

CHAPTER 5

RESEARCH IN NEUTRON PHYSICS AT CHALK RIVER

by

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The Low Power Pile at Chalk River

5-1 Introduction

In Canada, our interest in heavy water as a moderator in a chain reacting pile was inherited from Cambridge University and the Collège de France. In 1939 and 1940, Fermi, Szilard, Anderson, Zinn and others at Columbia University did preliminary experiments directed towards a slow neutron chain reaction. From this and later work it was decided to concentrate efforts in the United States towards a heterogeneous pile of uranium and graphite<sup>(1)\*</sup>. At about the same time Joliot, Halban, Kowarski and others at the Collège de France were carrying out exploratory experiments on mixtures of uranium compounds and ordinary water<sup>(2)</sup>. The chances for a chain reaction with ordinary water as a moderator did not look good, and attention turned to heavy water. In June 1940, when France fell, Halban and Kowarski escaped to England, taking with them about 160 litres of heavy water that had been obtained from Norway. A group including Halban and Kowarski was located at Cambridge University to study the possibilities of a chain reaction using ordinary water and heavy water as moderators. By the end of 1940 the British group had become convinced that a uranium and heavy water pile would chain react.

On December 2nd, 1942, the first self-sustaining chain reaction was produced at Chicago by Fermi and collaborators. The interest in plutonium as a military weapon greatly increased. In case some serious difficulty should be encountered in a production pile of the graphite type, work was continued towards a pile of the heavy water type. The production of heavy water was accordingly continued in the United States and Canada<sup>(1)</sup>.

Towards the end of 1942 it was decided to transfer part of the British effort to Canada and to increase its personnel and activities. The Montreal Laboratory was accordingly set up late in 1942 by the National Research Council of Canada. Halban's group arrived from Cambridge University, bringing with them well-developed techniques in neutron physics and the Norwegian heavy water. As time went on experimental results were accumulated and their accuracy greatly improved; information on this heavy water project continued to be exchanged with the United States.

It was agreed that the United Kingdom, the United States and Canada should design and build a heavy water pile in Canada. This is at Chalk River, Ontario. While this pile was being designed and constructed a low power pile was built there in order to provide a tool for nuclear research and the opportunity to study its behaviour. This pile was operated for the first time on September 5, 1945. It will be described to you later. The first self-sustaining chain reaction in a heavy water pile was, however, obtained by Zinn in May 1944.

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\*Superiors in parentheses refer to Bibliography at end of chapter.

### 5-2 Multiplication of Neutrons in a Heavy Water Pile

The multiplication of neutrons in a lattice of uranium rods and moderator can be conveniently described in terms of separate probabilities for the various processes that may occur. These concepts have been explained in the Smyth report<sup>(1)</sup> and by Fermi<sup>(3)</sup> and Wigner<sup>(4)</sup>. A very brief account will suffice here. We shall assume that the multiplying medium is infinite in extent, and thereby avoid the probabilities that a neutron can escape from the system while fast and while slow. Let us consider the life history of  $N$  neutrons from the instant they are born in the fission process until they die by capture.

The fast neutrons have a chance of generating further fast neutrons by fission of  $U^{235}$  or  $U^{238}$ , the latter being more important because of the relatively large fraction present in natural uranium. Besides this possibility the fast neutrons may suffer inelastic scattering in getting out of the uranium rods. Let us assume that the bonus from fast fission is  $\epsilon - 1$  per original fission neutron. The  $\epsilon N$  neutrons having energies below the fission threshold of  $U^{238}$  diffuse through the moderator and are slowed down. Some are lost by resonance capture in  $U^{238}$  to form the  $\beta$ -active  $U^{239}$ . The lowest resonance level in published literature was given as 5 ev by Anderson<sup>(5)</sup> in 1940. If  $p$  is the probability of escaping resonance capture, the number  $\epsilon p N$  reach approximately thermal energies. These disappear by capture in  $U^{235}$  producing fission, by radiative capture in  $U^{238}$ , by capture in the moderator, impurities, jacket material, and coolant (if any). If  $f$  is the probability of capture by the uranium, and  $\eta$  the number of fission neutrons produced per thermal neutron absorbed in the uranium, the number of fast neutrons beginning the second generation is  $\epsilon p f \eta N$ . Since we assumed that  $N$  fast neutrons started the first generation, the multiplication factor  $k$  is therefore

$$k = \epsilon p f \eta.$$

The constant  $k$  must be greater than unity for a self-sustaining chain reaction to be possible in a finite volume.

Fermi<sup>(3)</sup> has stated that  $\epsilon$  is about 1.03 for uranium in a graphite pile, which is the only published information. The calculations of  $p$ ,  $f$ , and  $k$  by Wigner and his collaborators<sup>(4)(6)</sup> reached a high degree of perfection and were extended from graphite to heavy and ordinary water moderated systems. Following their general methods, similar calculations have been made on uranium and heavy water lattices by Volkoff and collaborators in Canada. As the capture cross section of heavy water is very small, the thermal utilization  $f$  may almost reach unity if the heavy water is 100% pure and there are no other materials except pure uranium in the pile.

Let us consider qualitatively what happens to  $k$  if the spacing of given uranium rods is altered in a square lattice. As the rods are moved farther apart in the lattice the neutrons from a rod are given more moderator in which to slow down past the resonance energies before they encounter neighbouring uranium rods. The resonance escape probability increases. At the same time the chance of a thermal neutron being captured in the moderator increases, or the thermal utilization  $f$  decreases. It is clear that for very close spacing the factor  $p$  is small. At the other extreme - a few rods in a large amount of heavy water - the thermal utilization  $f$  is small. Between these two extremes the product  $p f$  and hence the multiplication constant  $k$  take maximum values. Experimental measurements

for uranium and heavy water systems have been carried out by my group leading to a determination of optimum lattice constants.

We paid some attention to two possible nuclear reactions in deuterium that might be expected to contribute to the multiplication constant. The first is an  $n-2n$  reaction, which has a threshold at 3.3 Mev. This had been studied by Elliott, Hincks, and May<sup>(7)</sup>, who used a Po- $\alpha$ -Be source of neutrons in heavy water in order to avoid the complication of neutron production by the  $\gamma$ -rays of a Ra- $\alpha$ -Be source. They found a very small  $n-2n$  effect in their experiment, and estimated that this reaction induced by the fission neutrons makes a negligible contribution to the multiplication constant.

The second nuclear reaction to be considered is the photodisintegration of the deuteron by  $\gamma$ -rays, which begins at a  $\gamma$ -ray energy of 2.18 Mev. In a chain reacting pile  $\gamma$ -rays come from fission, radiative capture of neutrons, and the accumulated fission products. The effect of the last depends on the previous history of the pile. While it is not easy to estimate the separate productions, their effect on  $k$  is small. The photoneutrons produced by the  $\gamma$ -rays of the fission products do, however, show up clearly after shut-down of a heavy water pile. The half-periods associated with the photoneutrons are those of the fission products emitting  $\gamma$ -rays of energy greater than 2.18 Mev. The ordinary delayed neutrons, which are of different origin, are 0.76% of the fission neutrons<sup>(8)</sup>. Recently, the photoneutrons produced by the  $\gamma$ -rays from the fission products in heavy water were estimated at 16% of the delayed neutrons<sup>(9)</sup>. We shall return to this subject in Sec. 5-7.

### 5-3 The Low Power Pile\*

A shallow box, made of structural steel, is supported high above the concrete floor by four steel posts at the corners. The box is subdivided into a central square compartment over the tank and four surrounding compartments that house the mechanical devices operating the control plates and emergency shut-off rods.

The tank that holds the heavy water is cylindrical in shape, has a flange at the open top and a convex bottom. It is made of aluminium of side wall thickness 1/8". The height is 8' 6" and the diameter 6' 9". The maximum capacity is about 10 tons of heavy water.

The tank is suspended from the central compartment of the elevated box, the flange resting on a rubber gasket around the hole in the bottom of the central compartment. The flange is clamped down with bakelite and stainless steel washers under the bolt heads. In general, care was taken to avoid having dissimilar metals in electrical contact, which might otherwise cause corrosion. The steel of the box is coated with 0.010" stainless steel to prevent rusting. The central compartment of the elevated box is closed with a square lid and gasket after the lattice of uranium rods is suspended from beams inside it.

Two steel I-beams are laid close to two of the ends of the central box. Across these two beams are laid a number of parallel beams, which bridge the open top of the tank and carry the uranium rods.

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\*The group who designed and built the low power pile included L. Kowarski, C.W. Gilbert, C. Watson-Munro, G.J. Klein, E.P. Hincks, F.W. Fenning, A.H. Allan, G. Fergusson, and D. B. Nazzari.

The steel beams are plated with copper, nickel and chromium to prevent corrosion. The spacing in the square lattice of uranium rods can be varied by altering the distance between consecutive beams.

The uranium metal in the form of short rods can be stacked up to the desired height in aluminium tubes closed at the lower ends with welded plugs. The purpose of the aluminium jackets is to prevent corrosion of the uranium. These jackets are flanged at the top to allow each to be clamped in a stainless steel head. The rod assembly is suspended from the parallel beams by a gimbal arrangement to ensure vertical positioning of the rods. The tubes can swing in the rings between the knife-edges that rest on the beams, there being line contact between the head and the ring.

The tank is surrounded by a graphite reflector on its sides and bottom. Such a reflector reduces the fractional loss of neutrons from the reactor and thus reduces the critical size of the multiplying medium for a chain reaction.

The reactor tank is connected to a stainless steel storage tank in the basement. There is a large gate-valve in the connecting pipe to dump the heavy water into the storage tank as a last resort in case the power runs away.

It is important that the isotopic composition of the heavy water does not deteriorate. Provision is made for passing hot air through the closed system and freezing out the moisture in a refrigerating unit in the basement. An electric heating coil around the outside and near the bottom of the reactor tank is an aid to drying. This moisture may be ordinary water vapour found in the closed system before the heavy water is admitted or heavy water vapour after the heavy water has been removed.

A stainless steel gear-type pump can be run in either direction to raise or lower the heavy water level in the reactor. The push-button controls are on the main control board. After a certain number of revolutions the pump stops automatically. This is a safety device to minimize the chance of neglecting the pump and have the level of heavy water rise above the critical level and the power run away. A selsyn is connected to the pump to give a rough indication of depth of heavy water in the reactor on a dial at the control board. The exact depth is read from a glass-tube manometer.

Two sets of four shut-off or emergency controls are provided inside the tank. Each set consists of four steel tubes, each 12" long, cadmium coated to at least 0.010" on the outside, and completely enclosed between two aluminium tubes. The four tubes are suspended on stainless steel wires, which pass over pulleys held in brackets attached to the underside of the bridging beams across the top of the tank, and run to drums on a common shaft attached to one of the I-beams. As we have noted, the control suspension is duplicated. During normal operation of the pile these emergency controls are held above the heavy water surface. For a quick shut-down they are released and descend under gravity with an acceleration of about  $\frac{1}{2}$  g. When the pile is not in operation both sets of controls are down in the heavy water. Intermediate positions between "up" and "down" are not used.

Each shaft that carries the winding drums in the central compartment passes through a gas-tight gland into an adjacent compartment. Close to this gland the shaft carries a dural disc that rotates between the poles of an electromagnet. A parallel shaft is operated from the main shaft through a gear reduction and drives cams that operate microswitches and the low speed selsyn, which indicates at the control board. One microswitch actuates the electromagnet for braking when the controls have

descended into the heavy water. Another is interlocked with the pump so that it cannot be operated when the controls are down and also indicates at the board when the controls are down. Another switch operates an indicating light at the board when the controls are up. Cams on the two parallel shafts are interrelated to bring into the way, stops limiting the upper and lower positions.

The main shaft, which goes through the gear box referred to, is broken by an electromagnetic clutch. When this is energized the controls can be raised or lowered by hand at the control board, the rotation applied to a hand-wheel being transmitted by long shafts and bevel gears. If the power supply fails or if the pile power exceeds a preset value, the clutch is released and the emergency controls descend under gravity into the reactor. In addition to the low speed selsyn there is a high speed selsyn geared to the transmission shaft before the magnetic clutch.

Four shafts for the transmission of rotation from the hand-wheels at the control board to the drives in the elevated box are provided. These run along a channel in the floor and then vertically to the elevated box. Two have been referred to in the description of the emergency controls; the other two operate the control plates.

Four operational control plates are suspended by wires in the gap between the tank and the graphite reflector at approximately  $90^\circ$  intervals. Three are operated together for coarse control and the fourth independently for fine control. These plates are slightly curved to conform to the curvature of the tank. They are made of steel and coated with 0.010" of cadmium. Approximate dimensions of the plates are 20" x 12". High and low speed selsyns are connected to each shaft to give indications of position on dials at the control board.

Boron trifluoride ionization chambers and amplifiers are placed at several points in the graphite reflector and indicate the power on meters at the control board. For fine indication a galvanometer in a null circuit is used.

The instruments for health monitoring are connected to meters on a separate board. A number of ion chambers are used in the room for monitoring slow neutrons, fast neutrons and  $\gamma$ -rays. The first type is filled with boron trifluoride, the second with hydrogen, and the third with argon. Water tanks, 3 ft thick, have been placed around the pile to improve the shielding. It is possible to operate the pile continuously at 3.5 watts without exceeding the tolerances in the room for an eight-hour exposure. Many experiments have been done at 30-50 watts, but the permitted exposure times were correspondingly reduced.

The fluctuations in the readings of the neutron detecting chambers are very noticeable under about  $\frac{1}{2}$  watt; the needles of the meters swing about mean positions when the average power is held constant. These arise from the fluctuations in the not extremely large numbers of neutrons in the pile and the variations in the number of neutrons emitted per fission.

Tangential channels in the graphite reflector and aluminium tubes extending down into the tank are very useful for activating materials and comparing cross sections by the swing method.

Owing to its smaller size, a heavy water pile produces a much greater maximum  $\rho v$  of thermal neutrons than a graphite pile for a given pile power.

Neutron Physics5-4 Diffusion of Thermal Neutrons in Heavy Water

Fast neutrons are slowed down in heavy water by collisions in which the energy of the neutron is progressively shared with the struck nuclei of deuterium and oxygen. Eventually the neutrons can no longer give up energy to the nuclei of the moderator but are in temperature equilibrium with it. If the temperature of the heavy water is about 20° C the Maxwellian distribution of thermal neutrons has most probable and average speeds of 2200 and 2500 m per sec respectively. We shall consider some details of the diffusion of thermal neutrons in heavy water.

The following symbols will be defined.

$\sigma_s$  = scattering cross section (cm<sup>2</sup> per atom or per molecule)

$\sigma_c$  = capture cross section (cm<sup>2</sup> per atom or per molecule)

$l_s$  = scattering mean free path (cm)

$l_c$  = mean free path for capture (cm)

N = average number of scattering collisions during the lifetime of the thermal neutron

$\tau$  = mean lifetime (sec)

v = speed of the neutron

n = number of atoms (or molecules) per cc

b = average cosine of the scattering angle relative to the initial direction of the neutron

D = diffusion coefficient

$l_t$  = transport mean free path

L = diffusion length

The following relations are well known:

$$l_s = \frac{1}{\Sigma n \sigma_s} \quad \text{and} \quad l_c = \frac{1}{\Sigma n \sigma_c} \quad (5-1)$$

$$\tau = \frac{l_c}{v} = \frac{1}{\Sigma n \sigma_c v} \quad (5-2)$$

The diffusion length for thermal neutrons may be defined in either of two ways, which are equivalent. First, suppose that thermal neutrons are emitted from a point source and diffuse through a moderator that is infinite in extent. If r represents the displacement from the source when the neutron is captured the average  $r^2$  may be taken for a large number of neutrons. The diffusion length is defined as follows:

$$L^2 = \frac{\overline{r^2}}{6} \quad (5-3)$$

The second definition of  $L^2$  is

$$L^2 = D\tau \quad (5-4)$$

It is not difficult to show that for the neutrons from the point source:

$$\overline{r^2} = \frac{2 l_s^2 N}{1 - b} \quad (5-5)$$

Using these relations and

$$l_t = \frac{l_s}{1 - b}, \quad (5-6)$$

it follows that

$$L^2 = \frac{1}{3} l_t l_s N = \frac{1}{3} l_t l_c = D\tau. \quad (5-7)$$

While the experimental measurements of the transport mean free path and diffusion length will be described later, their values will be used at once. Auger, Munn, and Pontecorvo<sup>(10)</sup> found that in heavy water

$$l_t = 2.4 \pm 0.1 \text{ cm.}$$

My group<sup>(11)</sup> has found experimentally that

$$L = 171 \pm 20 \text{ cm.}$$

in 100% D<sub>2</sub>O. From the published work of several investigators<sup>(12)</sup>

$$l_s = 2 \text{ cm.}$$

From these measurements

$$l_c = \frac{3L^2}{l_t} = \frac{3 \times (171)^2}{2.4} = 36,500 \text{ cm}$$

$$N = \frac{l_c}{l_s} = \frac{36,500}{2} \sim 18,000$$

$$\tau = \frac{l_c}{v} = \frac{36,500}{250,000} = 0.15 \text{ sec.}$$

Pure heavy water is a remarkable substance; a neutron of average thermal speed makes on the average about 18,000 scattering collisions and travels about 365 m in it before being captured.

What is the appropriate speed of the neutron to be associated with a capture cross section that can be deduced from the diffusion length and transport mean free path? Two assumptions are introduced. The transport mean free path is assumed to be reasonably independent of the speed. The capture cross section is assumed to vary as  $1/v$ , which makes  $\tau$  a constant. Eq. (5-7) may be written:

$$L^2 = D\tau = \frac{1}{3} l_t \bar{v}\tau = \frac{1}{3} l_t l_c, \quad (5-8)$$

where  $l_c = \bar{v}\tau$  is the capture mean free path for neutrons having the average speed  $\bar{v}$  of the neutron spectrum. Hence  $\sigma_c$  found from  $l_c$  corresponds to the neutron speed  $\bar{v}$ , which is 2500 m per sec at room temperature. Substituting the numerical values, it follows that

$$\sigma_c = (0.81 \pm 0.19) \times 10^{-27} \text{ cm}^2 \text{ per molecule D}_2\text{O.}$$

at  $v = 2500$  m per sec. This must be regarded as an order of magnitude owing to the unproved assumptions that had to be introduced.

### 5-5 The Transport Mean Free Path of Thermal Neutrons in Heavy Water

The transport mean free path of thermal neutrons in heavy water has been measured by Auger, Munn, and Pontecorvo<sup>(10)</sup>. A small tank of heavy water was embedded in the top of a graphite column of large cross section. The defining boundary in the heavy water was a flat cadmium sheet, which was level with the graphite surface. A Ra- $\alpha$ -Be source of fast neutrons was placed about 100 cm below the surface of the column. The density of thermal neutrons was measured with a very small BF<sub>3</sub> chamber at various distances from the strongly absorbing cadmium plate. In the region investigated the density was a linear function of the distance from the plate. When this straight line was extrapolated the density was found to vanish at a distance  $d = 1.64$  cm behind the plate. On the basis of transport theory, which supersedes ordinary diffusion theory near such a boundary where the distribution of neutron velocities is not almost isotropic, Placzek and collaborators<sup>(13)</sup> have found that

$$d = 0.71 \ell_t. \quad (5-9)$$

The final experimental result is  $\ell_t = 2.4$  cm in pure heavy water.

### 5-6 The Diffusion Length of Thermal Neutrons in Heavy Water

The diffusion length of thermal neutrons in heavy water is so great that a large quantity is necessary for a direct measurement in an exponential experiment. We had available about 7600 lb which was contained in a cylindrical steel tank, 160 cm in diameter and 165 cm high<sup>(11)</sup>. The tank was on a graphite pedestal having approximately the same shape and diameter as the tank and a height of 28 cm. This pedestal surmounted a rectangular parallelepiped of graphite 279 cm x 186 cm in horizontal section and 228 cm high. The source of neutrons was a block of beryllium at the end of the tube of a General Electric x-ray generator operated at 2000 kv peak and 1.4 ma. The beryllium was located on the vertical axis of the pile at a distance of 86 cm below the bottom of the tank. With this arrangement the neutrons were slowed down to thermal energies before they reached the heavy water. The exposed surfaces of the graphite and tank were covered with cadmium sheet to avoid distortion of the neutron density distribution in the tank by reflected neutrons.

A steady state is set up. Thermal neutrons enter the tank from the graphite, some are captured in the heavy water, and the rest escape through the walls into the cadmium. The steady density distribution was explored with indium foils, 1 cm square and weighing 88 mgm each. Different runs were normalized with the aid of a monitoring foil that was activated near the base of the graphite column. From analyses of the transverse and vertical measurements, the diffusion length can be found.

The diffusion equation for thermal neutrons is

$$\begin{aligned} D \Delta \rho - \frac{\rho}{\tau} &= -q \\ \text{or } \Delta \rho - \frac{\rho}{D\tau} &= \frac{-q}{D} \\ \text{or } \Delta \rho - \frac{\rho}{L^2} &= \frac{-q\tau}{L^2}, \end{aligned} \quad (5-10)$$

where  $q$  is the source density of thermal neutrons as the result of slowing down, and  $D\tau$  is set equal to  $L^2$ . Since no epithermal neutrons are present in the heavy water,  $q = 0$ . Eq. (5-10) will be written



in cylindrical coordinates. The origin is located near the bottom of the tank, and the positive direction of the z-axis is vertically upwards along its axis. The radial distance r is measured from this axis, and the angle  $\phi$  is measured from a vertical plane containing the z-axis.

$$\frac{\partial^2 \rho}{\partial r^2} + \frac{1}{r} \frac{\partial \rho}{\partial r} + \frac{1}{r^2} \frac{\partial^2 \rho}{\partial \phi^2} + \frac{\partial^2 \rho}{\partial z^2} - \frac{\rho}{L^2} = 0. \quad (5-11)$$

The solution of Eq. (5-11) is required subject to the boundary conditions:

- (1)  $\rho$  is finite on the axis of the cylinder,
- (2)  $\rho = 0$  at an effective radius  $r = R$  (to be evaluated experimentally),
- (3)  $\rho = 0$  at  $z = h$  (to be evaluated experimentally),
- (4)  $\rho$  is represented by a measured distribution expressed as a Fourier-Bessel series in the plane  $z = 0$ .

The desired solution of (5-11) is:

$$\rho = \sum (A_{\ell m} \cos \ell \phi + B_{\ell m} \sin \ell \phi) J_{\ell} (\lambda_{\ell m} r) \frac{\sinh \frac{h-z}{b_{\ell m}}}{\sinh \frac{h}{b_{\ell m}}}, \quad (5-12)$$

$$\ell = 0, 1, 2, 3, \dots$$

$$m = 1, 2, 3, \dots$$

where the relaxation lengths  $b_{\ell m}$  are given by

$$\frac{1}{b_{\ell m}^2} = \lambda_{\ell m}^2 + \frac{1}{L^2}. \quad (5-13)$$

If the experiment is well devised, the first term in the Fourier-Bessel series (5-12) dominates all others in a large part of the cylinder. In that case the harmonics ( $\ell = 0, m \neq 1$ ), ( $\ell \neq 0$ , any m) are at most small corrections on the dominant term:

$$\rho = A_{01} J_0 (\lambda_{01} r) \frac{\sinh \frac{h-z}{b_{01}}}{\sinh \frac{h}{b_{01}}}. \quad (5-14)$$

In Eq. (5-14)

$$\lambda_{01} = \frac{2.4048}{R},$$

and the diffusion length L follows from

$$\frac{1}{L^2} = \frac{1}{b_{01}^2} - \left( \frac{2.4048}{R} \right)^2. \quad (5-15)$$

Transverse analyses were made in three horizontal planes. The amplitudes of the harmonics were determined and found to be relatively small. The effective radius R of the tank was found as follows:

<u>z(cm)</u>	<u>R(cm)</u>
0	82.56
20	82.47
50	82.65
Average	82.56

After the harmonics had been removed, the vertical distribution was analysed for  $b_{01}$  and  $h$ . Corrections were applied for the capture of neutrons in the detectors and their supporting structure and in the light hydrogen present in the heavy water. The final result was

$$L = 171 \pm 20 \text{ cm in } 100\% \text{ D}_2\text{O}.$$

5-7 Shut-down of a Pile

The previous examples of neutron distributions were all of the steady state or time-independent type. The subject of pile kinetics or time-dependent phenomena is interesting but complicated. Nordheim<sup>(14)</sup> has given a theoretical treatment. We shall confine our remarks to the case of shut-down of the low power pile with shut-off rods and emphasize the role played by the delayed neutrons.

Let  $\tau$  stand for the mean lifetime of a neutron in the pile. It is a small fraction of a second. In addition, delayed neutrons come from fission fragments of several types whose mean lifetimes  $\tau_i$  are of the order of tens of seconds. If photoneutrons are included, the associated mean lifetimes are of the orders of minutes and hours. Let  $c$  be the fraction of fast neutrons that are delayed.

Suppose the pile has been run at a steady power ( $k_{\text{eff}} = 1$ ) for a long time so that the numbers of nuclei that produce the delayed and photoneutrons have approximately reached saturation. The shut-off rods are then dropped into the pile, and  $k_{\text{eff}}$  is reduced by  $\delta$  below unity.

$$1 - k_{\text{eff}} = \delta.$$

Shut-off rods are sufficiently effective that  $\delta > c$ .

Fig. 5-1 shows two tracings of the power of the heavy water pile at shut-down, taken with an Esterline-Angus recorder. The decay of the power is very rapid at first, whether it is caused by one or both sets of shut-off rods. The rather sudden change to the more gradual decay begins, however, at a higher value of the power in the case of the single set of shut-off rods. The power can be represented by a sum of decreasing exponentials with associated relaxation times. The relaxation time of the most rapid exponential is  $\frac{\tau}{\delta + c}$ . The other pile relaxation times are approximately the relaxation times  $\tau_i$  of the delayed neutron emitters if  $\delta > c$ . Using the initial conditions, it follows approximately

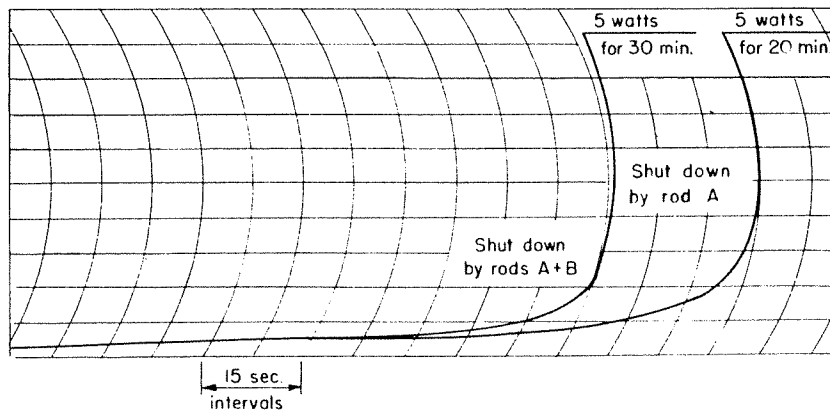


Fig. 5-1. Two tracings of the power of the heavy water pile at shut-down, taken by J. G. Bayly. The time is increasing towards the left.

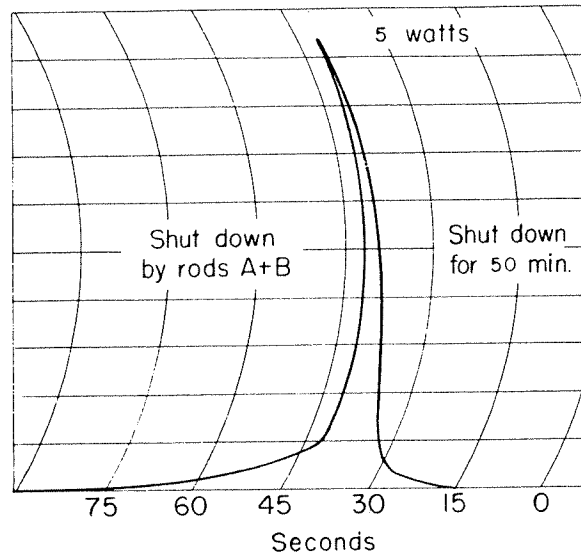


Fig. 5-2. Tracing of the power of the heavy water pile during a pulse, taken by J. G. Bayly. The time is increasing towards the left. The pulse was started by the withdrawal of a cadmium tube from the central thimble. When the power reached about 5 watts, shut-off rods A and B were tripped.

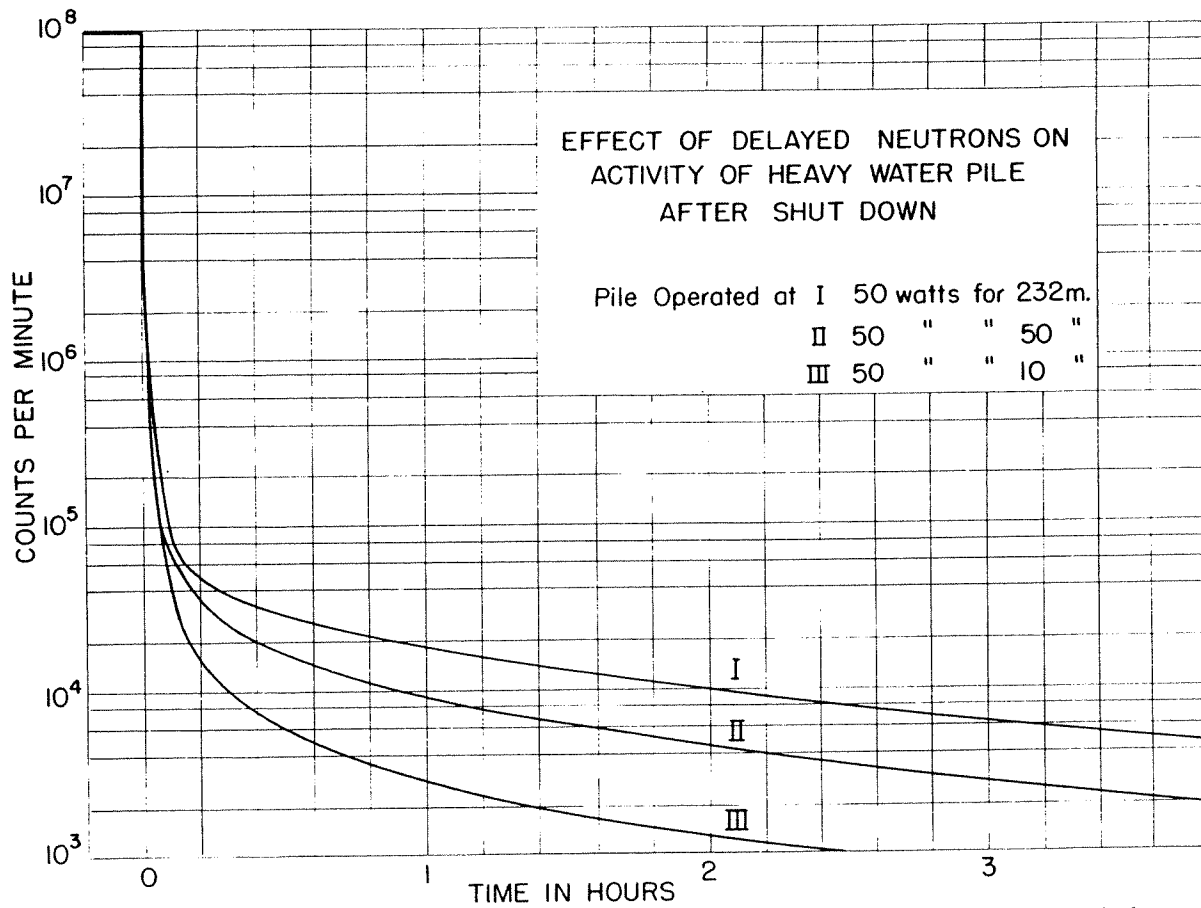


Fig. 5-3. The neutron counting rates are plotted on a logarithmic scale against the time before and after shut-down of the pile with shut-off rods A + B.

that the ratio of the initial drop to the subsequent drop is  $\delta/c$ . If  $c = 0.008$ ,  $\delta = 1.6\%$  for shut-off rods A and  $\delta = 2.6\%$  for shut-off rods A + B. Since rods A and B are about equally effective when used separately, their effects are not additive.

Fig. 5-2 shows the smaller effect of the delayed neutrons on shut-down when the pile is pulsed and the neutron contributing fragments are not permitted to reach saturation at the peak power. Such pulsing has been found useful in cloud chamber work.

Fig. 5-3 shows more clearly the effect of the photoneutrons. Here neutron counting rates are plotted on a logarithmic scale, instead of the linear scales in Figs. 5-1 and 5-2. These results were obtained by M. W. Johns and myself. Three proportional counters of very different sensitivities were used as neutron detectors in spanning a range of  $10^6$ . These contained natural uranium, uranium enriched in  $U^{235}$ , and  $BF_3$ . The three curves show clearly that the  $\gamma$ -ray emitting fragments were built up to various degrees during the three runs of different duration.

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