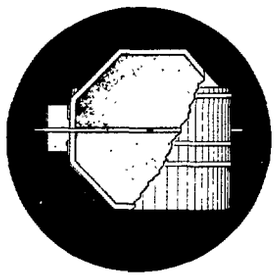


EARLY YEARS OF NUCLEAR ENERGY RESEARCH IN CANADA

by George C. Laurence

ABOUT THE AUTHOR

Given more time, more assistance, more funds and purer materials, the first man-made nuclear chain reaction might have been achieved in Canada. George C. Laurence made the first Canadian experimental attempt in 1940-42.

Born at Charlottetown in 1905, Dr. Laurence was educated at Dalhousie and Cambridge universities. He joined the staff of the National Research Council in 1930 and became active in improving the measurement of radiation dosage in the treatment of cancer and in promoting safety from radiation exposure.

He has been involved in nuclear energy development in Canada since its beginning, continuing in the Montreal nuclear energy laboratory in 1943-44 and at the Chalk River Nuclear Laboratories. He directed the staff that did the preparatory research and development and the conceptual design of the NRU reactor.

In 1946-47 he served as scientific advisor to the Canadian delegation to the United Nations Atomic Energy Commission in New York. In 1956 he was appointed chairman of the Reactor Safety Advisory Committee set up by the Atomic Energy Control Board to advise on the health and safety aspects of nuclear reactors and power stations. In 1961 he left AECL to become the president of the Atomic Energy Control Board from which he retired in 1970. Since then he has lived at his home in Deep River, Ontario.

He was awarded the MBE for his scientific work during the war, the Canadian Association of Physicists medal for achievement in physics in 1966, the W.B. Lewis medal for the Canadian Nuclear Association in 1975, and a number of honorary degrees.

EARLY YEARS OF NUCLEAR ENERGY RESEARCH IN CANADA

by George C. Laurence

Forty years ago the future role of Canada in nuclear research and development would have seemed impossible. There was little public confidence in our scientists and development engineers. Technology was something to import.

Research in the National Research Laboratories has always been predominantly "mission oriented", assisting industry and other government departments. Work of immediate and obvious application left little time for "purely curiosity-inspired" research. By 1940, the attention of the laboratories had been shifted almost entirely to war problems.

This isolation from basic research made it more difficult for the scientists to keep in touch with progress that was relevant to their work, but the scientific periodicals told us of the discovery of nuclear fission, that it sometimes happens when uranium atoms are hit by neutrons, and that more neutrons are released by fission than are captured to produce it. Therefore, a reaction might be possible in which the supply of free neutrons was constantly replenished, or even greatly increased. A very large number of fissions produced in such a reaction would release a very large amount of energy. There was evidence to show that a large increase in rate of producing fissions would be easier to accomplish if the neutrons were moving slowly. They would move more slowly if they encountered large numbers of very light atoms such as hydrogen atoms; therefore, it might be advantageous to associate with the uranium a suitable quantity of material containing hydrogen, such as ordinary water.

One report told of the attempt by Joliot, Halban and Kowarski in Paris to prove that a large release of energy by fission might be possible in a solution of a uranium compound (such as uranyl nitrate) in water. Their attempt failed because the ordinary hydrogen atoms, though they slowed the neutrons, captured so many of them that an insufficient number remained to produce more fissions.

They then decided to try heavy water with the uranium instead of ordinary water, because heavy hydrogen would capture fewer neutrons than ordinary hydrogen. Before they could do so however, the German Panzer Divisions by-passed the Maginot Line and advanced across France. Halban and Kowarski escaped to England bringing their heavy water with them, and did the experiment in Cambridge.

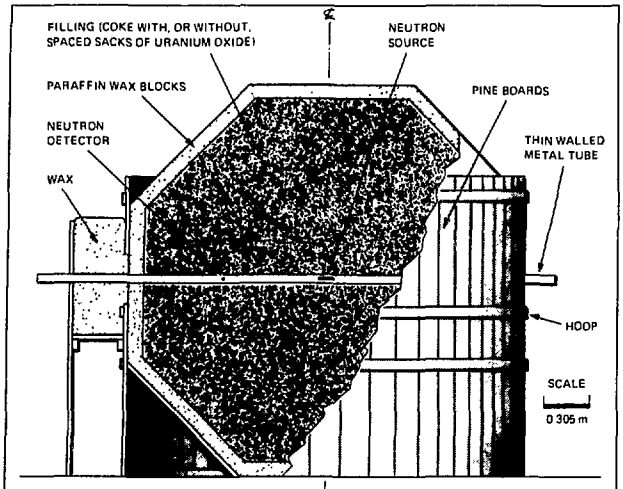
By this time, the nuclear scientists in England and the United States had stopped publishing the results of their research, but they continued their work in secrecy. We assumed that the German scientists were also hard at work, and we were convinced that if Germany produced a nuclear weapon first they would win the war.

Experiments in Ottawa 1940-42

Heavy water was scarce and costly to produce. The 185 kilograms that the French scientists had obtained from a hydroelectric plant in Norway and brought to England was most of the world's supply. Rough calculations with the inaccurate data then available suggested that it might be possible to obtain a large release of energy using some form of carbon instead of heavy water with the uranium. Carbon would be less suitable for the purpose but was cheaper and easier to obtain. I decided to experiment with carbon and uranium oxide. The experiment would have to be done mostly in overtime because my small section was very busy assisting Canadian industry to become proficient in the radiographic inspection of parts for military aircraft and other equipment. Months later, I learned without surprise that similar experiments with carbon and uranium had been started both in England and the United States at about the same time.

The purpose of the experiment was to determine whether a very large release of nuclear energy would be possible in a large bulk of the kinds of uranium and carbon which I had. It would be possible if at least as many neutrons were released by fission as were captured. That implied that if an independent source of neutrons is surrounded by a small quantity (i.e. a few tonnes) of the combination of uranium and carbon, more neutrons would reach the surrounding walls than if the combination of materials was not present.

In our experiments in Ottawa to test this, the source of neutrons was beryllium mixed with a radium compound in a metal tube about 2.5 centimetres long. Alpha particles, emitted spontaneously from the radium, bombarded atoms of the beryllium and released neutrons from them. The carbon was in the form of ten tonnes of calcined petroleum coke, a very fine black dust that easily spread over floors, furniture and ourselves. The uranium was 450 kilograms of black oxide, which was borrowed from El-



CUTAWAY DRAWING OF OTTAWA SUB-CRITICAL ASSEMBLY, 1941-42

dorado Gold Mines Limited. It was in small paper sacks distributed amongst larger paper sacks of the petroleum coke.

The sacks of uranium and coke were held in a wooden bin, so that they occupied a space that was roughly spherical, 2.7 m in diameter. The wooden bin was lined with paraffin wax about five centimetres thick to reduce the escape of neutrons. The arrangement is shown above, as a sectional view through the bin and its contents.

A thin wall metal tube supported the neutron source at the centre of the bin, and provided a passage for insertion of a neutron detector which could be placed at different distances from the source. In the first tests the detector was a silver coin, but in most of the experiments it was a layer of dysprosium oxide on an aluminum disc.

The experimental routine was to expose the detector to the neutrons for a suitable length of time, then remove it quickly from the assembly and place it in front of a Geiger counter to measure the radioactivity produced in it by the neutrons. The Geiger counter tubes and the associated electrical instruments were homemade because there was very little money to spend on equipment.

The relative rates of neutron capture and neutron release by fission were calculated from the data obtained. If the release had been greater than the capture it would have been possible to estimate the "critical quantity" of uranium and coke, that is the minimum quantity needed to produce a self-sustained reaction that would release a large amount of nuclear energy.

Prof. B.W. Sargent of Queen's University joined me in these experiments during the summer university vacations of 1941 and 1942. Progress was slow because the work was interrupted by other duties and we lacked the better equipment that would be available today.

By late summer in 1942, our measurements had shown that the release of neutrons by fission in our combination of materials was a few percent less than the capture. Therefore, it would not be possible to obtain a large release of nuclear energy in that combination of materials even if large quantities were used. There was too much loss of neutrons by capture in impurities in the coke and uranium oxide and in the small quantities of paper and brass that were present. We did not then realize how a little impurity could lead to failure.

Meanwhile in the United States, E. Fermi, H.L. Anderson. B. Field, G. Weil and W. Zinn, after a first attempt that was also unsuccessful, did succeed in showing that a large release of energy would be possible using purer uranium and very pure carbon in the form of graphite. Using the necessarily larger quantities, the Americans then built the first nuclear reactor and operated it on December 2, 1942. They called it an "atomic pile".

In the summer of 1940, R.H. Fowler visited Ottawa, followed soon by J.D. Cockcroft. They had been to the United States to stimulate greater American interest in research of military importance. They told me about the nuclear energy research in England and that in the United States which they had just seen.

With Prof. Fowler's introduction, I visited L.J. Briggs, who was chairman of the committee that coordinated the American nuclear energy research at that time, and also J.B. Conant, E. Fermi, H.C. Urey and P.H. Abelson and learned of their work. After my visit, we received in Ottawa copies of reports on the American nuclear energy research for the next two years. One of them that was particularly helpful was "A Study Concerning Uranium as a Source of Power" by J.B. Fisk and W. Schockly, dated September 17, 1940, a remarkable theoretical discussion of the feasibility of a nuclear reactor to have been written so early.

In response to Cockcroft's suggestion when he returned to England we received a gift of $5,000 from Imperial Chemical Industries, which was involved in the nuclear research in England, in support of our experiment. It was an important addition to our meager budget, but I valued it most as an expression to Dr. Mackenzie of British confidence in our work.

Joint British-Canadian Laboratory Established in Montreal

At first there was greater progress in Britain than in America. It was predicted that if the uranium-235 was separated from the natural uranium in which it occurs it could be used as a very powerful explosive for military purposes. The British estimated the quantity that would be needed to make a bomb, and they proposed methods for the separation of uranium-235. It was shown by theory and experiment that the release of nuclear energy from natural uranium would be accompanied by the production of plutonium, and that plutonium like uranium-235 was fissionable. They also estimated the quantity of plutonium that would be needed for a bomb.

Halban and Kowarski, then in England, carried out their experiments that they had been prevented from doing in France with a uranium compound dissolved in heavy water and concluded that a great release of nuclear energy might be possible with a much larger quantity of such a solution. At first, the interest in a "boiler", as they called it, using uranium with heavy water or carbon was based on the

hope of using it as a source of energy for industrial purposes. With the discovery that plutonium was fissionable the boiler had added importance; it could be used to produce plutonium for the construction of a bomb.

It was suggested that the nuclear research in Britain should be moved to the United States. At first the idea was more acceptable to the American scientists than to some of those in Britain. By the spring of 1942 the advantages to Britain of moving the scientists from there to this continent were more obvious because the industrial resources and effort that would be needed to produce nuclear weapons were already committed heavily to other war purposes. In the United States, however, the work had become well advanced, and the help that might come from England no longer seemed so valuable. The Americans felt that it was too great a security risk because the senior members of the group that would be sent from England included refugees from countries that were occupied by the Germans and it was thought that they might be influenced by pressure on their relatives in Europe.

The British then suggested that a joint British-Canadian laboratory be established in Canada for nuclear research leading to the construction of a pilot plant for the production of plutonium. It would be staffed by some of the scientists from England directed by H.H. Halban, with Canadian scientists recruited into the project. Vannevar Bush, Chairman of the U.S. National Defence Research Committee, informed Sir John Anderson, Home Secretary of the U.K., that the Americans would accept this arrangement and agree to the exchange of information on research that was relevant to the design of the pilot plant.

On February 19, 1942 Malcolm Macdonald, the British High Commissioner to Canada, with Sir George Thomson and W.A. Akers called on Dr. Mackenzie to discuss this proposal. Later that day, Dr. Mackenzie introduced them to the Hon. C.D. Howe and acquainted him with the proposal. Sir George Thomson, Malcolm Macdonald and Professor R.E. Peierls discussed it again on June 15th, with Mackenzie and Howe, and also with Mackenzie King. Dr. Mackenzie visited Vannevar Bush in Washington and they discussed the possibilities of American cooperation with the proposed British-Canadian laboratory. The British raised the question again on August 17 and on September 2.

The objective was speculative; it was doubtful if it could be completed before the end of the war. It would divert scientists, equipment and material from other war work, and would commit Canada to the expenditure of many millions of dollars, and there would be difficulties in the procurement of materials, particularly the many tonnes of heavy water.

Dr. Mackenzie said later that the deciding consideration was that when peace returned atomic energy would be bound to have applications of social and economic significance far beyond the possibilities of imagination and prediction, and the proposed Canadian-United Kingdom research effort would provide an opportunity for the training of Canadian scientists in this field. So, Mr. Howe agreed on September 2, 1942 that Canada would receive the scientists from England, provide the laboratory facilities and supplies and administer the project in Montreal as a division of the National Research Laboratories.

The first of the staff from England arrived about the end of the year 1942. They were P. Auger and B. Goldschmidt of France, G. Placzek of Czechoslovakia, S.G. Bauer of Switzerland, H. Paneth and H.H. Halban of Austria and R.E. Newell and F.R. Jackson of Great Britain. We temporarily occupied an old residence at 3470 Simpson Street belonging to McGill University. Three months later, we moved into a 200 square metre area in the large, new building of the University of Montreal, and more scientists and technicians arrived from England. It was part of my job to recruit Canadian staff, and Professor David Keys (C),* representing the Wartime Bureau of Technical Personnel, helped greatly in finding them, and in obtaining approval

* The names of the Canadians as they appear in the text will be followed by (C).

Some of the initial research staff of Montreal Laboratory, 1943.

Standing: A.M. Munn (C), B. Goldschmidt, J.W. Ozeroff (C), B.W. Sargent (C), G.A. Graham (C), J. Guéron, H.F. Freundlich, H.H. Halban, R.E. Newell, F.R. Jackson, J.D. Cockcroft (visiting the Laboratory), P. Auger, S.G. Bauer, N.Q. Lawrence, A. Nunn May.

Seated: W.J. Knowles (C), P. Demers (C), J.R. Leicester, H. Seligman, E.D. Courant, E.P. Hincks (C), F.W. Fenning, G.C. Laurence (C), B. Pontecorvo, G.M. Volkoff (C), A. Weinberg (U.S. Liaison Officer), G. Placzek.

for their transfer from other employment. The staff grew quickly to over three hundred, of whom about one half were Canadian.

The project was started in a mood of enthusiasm and expectation of great scientific adventure. Never before had such a talented group of scientists been brought together in Canada with a single purpose.

Soon, however, we became impatient as we waited for the expected close collaboration with the American scientists to develop. American anxiety about the security of information increased on account of the mixed national background of the Montreal team. They proposed that the exchange of information with the Montreal Laboratory become much more restricted, and they stopped sending us copies of their scientific reports, and deeply offended the British. The administration of their security measures became very tight after the U.S. Army assumed control of the whole American nuclear program in June 1942, but it was the senior American scientists, Vannevar Bush and J.B. Conant, who resisted most strongly close collaboration with the scientists in Montreal.

The choice of Halban as Director of the Laboratory had seemed logical, but turned out to be unfortunate. He was involved in the unhappy circumstances that brought bitterness and distrust into the relations regarding nuclear energy between France and the United States. With Joliot, Kowarski and Perin, he held patents which claimed control of the use of nuclear reactors for some of their most important applications. The interest of Imperial Chemical Industries in these patents provoked the American distrust of international cartels. An ill-timed visit by Halban to Joliot in France to discuss the patents aggravated American worries about security because Joliot was a member of the French Communist Party.

His associations with the National Research Council also did not always run smoothly. He was impetuous and vacillating in decisions and unreasonable in his demands of the administrative staff in Ottawa and unfair in criticising them. He failed to inform Dr. Mackenzie or any other Canadian about important decisions regarding the research program of the laboratory. Eventually, E.W.R. Steacie (C), then the Director of Chemistry division of the National Research Laboratories, acted as a part-time Assistant Director under him, but Dr. Steacie's influence came too late and was too remote from the administrative problems in Montreal.

At the Quebec Conference on August 17, 1943, Prime Minister Churchill discussed with President Roosevelt the very unsatisfactory state of British-American collaboration in nuclear energy research, including the work of the Montreal Laboratory. They agreed that arrangements should be made "to ensure full and effective collaboration between the two countries in bringing the project to fruition". A "Combined Policy Committee", under the chairmanship of H.L. Stimson, the U.S. Secretary of War, was named to work out the basis for implementing this agreement, but it rarely met. There was little progress towards effective collaboration, excepting a few scientific discussions on strictly limited topics. Morale in the Montreal Laboratory became very low. The scientists felt they would be better employed in other work.

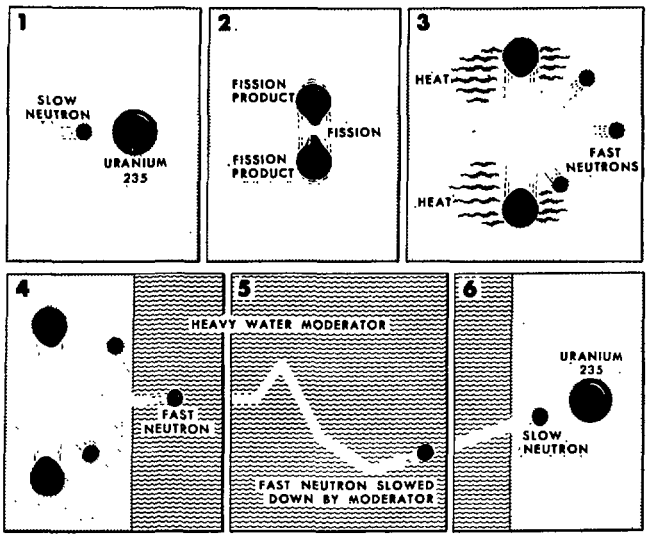
Good Research in Canada, 1943-1946, Notwithstanding Difficulties

In spite of the discouragement and the uncertainties of purpose which lasted until the end of 1944, a remarkable amount of good research was done in the Montreal Laboratory during that period as well as in the happier months that followed. It provided scientific data that were needed for the design of a fission reactor and of chemical plants for the extraction of plutonium and uranium-233 produced in the reactor, and it contributed to knowledge and understanding of the structure and behaviour of atomic nuclei.

Part of the research was investigation of the penetration of neutrons through the kinds of materials that might comprise the core of the reactor, such as heavy water, ordinary water and graphite, and combinations of these with uranium and other materials. This information was essential for the design of a reactor because a large release of nuclear energy by fission is possible only if sufficient numbers of the neutrons that are liberated by fission retain their freedom, avoiding capture in the wrong kinds of atoms, until they are captured again in fissionable atoms to produce more fissions.

There was interest particularly in the possibility of a reactor that would use natural uranium and heavy water. The Americans doubted the conclusion from the experiment by Halban and Kowarski in Cambridge University that a reactor would be feasible using a solution of uranyl nitrate in heavy water because it seemed improbable theoretically and the experiment was difficult to do accurately. The heavy water had been brought to Montreal, and F. Fenning repeated the experiment there and approximately corroborated its conclusions. For further confirmation, he investigated in particular the proportion of the slow ("thermal") neutrons captured in the solution that produced fission, and B. Pontecorvo measured the proportion of fast neutrons that were captured before their speed was reduced sufficiently to produce most of the fissions. Halban suggested that the theoretical objections to the experimental results might be too pessimistic because they overlooked the possibility of an "n - 2n effect" that would increase supply of neutrons, i.e. a reaction by which the capture of a neutron in a deuterium atom of the heavy water would result in the release of two neutrons. A. Nunn May, L.G. Elliot (C) and E.P. Hincks (C), however, showed that any n - 2n effect would be too infrequent to explain the discrepancy. It remained a mystery.

In any case, it was clear that the feasibility of a sustained nuclear reaction in a "homogeneous" mixture of uranium in heavy water would be greater if the concentration of the uranium was considerably increased. Unfortunately no suitable compound of uranium was known that could be dissolved in heavy water in sufficient concentration for the purpose. Hence, interest turned to a more concentrated mixture: a "slurry" consisting of a suspension of a finely



The Fission Process

A slow neutron (Fig. 1) strikes the nucleus of a uranium atom, causing it to split or fission (Fig. 2). Heat is produced. The fast neutrons released by the fission slow down as they bounce against the nuclei in heavy water molecules. Slowed sufficiently, the neutrons will cause other U-235 atoms to fission, maintaining a chain reaction.

divided compound of uranium in the heavy water which was called "mayonnaise" on account of its appearance. It was intended that the mayonnaise would circulate through the reactor vessel and through a heat exchanger where the heat produced by the nuclear fission would be extracted. It could be pumped directly from the reactor to a chemical plant where the used uranium could be replaced, fission products could be removed and plutonium recovered. H. Paneth, B.L. Goldschmidt, H.G. Heal and F. Morgan investigated the preparation of such a suspension, its stability at high temperatures and physical behavior and the effects on it of the intense radiation to which it would be exposed in a reactor. D.W. Ginns considered the engineering design of the reactor. S.G. Bauer and W.J. Knowles (C), investigated problems of removing heat from the slurry. G.S. Anderson and J.H.L. Matheson (C), worked on the design of suitable heat exchangers. The possibility of adding extracted uranium-235 to increase reactivity was considered.

Interest gradually shifted from "homogeneous reactors" using a slurry to "heterogeneous systems" in which the uranium was in the form of metal bars about 2.5 cm in diameter and several centimetres apart in the heavy water. There were several reasons for the change. It was realized that much less heavy water would be needed. Experiments by A.G. Maddock, N. Miller, Miss G. Gorey (C) and J. Hebert (C) gave warning that radiation from uranium and fission products suspended in the heavy water would decompose the heavy water into oxygen and deuterium so rapidly that the reactor could be operated only at a very low power. Other practical difficulties were expected.

Meanwhile, the possibility that the reactor to be built in Canada might use graphite instead of heavy water was not rejected as long as American collaboration remained in doubt. Early success with heavy water would depend on its supply and the Americans controlled the only important production on the continent, that at Trail, B.C., by a supply contract. Sargent and I, with Hans Paneth and H.G. Hereward, and later A.M. Munn (C), measured the migration of neutrons in a ten-tonne pile of graphite rods as they slowed from their original high velocities and continued to move at slow ("thermal") velocities through the graphite. The neutrons for the experiments were released from a block of beryllium by exposing it to the radiation from a two-million volt therapy X-ray machine. We used the same techniques to measure the diffusion of slow neutrons (the "thermal diffusion length") in heavy water containing lithium carbonate.

As I became involved then in other research, Sargent directed the further experiments on neutron migration in heavy water containing uranium bars in arrangements that might be used in a practical reactor. Associated with him in these other experiments on the motion of neutrons in heavy water were D.B. Booker, P.E. Cavanagh, H.G. Hereward and N.J. Niemi (C). These experimental studies of the motion of fast and slow neutrons in graphite and in heavy water confirmed theories of their motion in these materials developed by the theoretical physicists, thereby making it possible to use their theories with greater confidence in designing a nuclear reactor.

Other kinds of reactors were also considered. For example, S.G. Bauer was interested in "breeder reactors" which would replenish their fuel supply by producing plutonium from uranium-238 or uranium-233 from thorium. M.H.L. Pryce, E. Courant and B. Pontecorvo studied the possibility theoretically. Pontecorvo, B.H. Flowers, G.A. Graham (C) and H. Seligman also investigated the motion of neutrons in ordinary water containing bars of uranium, lead or iron to obtain information that would be relevant to the design of reactors that use enriched uranium and ordinary water, such as those now operating in the United States.

The theoretical physicists studied such questions as the minimum quantities of uranium and heavy water or graphite that would be required in a reactor, the saving in these quantities that could be made by surrounding the reactor with a thick layer of graphite to impede the escape of neutrons from it, the effectiveness of movable bars containing substances that capture neutrons, such as boron or cadmium, as a means of stopping or controlling the fission reaction, and other problems of design..

For the purpose of calculating such aspects of reactor design, G. Placzek, R.E. Marshak, B. Davison, E. Courant, J.C. Mark (C), F.T. Adler and others produced formulae which described the migration and distribution of neutrons by "diffusion" equations similar to those which are used to describe the flow of heat, sound, matter in solution or radiation in stars. They used "transport theory" (describing the motion of neutrons in vector notation) to show how the quantities in these formulae were related to information that could be obtained by measurements of the average distance between collisions with atoms, the changes in direction and speed caused by the collisions, and the risk of their capture by the atoms which they

encountered. They also used transport theory to calculate the net flow of neutrons from one material (e.g. heavy water) into another (e.g. uranium or other metal) where the surface between the two materials was not flat, a frequent problem in designing reactors. G. Volkoff (C), Jeanne LeCaine (C), P.R. Wallace (C), H.H. Clayton (C), S.A. Kushneriuk (C), M. Pryce, E.A. Guggenheim and others investigated how the release and distribution of neutrons in a reactor would be affected by the size, shape and relative position of the parts of the reactor. B. Carlson organized a computing section.

The role of the small group of engineers in the Montreal Laboratory was to conceive in outline the design of the reactor, how its uranium fuel would be cooled and how the heat would be dissipated, how it would be shielded to protect the operators from radiation, how the used fuel containing radioactive fission products would be removed and stored safely, how the operating power of the reactor would be regulated, what automatic protective devices would help to insure safe operation, and many other features of design. The group comprised R.E. Newell, D.W. Ginns, J.H.L. Matheson (C), G.S. Anderson, S.G. Bauer and others.

It was also their responsibility to advise those who would design the reactor and chemical plants. Restrictions that were very unusual in engineering experience had to be imposed on the choice of materials and other features of design in order to satisfy somewhat conflicting requirements of working temperatures, rates of heat transfer, permissible leakages of fluids, tendency to capture neutrons, speed of response of instruments and other details.

Since the original purpose of the project was to demonstrate the feasibility of producing plutonium in a heavy water-moderated reactor, the chemists and chemical engineers developed the process by which the plutonium would be separated from the uranium and radioactive fission products after the fuel was removed from the reactor. They also developed the process by which uranium-233 (another fissionable material) could be separated from thorium and fission products.

The development of these processes was made possible by contributions from the Americans of small amounts of plutonium and of uranium and thorium that had been exposed to neutrons and therefore contained the nuclear fuel and fission products produced in a reactor. A group in Montreal including B. Goldschmidt, L.G. Cook (C), T.J. Hardwick and others tested a very large number of solvents to find the most suitable for separating the plutonium and uranium from the very radioactive fission products by preferential dissolving. Another group in the National Research Laboratories in Ottawa, including S.E. Cambron (C), R.H. Betts (C), R. Mungen (C), E.E. Winter (C), L. Simínovitch (C), M.B. Wilk (C) and R.P. Cahn (C), further developed the process so that it was possible to obtain plutonium quite free from both the uranium and the fission products. I.R. Mills (C) and C.H. Simpkinson (C) designed the plant which was operated later in Chalk River until dismantled when it was clear that its plutonium production was not economically profitable at that time.

The comparable process for separating uranium-233 from the thorium in which it is produced and the accompanying fission products was developed by B. Goldschmidt, L.G. Cook (C), J. Guéron, F. Morgan, J.K.T. Spinks (C) and L. Yaffe (C). It was also built and used later at Chalk River. P.E. Gishler (C), R. Wilkinson, T. Boyer (C), P.J. Sereda (C) and C.R.G. Holmes (C) investigated the corrosion of alloys that might be used for protective covering of uranium fuel rods in the reactor by the water from the Ottawa River and the possible need of water treatment.

The chemical properties of uranium, neptunium and some of the fission products were investigated by J. Guéron, W.E. Grummitt (C), A.C. English, G. Wilkinson, C.E. Mackintosh and others. H.G. Heal experimented with electrochemistry of uranium compounds and H. Greenwood tested the corrosion resistance of uranium-silicon alloys.

It is impossible in a short history to mention all the important contributions to nuclear science by the Montreal Laboratory. A list of its scientists and engineers compiled in August, 1945 is appended. Many of them are better remembered today for their work in later years at Chalk River, or in universities and in the United Kingdom and France after leaving Montreal, particularly those who were in Montreal for only a few months.

A notable achievement in basic science was the delineation of the "4n + 1" series of nuclear isotopes, identifying them and observing their properties by T.E. Cranshaw, P. Demers,(C) A.C. English, J.A. Harvey,(C) E.P. Hincks,(C) J.B. Jelley and A. Nunn May. The "4n + 1" series is a group of heavy isotopes not found in natural minerals that is produced by successive disintegration from uranium-233. It is analogous to the three series of naturally radioactive isotopes that have long been known to result from the disintegration of uranium, thorium and actinium. Knowledge of properties of the "4n + 1" substances is important in developing methods of recovering pure uranium-233, which is a promising nuclear fuel that can be produced from thorium.

Nuclear fission provides two means by which the number of known kinds of atoms has been greatly increased: the production of fission products, and the release of neutrons which by impact on existing kinds of atoms transform them into new kinds. The increase in the variety of atoms available for study permitted research that has greatly extended our knowledge of the structure and internal behaviour of atomic nuclei. Some of the experiments involved bombarding the new substances with neutrons or other atomic particles or radiation, and observing the radiation or particles that emerged to discover what changes were caused in the atoms when they were hit. Some of the research in the Montreal Laboratory was of this kind using small quantities of fission product material received from the United States. It provided preliminary experience that led some of the young scientists involved to very productive careers in nuclear research later at Chalk River and elsewhere when much greater quantities of these materials could be produced in the nuclear reactors.

A useful experimental technique developed by P. Demers (C) involved the use of very fine-grained photographic emulsion in which the "tracks", roughly one hundredth of a millimetre in length left by individual alpha particles emitted from specks of radioactive matter resting on the emulsion, could be clearly seen with a microscope. The lengths of the "tracks" helped to distinguish the kinds of isotopes from which the alpha rays came. It also revealed the "tracks" produced by the fission fragments of single uranium atoms.

Other experimental techniques were developed and special instruments were devised. They included beta-ray spectrometers for measurement of the velocity of electrons by L.G. Elliott (C) and B. Kinsey, ion chambers of various kinds to detect neutrons and other atomic particles by H. Carmichael and J.F. Steljes, an electronic device called a "kick sorter" for counting atomic particles and distinguishing between those of different speeds by H.F. Freundlich, E.P. Hincks (C) and J.W. Ozeroff (C), and improved "kick sorter" by C. Westcott (C) and R. Hanna and others, electronic amplifiers for measuring the very small direct currents of electricity through ion chambers by R.J. Cox, F.J.M. Farley, J.D. Jackson and H.E. Gove, ion chambers for measuring the energy of motion of atomic particles by T.E. Cranshaw, J.A. Harvey (C) and others, and an accelerator to produce fast moving heavy hydrogen ions by A.G. Ward (C) and J. Warren, and other special pieces of equipment that could not then be obtained commercially. H.M. Cave (C), E.B. Paul (C), J.B. Jelley and P. Lamb (C) converted a 600,000 volt X-ray generator that I had built a few years before in Ottawa into an accelerator of positively charged atomic particles for nuclear research.

The biological effects and hazards of exposure to radiation and atomic particles, and other safety questions received much attention. J.S. Mitchell, W.V. Mayneord, and G.A. Butler (C), internationally recognized experts on radiation dangers, spent some time in the laboratory and greatly influenced its policy on protection of its employees and the public.

There were miscellaneous research and development activities which, after August, 1944, were grouped together in a division called Technical Physics under my direction. They included research on the transfer of heat from simulated reactor fuel rods to cooling water by S.G. Bauer, J.W. Knowles (C) and E.W. Guptill (C) in Montreal, and by P.E. Gishler (C) in the National Research Laboratories in Ottawa, in which particular attention was given to the effects of surface boiling, steam film formation and thin water films, the development of reactor control rods and the covering of uranium fuel rods with aluminum cladding to prevent corrosion by G.S. Farnham (C) and others in the Department of Mines and Resources, the development of control rod mechanisms and instruments by N.Q. Lawrence, the construction of Geiger counters and of "boron chambers" for the measurement of the flow of neutrons by N. Veall. H.F. Freundlich, J.W. Ozeroff (C), R. Callow and J. Elsey designed and supervised the construction of much of the electronic research instruments for the laboratory. D.C. Douglas (C) investigated the possible contamination by radioactive substances of air and water circulated through a reactor for cooling it. M.W. Lister (C) advised on the possible spread of any radioactive contamination in the atmosphere and G.W.C. Tait (C) used smoke tests to investigate the movements of air in the river valley where the reactor was to be built. Dr. C.B. Peirce supervised medical tests to reveal harmful effects of radiation on the health of employees.

Scientists in other laboratories contributed to the program. At McMaster University, Prof. H.G. Thode and others used mass spectrometer methods in testing heavy water and in separating isotopes. Help was received from Prof. F.E. Beamish at the University of Toronto with chemical analysis, from Prof. L.M. Pidgeon at the University of Toronto in uranium chemistry, and from G.S. Farnham, R.L. Cunningham and others in the Department of Mines and Resources in metallurgical subjects. McGill University provided library service.

Secrecy about the work of the laboratory was extreme. Younger scientists were forbidden by Halban to discuss their work with others in a different scientific field. When the distinguished Danish physicist, Niels Bohr, visited the laboratory he was addressed as "Mr. Baker". Code words were also used in referring to uranium compounds, heavy water, and other important materials.

Decision at Last

There was little benefit for Canada in continuing the research in the Montreal Laboratory without close co-operation with the British and American scientists and this view was expressed to the authorities in both countries. The situation was worsened in both by poor communication among heads of states, officials and scientists.*

Better understanding and good will were achieved, eventually, through the efforts of James Chadwick, the most renowned of living British atomic scientists; General Groves, head of the whole American nuclear effort; and Dr. Mackenzie. Groves and Chadwick were of very different backgrounds, disciplines and personalities but they trusted and respected each other, and Mackenzie understood very well the points of view of both sides. Their good sense prevailed; the Montreal Laboratory was saved.

The long-awaited decision to proceed at once with the design construction of a heavy water-moderated nuclear reactor in Canada was made at a meeting of the Combined Policy Committee in Washington on April 13, 1944 which was attended by both the Hon. C.D. Howe and Dr. Mackenzie. General Groves was present and we are told that he assisted greatly in reaching agreement. It was

* In this article, which discusses the scientific and engineering research, very little has been said about the misunderstandings regarding the supply of uranium and heavy water and political differences. A comparison of American, British, French and Canadian accounts of wartime nuclear cooperation reveals them clearly. See references cited at end of paper.

A group photo taken in 1945 shows a number of those involved in the construction of the Chalk River Nuclear Laboratories. From left to right: Major J.H. Brace, president, Fraser Brace Limited, Arthur N. Budden, Department of Munitions and Supply, unidentified, Dr. C.J. Mackenzie, president, National Research Council, F.J. Palmer, gen. supt., Fraser Brace Limited, H. Greville Smith, vice-president, Canadian Industries Ltd., (Defence Industries Ltd.) D.S. Kirkbride, gen. supt., Services, Petawawa Works, Defence Industries Ltd., unidentified, Major A.B. McEwan, manager, Special Projects div., D.I.L., H.J. Desbarats, manager, Petawawa Works, D.I.L., Dr. J.D. Cockcroft, director of the Canadian Project, 1944-46, C.H. Jackson, chief engineer, Special Projects div., D.I.L., Gordon R. Stephens, general manager, Fraser Brace Limited, H.S. Milne, resident engineer, Petawawa Works, D.I.L., M. Green, superintendent, Fraser Brace Limited.

agreed that there would be full exchange of information relevant to design of the reactor and the extraction of the plutonium it produced. Halban and other scientists who were not British subjects would leave, and the English physicist, John Cockcroft, would be Director of the Laboratory.

The atmosphere in Montreal changed quickly. The Americans fully supported the project. Scientific information, supplies of materials and help in many ways came from the United States, and scientists from Montreal visited American nuclear research centres where relevant work was being done.

Defence Industries Ltd. was engaged to do the engineering design of the reactor, the laboratories, the services, and the town where the employees would live, and to operate them for the National Research Council which would direct the research. Fraser Brace Ltd. would do the construction under contract to Defence Industries Ltd. After a score of possible sites was considered, one near Chalk River was chosen and called the "Petawawa Works". The location now known as Deep River was selected for the town. Design began almost at once, and construction proceeded rapidly in spite of difficulties in procuring materials and labour. The story of this construction is omitted here because it is more suitably a part of the history of NRX.

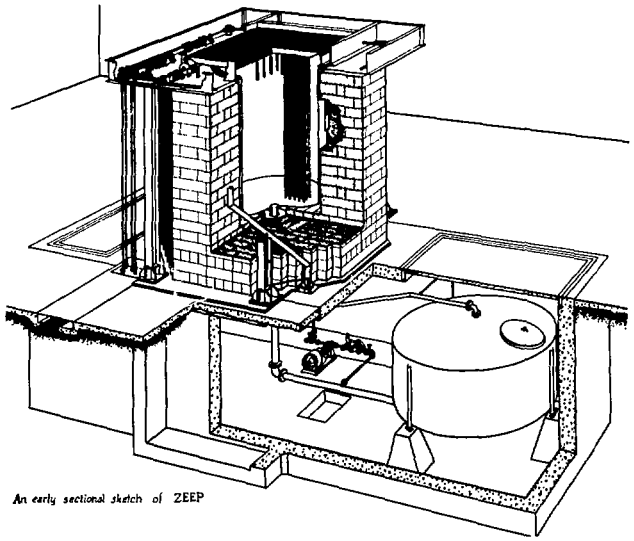
Dr. J.D. Cockcroft arrived at the CRNL site in April, 1944 and immediately reorganized the Laboratory. Under his direction morale improved and a sense of purpose was restored.

Cockcroft arrived on April 26, 1944 and the direction of the Laboratory was reorganized. E.W.R. Steacie (C) was its Assistant Director and acted also as Head of the Chemistry division after Paneth left. Halban became Head of the Nuclear Physics division. I was made Head of the Technical Physics division as mentioned earlier. Sargent (C) became Head of the Nuclear Physics division when Halban left at the end of March, 1945, and Volkoff (C) succeeded Placzek a little later as Head of the Theoretical Physics division.

Under Cockcroft, the administration of the laboratories became less difficult, morale improved and a sense of clear purpose was restored. While the laboratories were being built at Chalk River, the staff moved there gradually from the Montreal Laboratory which was closed down in July, 1946.

ZEEP

Success in operating the proposed new reactor, which was named NRX, would depend critically on the design of its "lattice". That is on the size, shape and composition of the uranium fuel rods and their distance apart in the heavy water. The dimensions had been calculated by the mathematical physicists in the Montreal Laboratory from theory. The general validity of the theory had been proved by the success of the first American reactors, including one in Chicago which used heavy water and was designed by a group under Canadian-born Walter Zinn. However, before the theory could be used as a final guide for the design of NRX, a confirmation was needed by experiment of the behaviour of neutrons in the kind of reactor lattice that would be used, and it was done in Montreal by Sargent (C), H.G. Hereward, A. Munn (C), P. Cavanaugh, D. Booker, M. Burrow, N. Niemi (C) and L. Nirenberg (C) with small quantities of the materials.



An early sectional sketch of ZEEP

(L-r) Dr. G.C. Laurence, Dr. C.J. Mackenzie, Hon. C.D. Howe, and Dr. J.D. Cockcroft in August, 1945, a few weeks before ZEEP started up.

This background of theory and experiment made it possible to decide the outline design of the NRX reactor, its shielding, the location auxiliary equipment and the design of the building that would house them, so that the construction could be started. Before NRX was completed, however, it was desirable to have some experience in operating a comparable reactor that could be easily altered. After two months of study it was decided, on August 24, 1944, to build a very simple reactor that could be completed quickly, and was so designed that its uranium rods and other parts could be easily changed or rearranged.

Lew Kowarski, who had declined to come to Canada to work under Halban, had joined the staff under Cockcoft. He, with New Zealander Charles Watson-Munro and Canadians George Klein and Don Nazzer, were given the task of designing this small reactor and putting it into operation. They were helped by A.H. Allan, F.W. Fenning, G. Fergusson, C.W. Gilbert, and E.P. Hincks (C). Kowarski named it ZEEP, which he said stood for "zero energy experimental pile".

Simplicity and flexibility were achieved in this reactor by omitting any provision for removing heat produced by the nuclear reaction, very heavy shielding to absorb radiation, and the more elaborate control and safety equipment that is needed in high power reactors.

ZEEP's reactor vessel is an aluminum cylinder about two and one half metres high and two metres in diameter, surrounded by blocks of graphite, as shown above. The uranium rods are hung vertically from a frame across the top. The heavy water is stored in a tank beneath, from which it can be pumped into the vessel. Small cylinders of cadmium were arranged so that if the power became dangerously high, they would drop automatically into the reactor vessel where they would stop the reaction by absorbing neutrons.

Dr. Lew Kowarski directed the ZEEP project which would provide experience useful in the design of more powerful reactors.

On September 4, 1945, at Chalk River, the construction of ZEEP was completed. The uranium metal rods, clad with aluminum, were in place; it remained to add the heavy water. The small team worked carefully, controlling the flow of heavy water into the reactor vessel, and watching the instrument that gave the first indication that nuclear fission had occurred in ZEEP.

They changed to less sensitive instruments designed by H. Carmichael, that would be suitable when operating ZEEP at the intended power. Ion chambers, sensitive to neutrons, were placed close to the reactor vessel. One of them was connected to a galvanometer on the control desk that projected a spot of light on a millimetre scale marked on a strip of glass for the operator to see. The power at which ZEEP operated would be shown by the displacement of the spot of light across the scale.

The next day, September 5, the heavy water was pumped into the reactor vessel again, a little at a time. When the vessel was partly full, the spot of light was seen to move very slightly. After that, each small addition of heavy water moved the spot faster and farther. At length, the spot showed that ZEEP was operating at the nuclear power for which it was designed.

Thus, for the first time a nuclear reactor had been operated outside the United States. They found that the amount of heavy water required was almost exactly what had been predicted from theory by J. Stewart (C) and G.M. Volkoff (C).

In later years, ZEEP has been used for important research on the behaviour of neutrons in reactors and other purposes by B.W. Sargent and others. It was used by

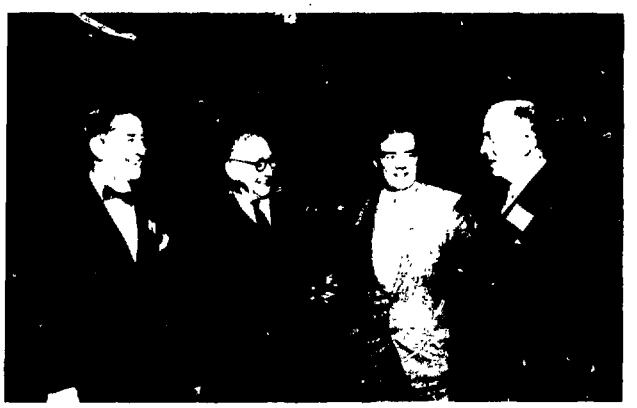
Andrew Pressesky (C), David Walker (C), D.W. Hone (C) and others to provide data for the design of other reactors.

In 1945 and 1946, most of the British scientists returned to England and began the research that was to lead the United Kingdom to become the third nuclear military power, and the first to produce electricity in large nuclear power stations economically. Some joined the Canadian staff and remained here.

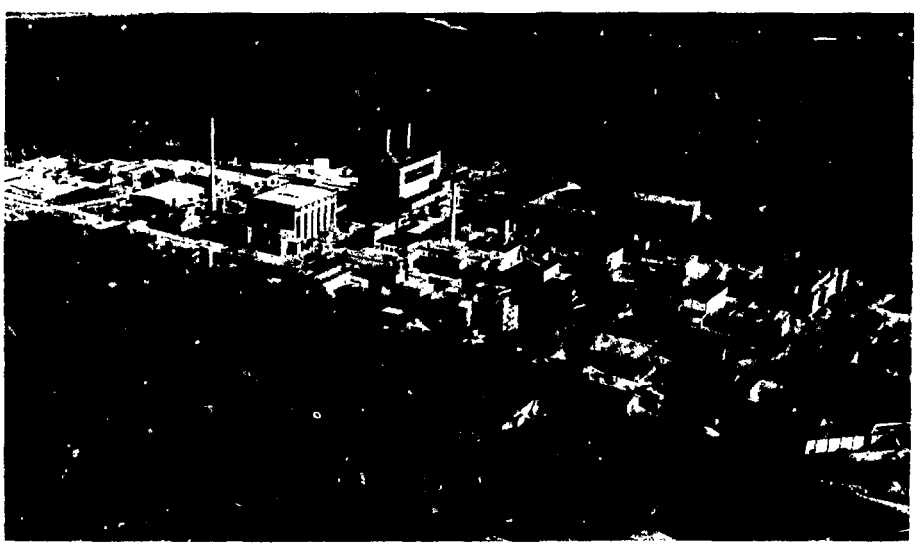
The first phase of nuclear research and development in Canada, when scientists and engineers from Great Britain, Commonwealth countries, France and other parts of Europe had contributed so much, and when so much help was received from the United States, was coming to an end. The centre of activity in Canada had moved to Chalk River and there was reorganization, new direction and new purpose. From that time, Canadian ideas regarding design and operation of nuclear reactors, nuclear power stations and nuclear safety began to diverge from those of other countries. Gradually the CANDU conception of nuclear power stations was to emerge.

I am indebted to Dr. Mackenzie and many of my former colleagues, particularly G.A. Bartholomew, W.E. Grummitt, G.C. Hanna, W.J. Knowles, S.A. Kushneriuk, R.R. MacLanders, B.W. Sargent, W.H. Walker and E.E. Winter, for their help in recalling events.

During a visit to CRNL in 1971, Dr. Lew Kowarski reminisces about ZEEP with Dr. C.H. Millar (C) and D.H. Walker (C). In August, 1944, Dr. Kowarski was placed in charge of the team that was to design ZEEP which went into service on September 5, 1945, little more than one year later.



Although most of the British scientists returned to England in 1945 and 1946 to continue their research there, close cooperation with United Kingdom researchers continued. From left, J.L. Gray, third president of AECL, retired December 1974; Sir John Cockcroft, who directed the scientific program in Canada and later led the U.K. program; Dr. W.B. Lewis, who succeeded Cockcroft and became senior vice-president, science, AECL, a post he held until his retirement; and Sir William Cook, United Kingdom Atomic Energy Authority.



The Chalk River Nuclear Laboratories, today, is Canada's largest establishment devoted entirely to research into the peaceful uses of atomic energy.

APPENDIX

Professional Personnel of the Montreal Laboratory Before August 1945

Canadians

W.J. Allan, Jeanne L. Agnew, C.A. Barnes, Mrs. D. Bate, A.H. Booth, T.W. Boyer, G.C. Butler, A. Cambron, H.M. Cave, H.H. Clayton, M.Cohen, L.G. Cook, D.S. Craig, A.J. Cruickshank, P. Demers, D.C. Douglas, D.M. Eisen, L.G. Elliott, S. Epstein, J.M.G. Fell, F.T. Fitch, C.M. Fraser, S.C. Fultz, P.E. Gishler, G.A.R. Graham, L.M. Grassie, W.E. Grummitt, E.W. Guptill, T.J. Hardwick, J.A. Harvey, E.P. Hincks, C.R.G. Holmes, D.G. Hurst, Miss M.E. Kennedy, Miss P. Kerr, D. Kirkwood, W.J. Knowles, S.A. Kushneriuk, Mrs. J. Laird, G.C. Laurence, J. LeCaine, W.R. Legge, M.W. Lister, J.G. Machutchin, S.N. Maldrett, J.C. Mark, J.H.L. Matheson, K.J. McCallum, L.A. McLeod, J.W. McKay, N. Miller, J.R. Mills, W.A. Mohun, N. Morrow, G.B. Moses, A.M. Munn, N.J. Neimi, L. Nirenberg, J.W. Ozeroff, E.B. Paul, W.S. Peterson, E. Prevost, D.S. Russell, B.W. Sargent, P.J. Sereda, C.H. Simpkinson, J.K.T. Spinks, E.W.R. Steacie, J.D. Stewart, B.M. Thall, A.L. Thompson, Miss A. Underhill, D. Van Patter, A. Vroom, G.M. Volkoff, Muriel Wales, P.R. Wallace, W.H. Walker, A.G. Ward, C. Westcott, L. Yaffe.

The following Canadian scientists worked elsewhere on atomic energy problems in association with the Montreal Laboratory.

In the Chemistry department at the University of Toronto, under the direction of Professor F.E. Beamish; H.E. Bewick, J.E. Currah, and D.E. Ryan.

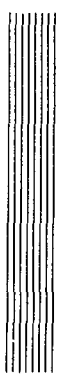
In the Chemistry department of McMaster University, under the direction of Professor H.G. Thode; G. Dean, H.E. Duckworth, R.L. Graham, A.L. Harkness, R.C. Hawkings, D.T. Roberts and S.R. Smith.

In the Metallurgy department at the University of Toronto, under the direction of Professor L.M. Pidgeon; W.A. Alexander and A.C. Topp.

In the Department of Mines and Resources - Fuel and Ore Laboratory, under the direction of Dr. G.S. Farnham; R.L. Cunningham, H.J. Nichols, G. Ensell and Miss A. McDowell.

From Other Countries

F.T. Adler, A.H. Allen, C.B. Amphlett, G.S. Anderson, W.J. Arrol, H.S. Arms, P. Auger, A.F. Barr, S.G. Bauer, D.B. Booker, W.E. Burcham, R. Callow, B. Carlson, H. Carmichael, P.E. Cavanagh, K.E. Chackett, J.D. Cockcroft, S.G. Cohen, G.B. Cook, E.D. Courant, R.J. Cox, T.E. Cranshaw, B. Davison, J. Diamond, J.V. Dunworth, J. Elsey, A.C. English, F.J.M. Farley, F.W. Fenning, G.J. Fergusson, B.H. Flowers, H.F. Freundlich, K.D. George, C.H. Gilbert, A.H.C.P. Gillison, D.W. Ginns, B.L. Goldschmidt, M. Goldstein, H.E. Gove, H. Greenwood, J.W.G. Gregory, J. Guéron, E.A. Guggenheim, H.H. Halban, R.G. Hanna, B.G. Harvey, H.G. Heal, H.G. Hereward, R.P. Hudson, J.D. Jackson, F.R. Jackson, J.B. Jelley, K.D.B. Johnson, N. Kemmer, B. Kinsey, L. Kowarski, P. Lamb, N.Q. Lawrence, C.E. Mackintosh, A.G. Maddock, R.E. Marshak, G.R. Martin, A. Nunn May, P.M. Milner, J.S. Mitchell, F. Morgan, W.K.R. Musgrave, R.E. Newell, H.R. Paneth, C.O. Peabody, G. Placzek, B. Pontecorvo, H. Preston-Thomas, M.H.L. Pryce, C. Reid, D.T. Roberts, H. Seligman, K. Smith, B.S. Smith, R. Spence, J.F. Steljes, F. Sterry, J. Sutton, J. Thewlis, H. Tongue, N.J. Veall, C.H. Westcott, J.B. Warren, C.N. Watson-Munro, D.West, W.J. Whitehouse, G. Wilkinson, R. Wilkinson, W.W. Young.



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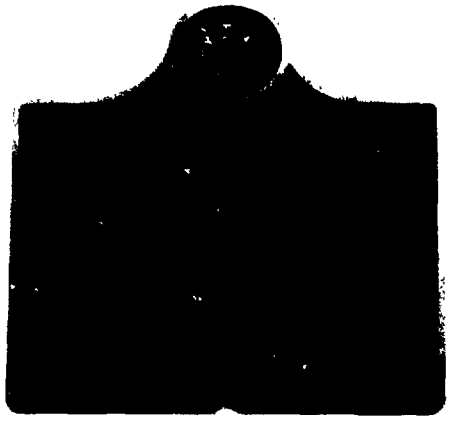

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Chalk River Nuclear Laboratories
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