Fig. 1

the NRX pile

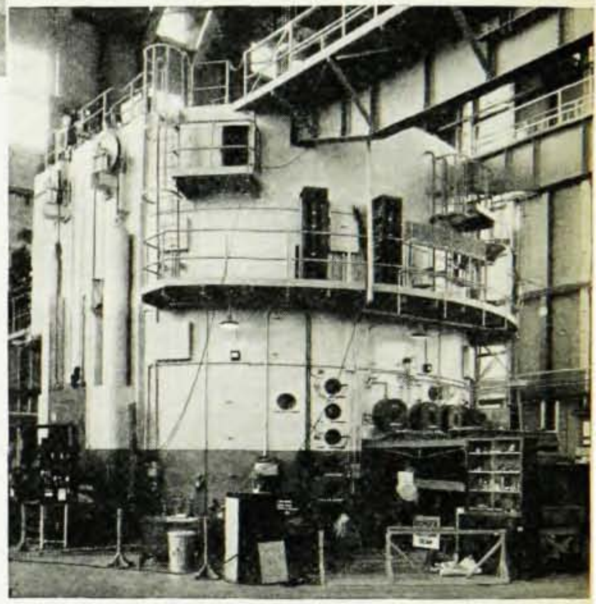

Fig. 2

The following pages contain a description of Canada's high flux nuclear reactor, the heavy water and uranium NRX pile.

THE NRX pile at Chalk River is distinguished among the known experimental reactors by its high neutron flux, which at its maximum is 6 x 10^{13} neutrons/cm^2/sec. It ranks among the high power experimental reactors and normally operates above its designed power rating of 10 Megawatts (10,000 kilowatts). The neutron flux is about 10 to 20 times that of a graphite reactor of comparable power and this is due to the smaller physical size of the NRX reactor made possible by the use of heavy water as the moderator to slow down the neutrons. It should be noted that the rating is attained using only natural uranium metal, and enrichment of the fissionable U-235 isotope is not necessary. On the other hand, because of the small size of the reactor and the low total amount of uranium used, enrichment by plutonium or U-235 yields a quick return of available neutrons.

The NRX pile has been operating now for about four years. It is situated on the south bank of the Ottawa River about 125 miles west-north-west of Ottawa. The large brick building shown in Figure 1 houses the pile. Figure 2 shows the reactor itself enveloped by thick steel and concrete radiation shields.

The reactor vessel is a cylinder about ten feet (300 cm) high by eight feet in diameter through which pass vertical tubes containing a total of 176 uranium metal rods, cooled by water from the river.

The nuclear fission chain reaction is started by pumping heavy water up from the storage tanks into the reactor until a critical depth is exceeded. The power developed then builds up and may be followed by observing the neutron flux detected by a suitable ion chamber. When the power reaches the required level, the depth of water is adjusted until the power stays constant. The steady state represents a delicate balance between the neutrons released and captured. Fortunately, as is well known, the achievement of this balance is relatively easy, as nature has provided a stabilizing delay in the release of some of the neutrons from fission. The adjustment for balance is, however, sensitive; for example, a change of depth of 2 cm in 250 cm might double the power in two minutes, and for steady running the heavy water level would have to be set to a fraction of a millimeter. To ease the adjustment a cadmium control rod is provided. Moreover, in common with most reactors, the NRX pile is thermally stable; if it heats up it becomes less reactive.

The reactor runs very steadily, usually under an automatic control by which the control rod is moved according to the current from the neutron-sensitive ion

at Chalk River

By W. B. Lewis

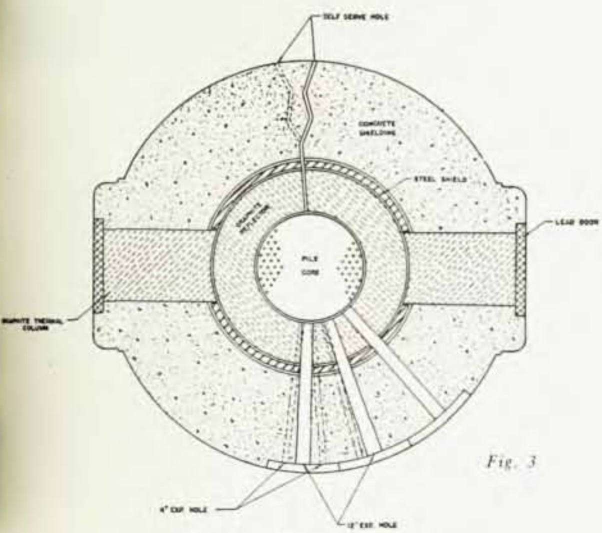

Fig. 3

PLAN THROUGH WORKING ℄ OF NRX PILE

chamber. The power is thus kept within ½% of the chosen level.

If something goes wrong, and the pile itself with its large number of cooling systems and the variety of materials and structures loaded into it are so complex that sometimes this happens, it may be necessary to stop or shut the pile down very quickly. This is provided for by neutron-absorbing rods, the shut-off rods, which can be projected by compressed air into some of the tubes which are left empty to receive them.

The engineering of all these control devices is very straightforward, contrary to a common supposition. The real calls for ingenuity have come when a sample being irradiated has burst its container and become stuck somewhere inside the pile, a region which is, of course, unapproachable on account of the permanently high radioactivity.

It should be made clear that it is a research reactor, so that in the interests of new knowledge it may be operated at any power within its range or may be shut down if necessary. It has, however, to serve quite a number of people having different interests. Usually a majority wish the pile to run steadily at its maximum power. For this reason and because large changes in power level give rise to transient changes of reactivity, shut down periods are kept to a minimum and all the jobs which require the pile to be shut down are crowded together in these periods.

Figure 3 shows some of the facilities provided by the pile and so will indicate the uses. At the top is shown one of the self-serve arrangements which permits samples for irradiation to be introduced and withdrawn without shutting down the pile. The sample is sealed in a cylindrical capsule placed in a spherical aluminum ball which is rolled down a winding tube through the shielding to a cup which is then pushed in through the graphite reflector to the irradiation position.

On either side it may be noted that the graphite extends out through the concrete shield to form a thermal column, where neutrons of thermal energy may be obtained free from fast neutrons. These thermal columns have proved useful for physics experiments on the gamma-rays from neutron capture, and on the products of fission and other reactions releasing fast neutrons which it is of interest to observe. The flux of thermal neutrons available 8 ft from the reactor wall is 5.8 x 10^9 neutrons/cm^2/sec, and the density of thermal neutrons is 25,000 times the density of neutrons dropping into the thermal energy range. This ratio is known as the cadmium ratio and is determined from the activities induced in thin indium foils unshielded and shielded with 2 mm thickness of cadmium. The maximum cadmium ratio to be found in the column is estimated to be about 90,000.

Among the interesting experiments which have made use of these thermal columns may be mentioned the observation of the capture of neutrons by hydrogen $H(n, \gamma)D$. From the high energy of the gamma-ray observed, Bell and Elliott (1948, 1950) concluded that the neutron was significantly heavier than the previously accepted value.

Another experiment by Almqvist (1950) led to the observation of the fast neutrons from secondary reactions produced by tritons liberated in the slow neutron reaction $Li^6(n, \alpha)T$. These tritons produced fast neutrons by the reactions $Li^{6,7}(T, xn)Be^{8,9}$ (or $He^4 + He^{4,5}$) and $D(T, n)He^4$.

In the core of the pile itself the few available empty tubes are in great demand for irradiations in the highest neutron fluxes available. It may be mentioned that radio-cobalt (Co^{60}) sources of 1500 curies have been produced by irradiating cobalt metal. Radio-cobalt has a half-life of 5.3 years and the high neutron flux in the reactor produces in 18 months' irradiation of metallic cobalt a specific activity of 35 curies per gram. This makes the self-absorption of the 1.1 and 1.3 Mev gamma-rays in a source, even as large as 1500 curies, relatively small, and it is expected that these sources will be used to replace million-volt x-ray machines for certain purposes, particularly for therapeutic work in hospitals. Even the large number of neutrons available

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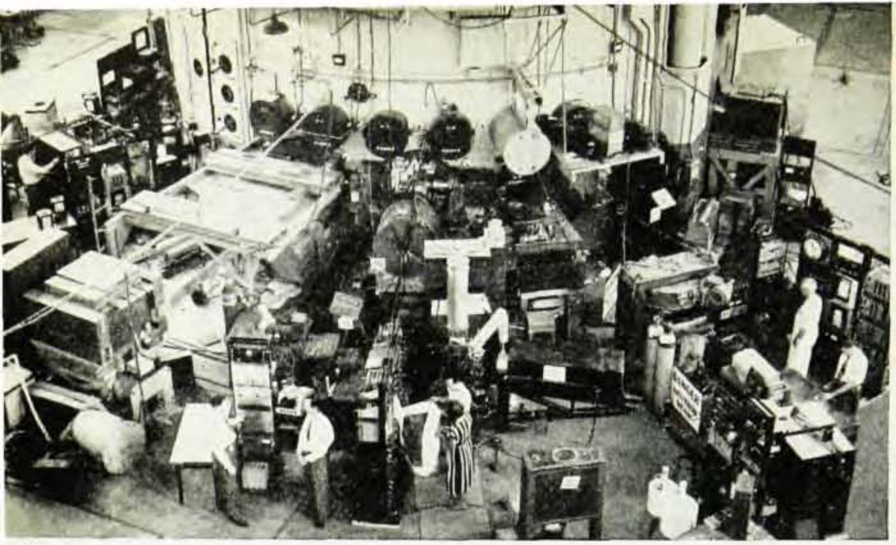


Fig. 4

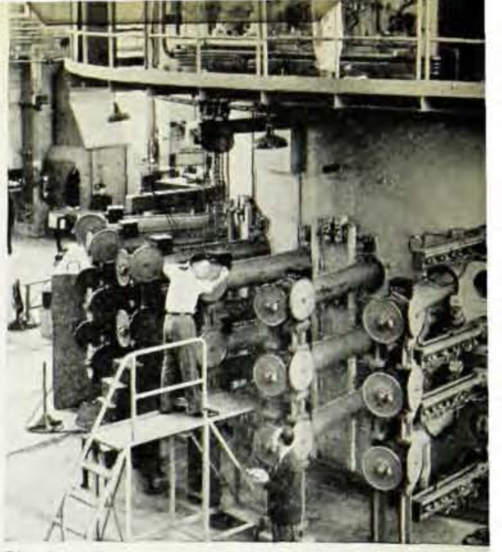


Fig. 5

in the pile is, however, insufficient to meet the demand for such radio-cobalt sources.

Isotope production is now carried out on such a scale that it has proved convenient to have in mind a basic cost for neutrons of $100,000 per gram. The total production can be increased at the expense of plutonium production by enriching the pile with uranium-235 or plutonium.

The radioisotopes normally produced by neutron irradiation are those isotopes which are relatively rich in neutrons, and consequently decay by ordinary beta-ray emission. It has, however, proved practicable to make useful sources of neutron-deficient isotopes which are positon emitters. In this way Na^{22} has been made presumably by the reaction $Ne^{20}(T, n)Na^{22}$ by irradiating turnings of lithium alloy in a high pressure atmosphere of neon.

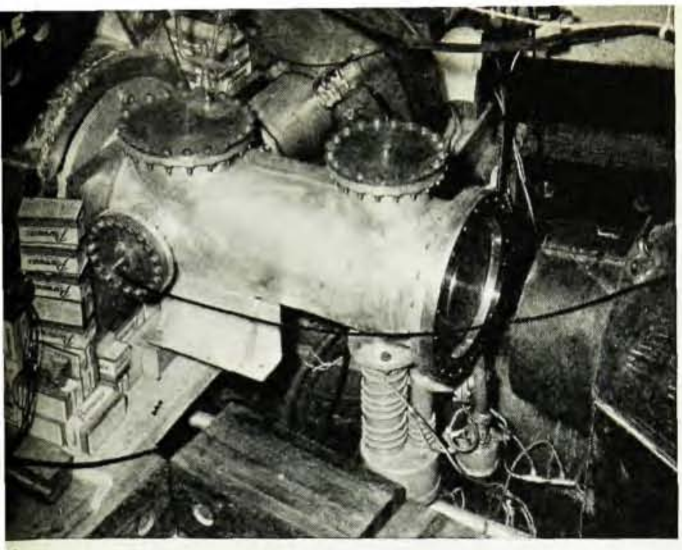
In the lower part of Figure 3 are shown the experimental holes which are used for long irradiations and for letting collimated beams of neutrons or gamma-rays out of the shielding for various experiments. A photograph of this side of the pile is shown in Figure 4. The doors closing five, of the six, four-inch diameter holes in the upper row can be clearly seen. On the right is the pair-production gamma-ray spectrometer, which will be discussed later. Next to the left comes one of the neutron spectrometers. Then, using one of the twelve-inch holes, is the apparatus with which Robson is studying the radioactive decay of free neutrons. Below the heavy table is another neutron spectrometer and on the extreme left some of the nuclear engineers' apparatus for studying the behavior of materials while under irradiation.

It may be noted in general that the results are recorded on continuously running pen recorders, some of which can be seen in the photograph (Figure 4). These are actuated by electronic counting apparatus. It has been noted that Friday afternoon tends to be one of the busiest times around the pile when experimenters are setting up their apparatus to work for them on a long run over the week-end. This implies faith in the reliability of the electronic apparatus which has only been won by much attention in design and maintenance specifically directed towards achieving reliability.

Figure 5 shows the other side of the pile with the external arrangements for the self-serve irradiation holes. The large pipes are shielding tubes for the ends of the rods carrying the cups for introducing the samples through the inner graphite reflector.

Figure 7 shows the arrangements of Dr. Kinsey's gamma-ray pair-spectrometer of the Walker and McDaniel (1948) type. Against the pile face is a block of bismuth which absorbs the gamma-radiation from the pile, but allows neutrons to pass. Next to it the target sample is placed. The resulting gamma-rays spread in all directions, but a small fraction, about one in 20,000, pass through the collimator and reach the radiator foil. The neutrons passing through the target sample are abserbed by the boron and paraffin plug. The radiator is a foil of a heavy element in which gamma-ray quanta of sufficient energy produce pairs of positive and negative electrons. Most of these are projected forward close to the original direction of the gamma-quantum. Their paths are curled round in opposite directions in the magnetic field. In a given magnetic field a coincident count in the two counters can be produced by a pair only for one value of the combined energy and only if the relative distances from the counters of the point of origin in the foil correspond to the momentum ratio of the pair. The sensitivity is such that one coincidence can be obtained for 10^{12} quanta originating from neutron capture in the target for a quantum energy of 2.75 Mev. For 7.4 Mev energy the sensitivity would be about forty times as high.

These figures are given here to emphasize the value of having the high neutron flux which is about 7×10^{12} $n/cm^2/sec$ at the position of the sample. The results already obtained compare favourably in resolution and sensitivity with other methods and have yielded significant information of the changes in spacing of available energy levels associated with the magic numbers of protons and neutrons believed to represent closed shells of these nucleons. In particular, the gamma-ray spectra obtained for capture in lead-206 and 207 (Kinsey and Bartholomew, 1950, 1951) have the same simple character as those from light elements. This simplicity is attributed to the nucleus being at or near



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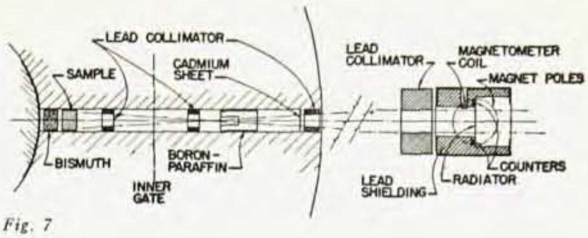

Fig. 7

the two magic numbers of 82 protons and 126 neutrons. The resolution of this gamma-ray spectrometer is, however, far broader than the natural line breadth of most gamma-rays and the line separation for most nuclei. Still higher fluxes and other improvements in technique could yield results of much greater detail and precision about the energy levels of nuclei.

Figure 8 shows the apparatus used by Robson to determine the spectrum of the beta-rays resulting from the radioactive decay of the free neutron. The beam of neutrons travels along the wide vacuum chamber entering and leaving through thin aluminum windows. When the neutron decays the reaction is $n \rightarrow p + e + \nu + 783$ kev. By the momentum balance most of the energy goes to the light particles, namely, the neutrino and electron, and the proton will at the most have a few hundred electron volts energy. The electron can therefore pass through the thin metal of the high voltage electrode into the beta-spectrometer, while the proton is repelled by the high potential and enters the proton spectrometer. To eliminate the background, electrons are counted only when the pulses they produce, delayed by 0.9 microsecond, coincide with pulses from the proton counter. This delay allows for the time of flight of the protons through the proton spectrometer. In the experiments it was found that reducing the delay to 0.5 microsecond dropped the coincidence count to the level of the chance coincidence background. By this and other checks it was verified that both the protons and electrons observed must result from the disintegration of free neutrons. The beta-spectrum obtained gave a normal straight line on a Kurie plot with a maximum energy end-point of 782 ± 13 kev. The radioactive half-life of the free neutron was also evaluated as 12.8 ± 2.5 minutes by measuring the intensity of the initial beam of neutrons, which was about 2×10^9 neutrons per second, and by assessing the fraction of these whose decay products, protons and electrons, would be collected.

The photograph in Figure 6 shows Robson's apparatus before the addition of the beta-ray spectrometer.

A word may be added about the neutron spectrometers, which in addition to being used for studying the velocity dependence of neutron reactions, have been turned to study molecular structure. Used in this way the spectrometer is closely analogous to a double axis x-ray spectrometer, but may better be regarded as complementary in function for neutron diffraction is sensitive to hydrogen and other light nuclei in the molecular structure, whereas x-rays respond more to the greater electron density around the heavier nuclei. With the neutron spectrometers it has been possible to observe the molecular structure of gases. In this work Hurst and Alcock (1950) determined also the scattering properties of the deuteron for slow neutrons. More recently it has proved possible to unravel the change taking place at the lambda-point transition at $-30°C$ in ammonium chloride (Goldschmidt and Hurst, 1951), where the ammonium group becomes free to oscillate but not to rotate.

These neutron spectrometers, in common with other apparatus mentioned, depend for their success on the high flux of neutrons of thermal velocities available and the possibility of keeping background effects to a very low level. The shielding and access facilities built into the NRX reactor have proved highly satisfactory. Nevertheless, it is hoped to do even better in the new NRU reactor about to be constructed at Chalk River.

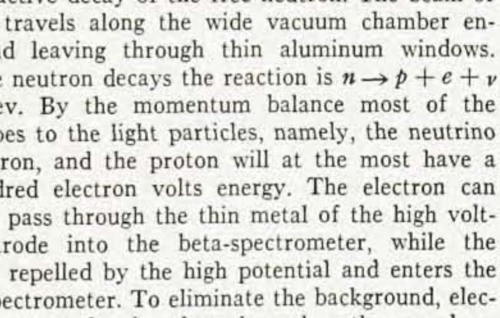

Fig. 8

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