CANDU ORIGINS AND EVOLUTION – PART 2 OF 5

"WHY CANDU"

Prepared by
G.L. Brooks[1] - 2001 February

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[1] Former Chief Engineer, AECL

Summary:

This monograph is intended to answer, in simple terms, the question of "Why CANDU"; that is, why the CANDU nuclear power reactor is the way it is and why it differs from other commercially developed nuclear power reactors, particularly the light water type of reactors originally developed in the United States and now used in many countries.

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In the most basic terms, the answer to "why CANDU" lies in the technology and manufacturing capabilities available in Canada during the early years of the nuclear age, that is, the 1940's and 1950's when the CANDU reactor was first developed.

To elaborate, we need to start with a few facts of physics. Of primary interest is a process called nuclear fission which involves the fission or "splitting" of the nuclei of atoms through their interaction with subatomic particles called neutrons. When such fission or "splitting" of the nuclei releases new neutrons to replace the ones which cause the fission, a self-sustaining "chain" reaction is possible. Such a chain reaction process produces not only new neutrons but also large quantities of energy in the form of heat. As found in nature, there is only one material which readily can support such a chain reaction. This material is a particular isotope of the element uranium, specifically the U-235 isotope. In nature, this isotope comprises less than 1% of uranium, most of the remaining uranium comprising the isotope U-238 which does not readily split in a chain reaction. Trying to achieve and maintain a chain reaction with this "natural" uranium is somewhat akin to trying to burn a very poor grade of coal where the reactive carbon is heavily diluted with other materials such as clay which will not burn. What to do? An obvious answer is to remove U-238, thereby concentrating the U-235. This would be similar to removing clay from the poor grade of coal to make it a higher grade and, hence, easier to burn. Unfortunately, such a process is extremely difficult in the case of uranium because the U-238 is chemically identical to the U-235 so conventional chemical refining techniques will not work. The only ways around this separation problem rely on the fact that U-235 atoms are slightly smaller and slightly lighter than U-238 atoms. Such separation techniques were developed in the U.S. during World War II in order to produce the highly concentrated U-235 needed for atomic bombs. The production plants employing these techniques were, however, extremely expensive to build and operate. Is there another way, that is, is there a way in which the dilute mixture of U-235 in U-238, as found in nature, can be used "as is"? Fortunately, the answer is yes.

To understand this answer, we need to look at a few more facts of physics. Firstly, as already noted above, neutrons are key to the fission process. In a chain reaction, as already noted, new neutrons are produced which replace those "used up" in creating fissions. These new neutrons, as they are released by the fission of the nuclei of U-235 atoms, are very energetic, that is, they travel at very high velocities. One might think, intuitively, that these energetic neutrons would be just the things to readily split more U-235 nuclei. Such is not the case, however. While it may seem odd at first glance, if these neutrons are slowed down, they have a much greater chance of causing U-235 nuclei to fission. In technical terms, this slowing down of the neutrons is called "moderation".

With this background, we can now see a possible way in which a chain reaction might be possible with uranium as found in nature - "natural" uranium. If this uranium is "mixed" with some other material which can slow down or moderate the neutrons, then, despite the dilution of the U-235 with U-238, a chain reaction may proceed. This moderating material must have special characteristics. It must be effective in slowing down the neutrons but, at the same time, it must not absorb, or "waste" too many of the neutrons. The best practical material for this task is heavy water. The next best practical material is graphite, a form of carbon. Ordinary water, often called “light” water, to distinguish it from heavy water, is very effective in slowing down neutrons but, unfortunately, it wastefully absorbs many more of the neutrons than does heavy water. As a result, a chain reaction cannot be achieved with any combination of natural uranium and light water. To make this combination work, it is necessary to artificially enrich the uranium with the U-235 isotope - as is done in the case of light water moderated nuclear reactors as will be discussed later. One further point is important. The “mixing” of natural uranium and the moderator must be done in a certain way if a chain reaction is to be achieved. The “mixing” must be rather coarse in geometry rather than a homogeneous mix. In practice this calls for the uranium to be in the form of solid geometric shapes such as cylindrical rods with the spaces between such rods being occupied by the moderator. Such an arrangement is called a lattice.

We can now turn to history. Scientists knew the basic physics discussed above in the late 1930’s and early 1940’s. With the advent of world war II, scientists in a number of countries theorized that a powerful new weapon could be produced based on a nuclear chain reaction since such a chain reaction offered the potential of releasing enormous quantities of energy in the form of heat. Led by the United States, with its Manhattan Project, the western allies mounted a major effort in this direction. One approach adopted by the Manhattan Project was the production of highly concentrated U-235, as core material for such a weapon. With highly concentrated U-235, a chain reaction can be achieved without the need for a moderator. Furthermore, a relatively small quantity of such highly concentrated U-235 is needed, thereby making possible a very compact “bomb” core. Such highly concentrated U-235 can be produced through two alternate isotope separation processes, electromagnetic separation and gaseous diffusion separation. Both routes were eventually successful. Another route to a compact “bomb” core was also identified. This involved the production of a new material not found in nature which was named plutonium. Artificially produced plutonium, like U-235, can very readily support a nuclear chain reaction and, hence, was early identified as a likely candidate for use in such weapons. How was this plutonium to be produced? From our earlier discussion, the reader will recall that U-238 is the predominant isotope found in natural uranium. While not directly useful in the chain reaction process employing natural uranium, U-238 absorbs neutrons. While this tends to inhibit the chain reaction itself, in absorbing neutrons U-238 is converted to plutonium. Since plutonium is chemically different from uranium, the plutonium can be chemically separated from the uranium once it is produced. The machine in which this plutonium is produced is a type of what is commonly called a “nuclear reactor”. In this machine, natural uranium undergoes a controlled and extended period of chain reaction during which a significant fraction of the U-238 is converted to plutonium. The uranium, referred to as the “reactor fuel”, is then removed from the reactor and chemically processed to separate and concentrate the plutonium.

Two types of such reactors were developed during and immediately following the war. The first type, developed as part of the Manhattan Project in the U.S., used natural uranium fuel and graphite as the moderator. While, as noted earlier, graphite is not as efficient a moderator as heavy water, it is readily available and, hence, was chosen in the interest of enabling plutonium production at the earliest possible date. Development of the second type, employing uranium fuel and heavy water as the moderator, was assigned by the western allies to a team of British, French, and Canadian scientists who set up shop in Montreal. They were initially provided with a small quantity of heavy water originally produced in Norway prior to the war which was smuggled out of France just ahead of the German army in 1940 by a group of French scientists. A small heavy water production plant was established in Trail, B.C. under U.S. sponsorship. The Montreal-based team designed a small experimental heavy water moderated reactor, called

ZEEP, which was constructed at a new facility established on the Ottawa River, near the village of Chalk River. This facility became the Chalk River Laboratory. The ZEEP reactor went into operation in 1945 and was the first reactor to operate outside of the U.S. Prior to the operation of ZEEP, work started on the design and construction of a much larger heavy water moderated reactor, NRX, which was also located at Chalk River. NRX went into operation in 1947.

With the end of the war, the British and French scientists returned to their own countries to start atomic energy programs and Canada, under the National Research Council, took over the program at Chalk River. Since the Canadian government decided that Canada would not pursue the field of atomic weapons, the post-war programs at Chalk River were redirected to basic nuclear research, the production of radioisotopes, and other potential peaceful uses of nuclear energy. One of these was the possible use of nuclear energy to produce electricity.

In considering the possible development of nuclear energy for the production of electricity, the Canadian government established, as basic objectives, that such development should be aimed at potential application by Canadian utilities and that existing Canadian technology and manufacturing capabilities should be utilized to the maximum practical extent. Ontario Hydro expressed an early interest since Ontario's potential new hydraulic generating sites were limited and Ontario did not possess significant reserves of fossil fuels. On the other hand, Ontario did possess significant reserves of uranium. Since Canada did not possess facilities for the enrichment of U-235 and did not plan to construct such facilities for nuclear weapons purposes, there was a major incentive to develop a nuclear power system which could utilize natural, un-enriched uranium. Furthermore, as earlier discussed, Canada had already developed a significant body of technology related to heavy water moderated reactors which were well suited to the utilization of natural uranium fuel. It is therefore hardly surprising that Canada chose to follow the natural uranium, heavy water moderated reactor route to nuclear power. From these basic considerations, CANDU was born.

At this point in our discussion, it is worthwhile considering why other countries adopted different routes to nuclear power than that chosen by Canada. Firstly, let's look at the situation in the U.S. in the years following World War II. Two major factors influenced the U.S. route. The first was the existence of large facilities for the enrichment of uranium which had been constructed during the war for weapons purposes. These facilities had sufficient surplus capacity to provide enriched uranium fuel for a civilian nuclear power program. The military program had paid the enormous capital cost of these facilities. Their operating energy costs were also high but could be accommodated while providing enriched uranium at a reasonable price for electrical utility use. The second major factor was the U.S. navy decision to develop light water moderated and cooled reactors for submarine propulsion. Light water reactors were attractive for this purpose because they are relatively compact in size. Their need for enriched uranium fuel was not really a disadvantage because by highly enriching the fuel, the submarines could operate for long periods of time before requiring refuelling - obviously a great advantage for military operations. The U.S. navy paid for the development of this type of reactor and, as a result, the contractors in the U.S. who undertook the work were provided with the basic technology for this type of reactor. This allowed two of the leading contractors, Westinghouse and General Electric, to enter the commercial nuclear power field with relatively little investment of their own money since they were basically just adapting the submarine reactor technology.

Turning now to Britain and France, these two countries followed similar paths to nuclear power although their programs were relatively independent of each other. Immediately following the war, both countries decided to pursue the development of their own nuclear weapons. Not surprisingly, both followed the same basic routes as had been pioneered during the war in the U.S. These routes involved the construction of uranium enrichment facilities to produce U-235 and the construction of air-cooled, graphite moderated, natural uranium fuelled, reactors for the production of plutonium. The first such reactors built in both countries were dedicated to the production of military plutonium. In addition to such military applications, both countries were interested in the early development of reactors for electricity generation. They both concluded that the graphite moderated, natural uranium fuelled reactor could be readily adapted to electricity production by using pressurized carbon dioxide gas rather than low-pressure air to cool the reactor fuel. The heated carbon dioxide gas leaving the reactor would be passed through heat exchangers to produce steam to drive a turbine-generator to produce electricity. The plutonium produced in the fuel could then be used for military purposes or for a second purpose which was considered potentially attractive. This attraction arose because, unlike Canada and the U.S., neither Britain nor France possessed their own uranium reserves and were therefore dependent on importing their uranium. The attractive second purpose for plutonium was as fuel for a new type of reactor, called a breeder reactor. In this type of reactor, which is fuelled with both plutonium and uranium, more plutonium is produced from the uranium, than is used up - hence the term “breeder”. This type of reactor offered the potential for extracting far more energy per unit of uranium than other reactor types and, hence, would greatly reduce the dependency of these countries on the availability of imported uranium. As a result of these considerations, both countries embarked on major nuclear power programs based on the graphite moderated, natural uranium type of reactor as a first stage, to be followed, according to their long-range plans, by breeder reactors. Development of the latter has proven to be extremely difficult and costly and, as a result, both countries eventually switched to U.S. type light water reactors which proved to be more economic than the graphite moderated types which they earlier constructed. Both countries subsequently (France only very recently) abandoned the development of fast breeder reactors.

Returning now to the evolution of CANDU, we have discussed the reasons underlying the basic choice of natural uranium fuel and heavy water moderation. The next task was to evolve a suitable reactor design. In the early 1950’s, a team of engineers was established at Chalk River to undertake this task. They had available to them Canada’s several years of operating experience with the NRX reactor, which as noted earlier started operation in 1947. At the time the team was established, a new and much more powerful research reactor was under construction at Chalk River. This was NRU. It was designed to use natural uranium fuel and was both moderated and cooled with heavy water; in this latter respect it differed from NRX which used light water (from the Ottawa river) for cooling. The design of NRU also incorporated a further new feature which was the ability to change fuel while the reactor continued to operate at full power. This feature was considered particularly desirable for future electrical power production reactors since electricity production would not have to be interrupted by periodic shutdowns for fuel changing. While the team initially considered a number of possible alternative concepts, they decided to focus their efforts on a design which was generally similar to that of NRU but which could operate at much higher temperatures, this being necessary in order to produce steam at useful pressures for driving a turbine-generator unit. In order to achieve these higher temperatures, it would be necessary to operate the reactor at high pressure; hence, the NRU reactor structure would have to be replaced by a steel pressure vessel which would contain the reactor core, that is, the fuel and the heavy water moderator and coolant. In addition, the design of the reactor fuel would have to be changed to permit it to operate at high temperature. Fortunately such fuel was, at the time, being developed by the U.S. navy for their submarine program and the NRX reactor was being used, under contract, for the testing of this fuel. This provided Canada with a valuable technological base for the new fuel design.

By the mid-1950's the work of the concept team at Chalk River had advanced sufficiently for a decision to be taken to build a small-scale prototype reactor which was called the Nuclear Power Demonstration (NPD) reactor. Detailed design was undertaken by a team established by the Canadian General Electric Company at Peterborough. The design concept did, however, suffer from one fundamental problem and this related to the steel pressure vessel necessary to enclose the reactor core. Even for the small-scale prototype reactor, the size and weight of this pressure vessel exceeded available Canadian manufacturing capabilities. It was recognized that this problem would become much more severe in the case of the much larger reactors which would be necessary for full commercial operation in Canadian utilities. Fortunately, at the time, development work was well advanced in the U.S. for the production of tubes made of an alloy of zirconium which could withstand operation at high temperature and pressure and which did not absorb many neutrons. The availability of such tubes made it possible to construct a reactor which employed a large number of such tubes to contain the fuel and the high pressure and temperature heavy water coolant while being surrounded by the heavy water moderator which could operate at low pressure and temperature and could, therefore, be contained in a relatively light weight but large tank. This arrangement became known as a pressure tube reactor to distinguish it from the pressure vessel type of reactor earlier considered and was much better suited to Canadian manufacturing capabilities. Work as therefore stopped on the initial design of NPD and restarted employing the new pressure tube reactor arrangement. Thus the basic CANDU design, as we know it today, was established.

There is one further aspect of the question "why CANDU" which logically may arise in the minds of readers. Even though, as summarized in this monograph, the CANDU design was a logical development given the conditions that existed in Canada in the early days of the program, was its continued development logical as time passed and these conditions inevitably changed? To answer this question properly requires addition of more background information about later developments. However, the short answer is 'yes'. Given the generation needs of Ontario Hydro in the 1970's and 1980's there was no choice for further generating capacity in Ontario, other than to build CANDU plants. Fortunately, the research and development work had been largely done, so that Ontario Hydro could proceed to install large amounts of generating capacity using mostly local industrial capabilities. Expenditures were made predominantly within Canada, thus lessening the financial impact of this large program. Quebec and New Brunswick each installed single-unit CANDU stations. Quebec enjoys huge hydroelectric resources, so they did not need to install large amounts of nuclear capacity. New Brunswick has a relatively small requirement that has been satisfied over the last two decades by the one unit already in operation.

The more efficient fuel cycles available through CANDU will be a valuable phase in the development of nuclear power. They cannot be as efficient as breeder cycles, but there will be a long stretch of time when gradually increasing fuel efficiency (and broadening of fuel resources, including thorium) will be very useful. The design itself has considerable latitude for improvement while still retaining the good features of the original concept. And a nice thing about CANDU is that greater fuel efficiencies are realized in the same reactor, so cycles can be switched during the life of a reactor. Therefore, the investment in reactors is secure even in the face of a changing resource picture.

Of course when this continued development was started in the seventies it was thought that nuclear power would advance much faster than has, in fact, been the case. In addition, a large amount of new uranium has been discovered since that time. The need for more efficient fuel cycles would have been reached much sooner had these changes not occurred. As it happened, however, other countries also were interested in this type of reactor. By helping them Canada has established a broader base for the more efficient CANDU fuel cycles, although even the first of these may not be needed for fifty years. The need will come. In the meantime, a new and fully mature power source exists that is immune to fossil fuel shortages, emits no greenhouse gases, and which is economically competitive. This answers the question: 'Why CANDU?'