/_{4}$-in. pseudosphere indicates pressings which were cylinders of 3 $^{1}/_{4}$ in. diameter and 3 $^{1}/_{4}$ in. height, but which had the edges cut off at 45° so that they were roughly spherical. The designation 3-in. cylinder means a cylinder of height and diameter of 3-in. Since five varieties of uranium lumps and four brands of graphite

Table VIII. Graphite in pile

Source	Brand	Lbs	
National Carbon Co.	AGOT	510 000	
Speer Graphite Co.		145 000	
U.S. Graphite Co.	U.S.	32 000	
National Carbon Co.	AGX	60 000	
AGX + Speer (Pier only)		24 000	
		771, 000	= 385.5 tons

Table IX. Uranium in pile

Geometrical shape	Compound	Weight	Density	Number	Total weight in pile	
2 1/4-in. Cylinder	Metal	6.0 lb	18 g/cm^3	2060	12400	
3 1/4-in. Pseudosphere	UO_2	4.72	6.10	14.840	70000	
3 1/4-in. pseudosphere	U_2O_3	3.99	5.17	1200	4790	
3-in. cylinder	UO_2	4.56	6.14	540	2460	
3-in. cylinder	U_3O_8	3.97	5.20	840	3340	
				19, 480	92, 990	=46.5 tons

were used a considerable variation in the combination making up the cell was possible.

Metal – AGOT. Uranium metal cylinders combined with the highest quality AGOT graphite.

AGOT Br + AGOT. 3 1/4-in. pseudosphere of UO_2 inserted in an AGOT graphite brick and combined with undrilled AGOT Bricks to make up the lattice.

Sp Br + Sp. 3 1/4-in. pseudosphere of UO_2 inserted in a Speer brick and combined with undrilled Speer bricks to make up the lattice.

AGOT Bl + Sp. 3 1/4-in. pseudosphere of U_3O_8 inserted in a drilled brick of AGOT graphite and combined with undrilled Speer bricks to make up the lattice.[3]

figure 5 is a photograph of the 19th and 18th. layers. The roughly spherical from of the structure is shown and also some of the supporting wood frame work. The lattice is maintained in the vertical direction by inserting between two oxide bearing layers a layer of dead graphite. Layer 19 as shown in the photograph is only partially completed.

A total of 10 slots passing completely through the pile were provided. Three of these near the center are used for the control and safety rods, the remainder being available for experimental purposes. In addition one row of bricks carrying uranium lumps and passing very close to the center of the pile is arranged so that it can be pushed completely out of the pile. This construction permits the removal of samples from the pile and is useful for experimental purposes.

[3] A brief omission at this point from the original report involved discussion of diagrams not included in the published report. – Editor.

Appendix II. Monitoring and Controlling the First Pile

H. Barton, T. Brill, S. Fox, R. Fox, D. Froman, W. Hinch, W.R. Kanne, W. Overbeck, H. Parsons, G. Pawlicki, L. Slotin, R. Watts, M. Wilkening, and V.C. Wilson[4]

The construction and operation of equipment for monitoring and controlling the first pile was undertaken by the circuit group. This job was subdivided as follows:

1. Monitoring the pile during construction.

[4]Present addresses:
H.M. Barton, Jr.
Phillips Petroleum Company
Bartlesville, Oklahoma.

Thomas Brill,
Argonne National Laboratory,
P.O. Box 299
Lemont, Illinois.

R.J. Fox,
508 Michigan Avenue,
Oak Ridge, Tennessee.

Stewart Fox,
Nuclear Instrument & Chemical Corporation,
233 W. Erie street,
Chicago, Illinois.

Darol Froman,
Los Alamos Scientific Laboratory,
P.O. Box 1663,
Los Alamos, New York.

W.H. Hinch,
U.S. Bureau of Reclamation,
Denver Federal Center,
Denver, Colorado.

W.R. Kanne,
Knolls Atomic Power Laboratory,
Schenectady, New York.

2. Monitoring the pile while operating.
3. The control rods.
4. Electrical controls.

1. Monitoring the Pile During Construction

A slot of 2 $^1/_2 \times 2$ $^1/_2$-in cross section running from the north face of the pile to slightly beyond the center of the pile was built into the 11th layer. A BF_3 proportional counter in a $2 \times 2 \times 12$-in. graphite block was pushed along this slot to the center of the 11th layer. The counting rate was recorded both by a scale of 128 scaler and a pulse integrator operating a recording milliammeter. In this way a continuous history of the construction was obtained. The integrator also operated an alarm relay.

W.P. Overbeck,
E.I. du Pont de Nemours & Company,
Savannah River Plant,
P.O. Box 117,
Augusta, Georgia.

J. Howard Parsons,
Los Alamos Scientific Laboratory,
P.O. Box 1663,
Los Alamos, New Mexico.

G.S. Pawlicki,
Oak Ridge National Laboratory,
P.O. Box P,
Oak Ridge, Tennessee.

Lous Slotin,
(decreased)

M.H. Wilkening,
New Mexico Institute of Mining & Technology,
Campus Station,
Socorro, New Mexico.

V.C. Wilson,
General Electric Company,
P.O. Box 1088,
Schenectady, New York.

Figure 6 shows the counting rate as a function of the number of layers completed.

2. Monitoring the Pile While Operating

When the pile was nearly large enough to become chain reacting, a second BF_3 proportional counter and four BF_3 ionization chambers were set up to monitor the pile. The automatic control rod and the safety rods are actuated by signals originating in these BF_3 ionization chambers. The amplified ionization current is also used to operate recording power-level indicators. One chamber is battery operated. The other three chambers are powered by ordinary power packs with VR-tube stabilization. The power for these pack is derived from voltage regulating transformers. A diagram of the ionization chamber with the first two stages of amplification and the power supply is shown in Fig. 7. The level indicator output terminals are shown as well as the output terminals to feed the amplifiers for the control and safety rods. actually, different sets are used for the three different purposes.

The suppressor grid of the 959 tube is used for detection of the ionization current in order to secure a high leakage resistance of the tube. At the plate, screen, and filament voltages used, the over-all leafage resistance is greater than 10^{13} ohms at all voltages impressed on the suppressor grid in practice. This introduces no appreciable error when resistors less than 10^{11} ohms are used in the grid circuit. The voltage gain in the tube is about 1. 5. If the control grid had been used the voltage gain would have been about 15, but except very near its floating potential, this grid shows an appreciable leakage. Moreover, this leakage is far from constant as the grid is swung over the values encountered in practice. In the circuit the connections are made to the suppressor grid terminal by soldering directly to it, thus eliminating leakage in a socket. The insulators in the ionization chamber were made of clean, dry plate glass. The outer surfaces of the insulators were heated and coated with ceresin wax. The 959 tube also was heated to about 100^{circ}C and dipped in molten ceresin. The wax keeps surface leakage to a minimum even under conditions of high humidity.

Operating experience with a divergent pile has brought to light several defects in these instruments. These defects are enumerated below with brief suggestions for correction or improvement. An instrument with the improved design is to be tested on this pile before similar apparatus is constructed for future piles.

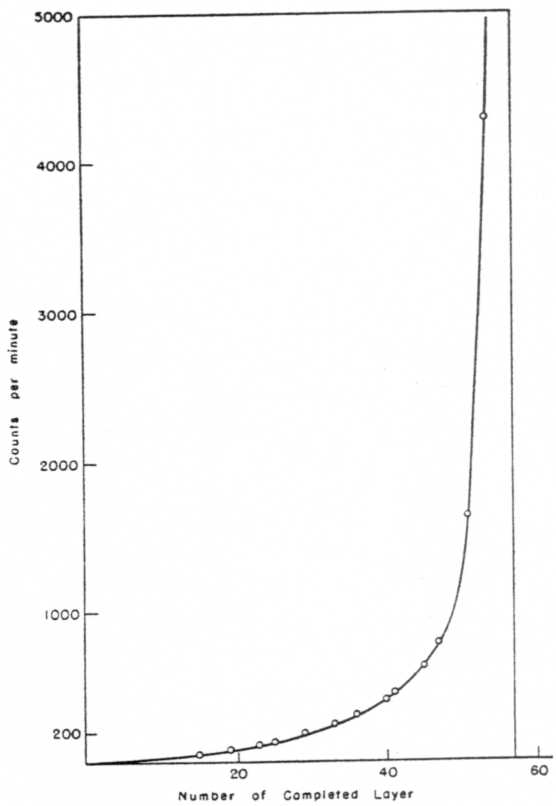

Рис. 6: Intensity of reaction during construction.

1. The chambers are too large to handle easily and are unnecessarily large for the required sensitivity. A volume of 2 liters instead of 18 seems adequate.

2. The variation of output of the instruments with line voltage is too great. A triode-pentode voltage regulator should be used, dispensing with the regulating transformers and VR tubes.

3. A more powerful tube such as 6J7 should be used in place of the 1N5 tube in the second stage. This will allow using a 1 milliampere-movement recording meter as a voltmeter on the plate of this tube in place of using the meter in the plate circuit. This has the distinct advantage that the meter reading can be made accurately proportional to the current collected in the chamber. In the present instruments the meter reading decreases with

increased intensity, and it becomes highly nonlinear as the tube goes to cut off.

4. The electric field for the collection of ions in the chamber is very far from the saturation value. This condition can be improved both by increasing

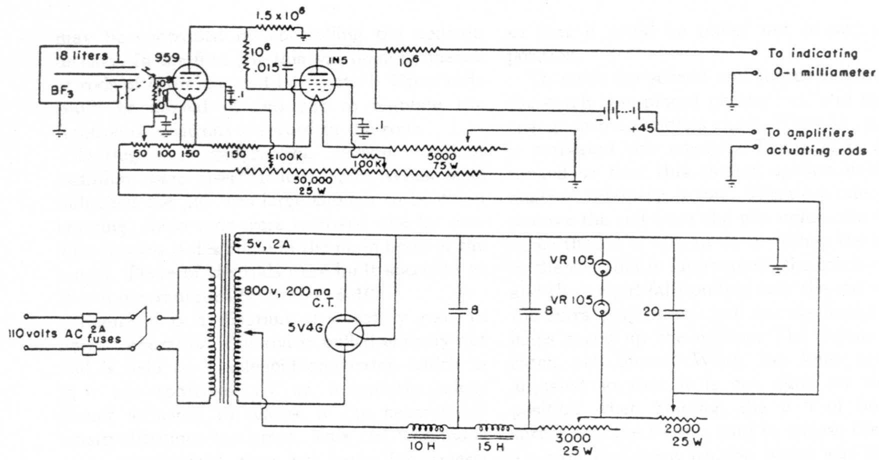

Рис. 7: Ion chamber circuit.

the applied voltage and by a better shape of the electrodes.

5. The amplifiers being built right on the chambers are rather inaccessible and, in order to change sensitivity, a resistor must be replaced by soldering in the amplifier. The leads from the chamber to the amplifier should be long enough to pass through a protecting barrier and range change should be made with a multiposition switch.

6. For high power piles the chambers should be made of, or lined with, a material from which no long-lived radioactive product is formed.

3. The Control Rods

Since the power produced by a chain reacting pile is proportional to the neutron density, a pile may be controlled by controlling the neutron density. In the first pile this was done by means of rods of cadmium and boron steel. These rods could be moved in and out to regulate the fraction of neutrons absorbed in the rods.

During the construction several rods of cadmium were inserted in the pile. When tests indicated the pile was large enough to be chain reacting, these rods were removed one by one. This process is described in the main body of the report. Three of the rods were built specially as shown diagramatically in Figs. 8–10.

Figure 8 is a diagram of a safety rod. In normal operation, this rod is pulled entirely out and is held by a solenoid and catch which in turn are controled by an automatic safety circuit adjusted to release if the neutron intensity becomes too great. This rod was made more complicated than necessary for several reasons. First, it was thought that the pile would need to be evacuated and so the rod was built in a vacuum-tight steel case with remote control. Secondly, it was thought that we should try to have the rod go in in less than a second. Third, it was thought that the pile would be run hot and so no rope could be placed in the pile and a steel cable would absorb too many neutrons. These restrictions prevented pulling the rod through. Fourth, it was planned to have the rod so that it could be pulled out to any described position.

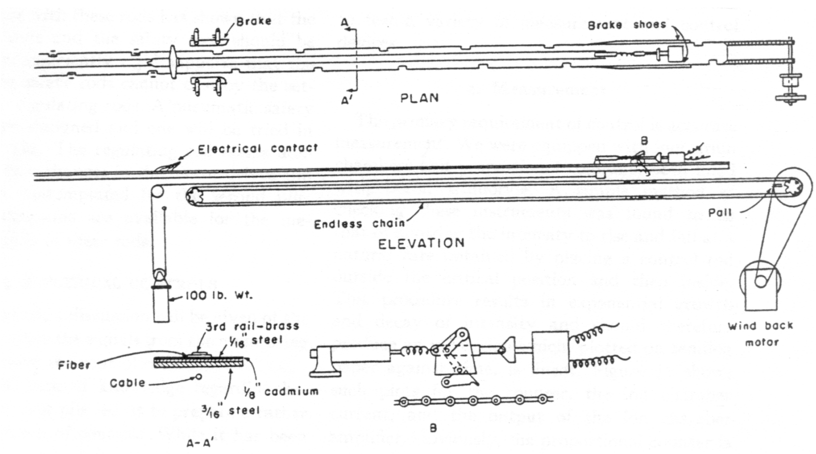

Рис. 8: Details of safety rod.

To meet the second and fourth requirements the catch was placed on the rod, and made to engage into an and less chain. When the solenoid is activated this engages. The circuits are arranged so that this cannot operate unless the neutron intensity is low. Therefore one cannot remove the rod from the pile unless the circuits agree that it is safe to do so. When the current in the solenoid is interrupted, the catch releases and the weight falls pulling only the rod without the extra drag of any pull out mechanism. This helps speed up the motion. The details of the catch are shown. When the knee action is adjusted so that it is not quite on the zero position when holding, the pull of both the spring and the weight tend to release the catch.

To stop the rod a fraction brake was designed which binds in the forward direction but automatically releases when the rod is pulled back.

Figure 9 is a diagram of a simpler safety rod which was built when it became apparent that it would not be necessary to evacuate the pile. This is pulled out and set by hand but may be released from the control table or by the safety circuits.

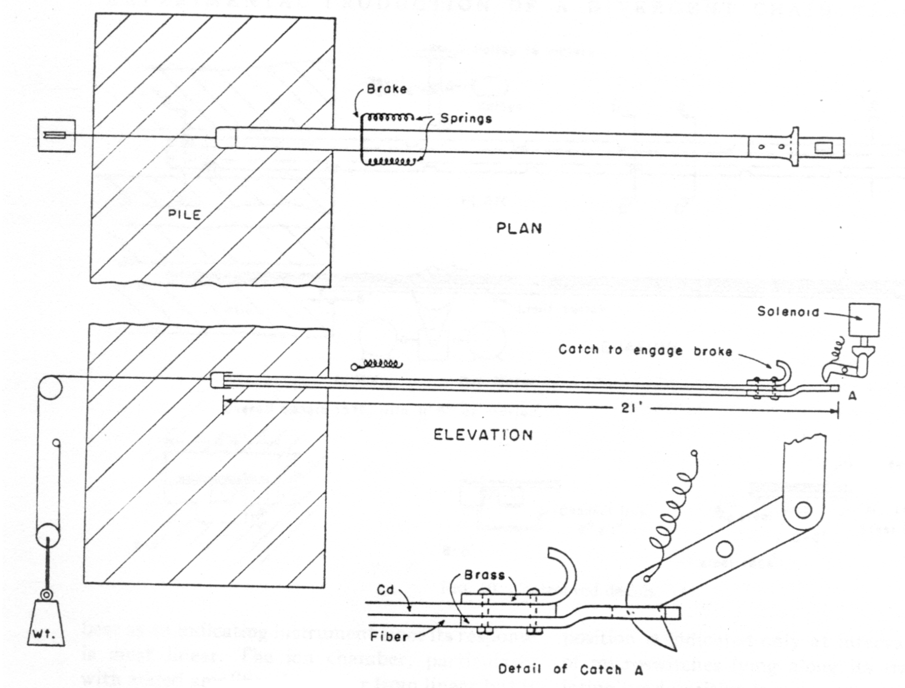

Рис. 9: Deatails of "Zip" rod.

Figure 10 is a diagram of the regulating rod used. The rod was built as a sandwich. The center piece contained 1.5 percent of boron by weight.

Experience with these rods has shown that the regulating rods and the safety rods should be mounted on sufficiently rigid supports that the shock of the safety rods cannot destroy the setting of the regulating rods. A pneumatic safety rod has been designed and one will be tried in the second pile. The regulating rod seems adequate and only changes in the motor drives and gearing are contemplated for the second pile. Complete diagrams are available for the mechanical details of these rods.

4. Electrical Controls

In this section, a discussion will be given of the attempt to utilize the signals from the monitoring devices to move the control rods.

The initial lack of knowledge regarding behavior of the first pile led us to prepare a rather elaborate system of controls. While it has been found that these controls may be simplified and improved, our preparations have made it possible to test a variety of measurement and control devices.

a. Measurement

The primary requirement of control is accurate measurement. we were equipped with ionization chambers and proportional counters, both filled with boron trifluoride. A simple method of checking these instruments was found to be that of allowing the intensity to rise and fall at a natural rate obtained by placing a control rod outside the critical position and then inside. This procedure results in exponential growth and decay of intensity and should therefore produce an indication which, plotted on semilog paper against time, is linear. Figure 11 shows such plots for the counter, the ion chamber current, and the output of the ion chamber amplifier. Obviously, the proportional counter is

best as an indicating instrument since its response is most linear. The ion chamber, particularly with added amplification, is far from linear but is satisfactory as part of an automatic control system since its readings are reproducible.

The curve shown for the ion chamber with galvanometer was obtained with the circuit shown in Fig. 12. This circuit is the simplest indicating system which we have used and has a great advantage in that only the ion chamber is located near the pile. Everything else is readily accessible.

b. Indication

One of our most important duties was to provide remote indication of the various actions of the pile. Since it will be impossible, at high intensities, to remain close to the pile, we must have remote indications of both intensity and of control rod positions. with regard to neutron intensity, our present setup includes remote indication from four ion chambers and two proportional

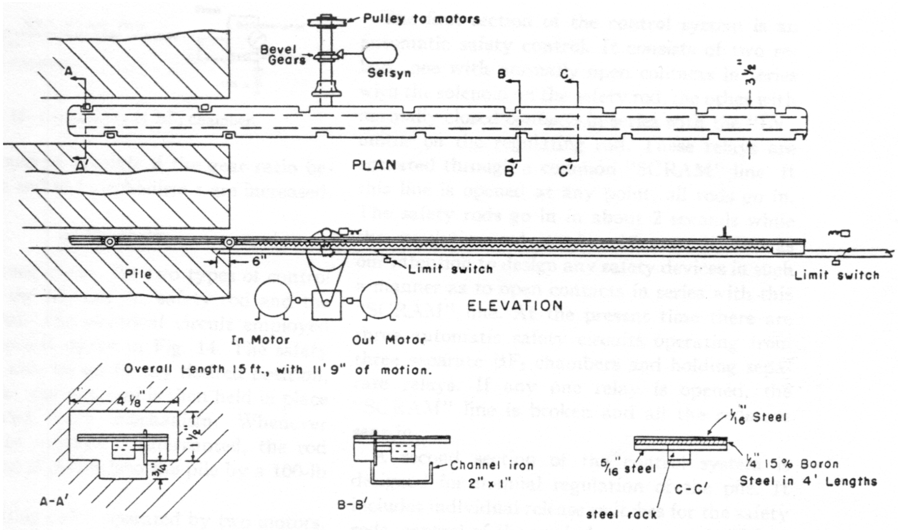

Рис. 10: Control rod details.

counters. Details of the circuits for these instruments are given elsewhere in this reports.

Figure 13 shows the system employed to indicate control rod positions. The “safety” rod position is indicated only at intervals by means of microswitches lying along its tracks. “Regulating” rod position is more accurately indicated by selsyn units. As shown in the diagram, we have one selsyn generator coupled to the regulating rod mechanism and two selsyn motors; one operating a dial indicator, the other a recording pen. In the present setup, it has been found possible to set the rod position within 0.05 inch of any desired value. A higher degree of

Accuracy would be possible if the gear ratio between selsyn and rod mechanism were increased.

c. Controls

As mentioned above, the two types of control rod used in the pile are the safety rod and the regulating rod. The electrical circuit employed with these rods is shown in Fig. 14. The safety rod (Fig.8) may be set to any desired position, usually all the way out, and is then held in place by a solenoid

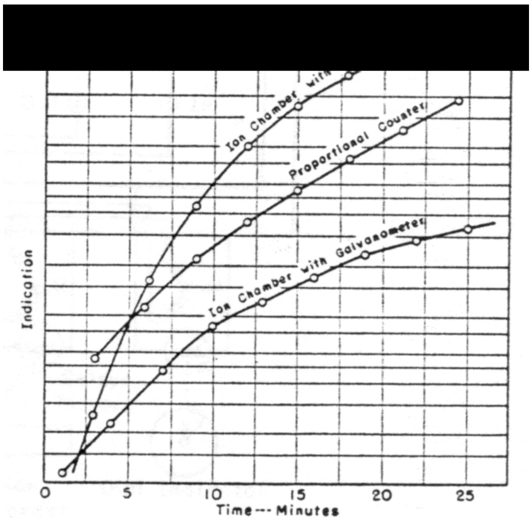

Рис. 11: REcording of various monitoring devices.

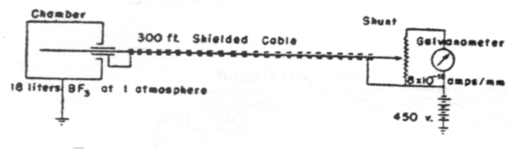

Рис. 12: Connections of BF_3 chamber.

catch mechanism. Whenever current to the solenoid is interrupted, the rod is released and is pulled into the pile by a 100-lb weight.

The regulating rod is operated by two motors, one of which drives inward, the other outward. The use two motors rather than a single reversible motor is for adaptation to an automatic regulating circuit to be described later.

The first section of the control system is an automatic safety control. It consists of two series with the solenoid on the safety rod, the other with normally closed contacts in series with the "IN" motor on the regulating rod. These relays are actuated through a common "SCRAM" line. If this line is opened at any point, all rods go in. The safety rods go in in about 2 seconds while the regulating rod requires 20 seconds. It was our intention to design any safety devices in such a manner as to open contacts in series with this "SCRAM" line. At the present time there are three automatic safety circuits operating from three separate BF_3 chambers and holding separate relays. If

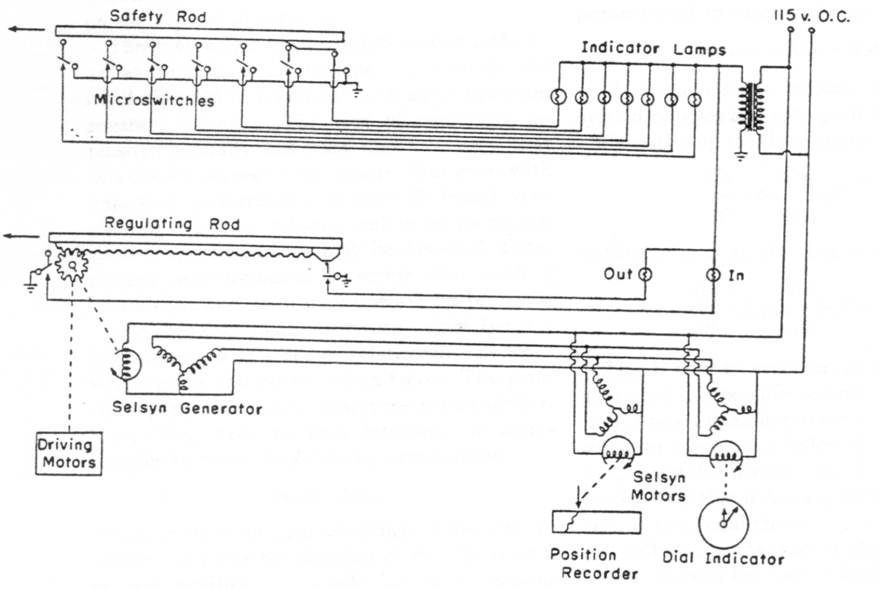

Рис. 13: Rod position indicator system.

any one relay in opened, the "SCRAM" line is broken and all the rods are sent in.

A second section of the control system is designed for manual regulation of the pile. It includes individual release switches for the safety rods, control of the rewind motors on the safety rods, a resetting switch for the solenoid catch, and a two directional variable speed control for setting the regulating rod. The latter consists simply of a variac whose winding is split so that it forms

a variable inductance in series with each motor. Thus, direction of motion depends on direction of rotation of the variac knob and speed depends on the amount of rotation.

The final section of the control system includes an automatic circuit designed to operate the regulating rod in a manner such as to maintain constant intensity. The task of regulating intensity manually has been found so easy that this circuit has seen little service. However, with improved performance, it may be found very useful in experimental work and, in future plants, some modification of it may be essential. From present measurements, it seems that such a future control system may operate on temperature rather than neutron intensity since the pile appears to have a stable relationship

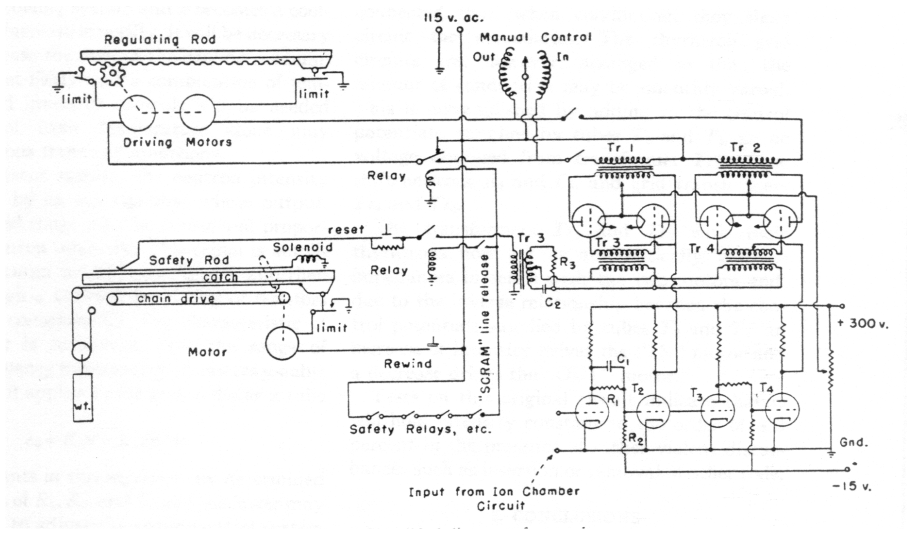

Рис. 14: Simplified diagram of control system.

between temperature and reproduction factor. The principles of precise control, however, remain similar. Controlling from neutron intensity, it seems possible to make the following assumption:

$$dn/dt = K_1 x,$$

where dn/dt is the rate of change of neutron intensity, and x is the distance of the rod from a neutral position at which intensity remains constant.

Suppose, then, that the control system is designed to move the rod at a speed partly proportional to the neutron intensity and partly proportional to rate of change of intensity, i.e.:

$$dx/dt = -K_2 n - K_3 dn/dt.$$

The minus signs indicate that the control system opposes any change of neutron intensity. Differentiating this last equation, we obtain

$$\frac{d^2x}{dt^2} + K_3 \cdot \frac{d^2n}{dt^2} + K_2 \cdot \frac{dn}{dt} = 0.$$

Substituting from the first equation, we obtain

$$\frac{d^2x}{dt^2} + K_1 K_3 \cdot \frac{dx}{dt} \cdot K_1 K_2 x = 0.$$

This is now an equation of motion for the rod alone and it is possible to insert any initial condition in terms of an initial error in rod position and solve for the motion followed by the rod in correcting for this disturbance. It is found that this motion is stable if K_3 is greater than $\sqrt{(K_2/K_\lambda)}$ and, if this requirement is not fulfilled, the control will be unstable and oscillatory. In the event that a temperature control is found more suitable for high intensity operation, the rod may be replaced by a cooling system and x becomes a cooling rate. To increase intensity, it will be necessary only to increase the flow of the cooling medium. It seems most likely that a combination of temperature and intensity controls will be needed since control from temperature alone may produce vicious fransient conditions.

In the present system, the neutron intensity is measured by an ion chamber whose output, over a limited range may be considered proportional to neutron intensity. This signal is amplified by a vacuum tube (T_1 in Fig. 14) and then passes through a network consisting of resistors R_1, and R_2, and consenser C_1. The characteristic of this network is such that, over the range of possible frequency components of any reasonable disturbance, it applied to the grid of the next tube T_2 a voltage

$$e_q = K_4 n + K_5 dn/dt.$$

The constants in this equation are determined by the values of R_1, R_2, and C_1 and the latter may thus be used to adjust the entire control system for stable performance.

Tubes T_3 and T_4 produce an inversion of the control signal without amplification. Thus, changes in anode potential of T_2 are accompanied by equal and opposite changes at the anode of T_4.

In series with each of the regulating-rod motors, is the primary winding of a transformer, Tr_1 and Tr_2. Each transformer has a secondary winding across which two thyratron tubes are so connected that, when conducting, they short circuit the secondaries. The thyratron grid circuits are, however, arranged so that the amount of conduction may be smoothly varied. This is accomplished by adding to the control potentials, supplied by tubes T_2 and T_4, an ac voltage obtained from transformer Tr_3, phase shift network R_3 and C_3, and grid transformers Tr_4 and Tr_5.

The transformers Tr_1 and Tr_2 with their thyratrons now act as automatically variable impedances in series with the two motors and, due to the inverse relationship between the control potentials supplied by tubes T_2 and T_4, an increase of intensity drives the "IN" motor and a decrease drivers the "OUT" motor.

Tests on this original circuit indicate that it will hold intensity constant to the order of ± 3 percent in the presence of rather violent disturbances such as insertion or removal of other rods.

5. Conclusions

While our initial experiments indicate that fairly precise control may be obtained with simple manual regulation, it also indicates that stable automatic control is possible, and that it may be made much more precise than the present system. Our future program, already under way, therefore consists of further development and improvement of such controls so that they will be available when needed.