A Short History of the CANDU Nuclear Power System

by
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Summary:

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Executive Summary

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The CANDU system traces its origins to as early as 1898 when a leading pioneer in the field of atomic physics, Lord Rutherford, was appointed Professor of Experimental Physics at McGill University. The next 40 years saw steady progress in the understanding of the atom with Canadian scientists playing a significant role in this worldwide endeavor. With the advent of World War Il, Canada's program was joined by participants from other allied countries, particularly the U.K. This led to the establishment of the Chalk River laboratories and the development and construction of the early Canadian heavy water moderated research reactors ZEEP, NRX, and NRU.

By the early 1950's, the use of nuclear reactors for the commercial production of electricity was under development in several countries. After careful study of possible alternative reactor types, Canada chose to develop the heavy water moderated power reactor which became known as CANDU. This choice made best use of Canada's experience with heavy water research reactors and, of particular importance, enabled the use of Canadian uranium as reactor fuel without the necessity of enriching the uranium in foreign facilities. At that time all such facilities had been built and operated primarily for military purposes.

In 1955, the first small-scale prototype CANDU type reactor was committed as a joint undertaking by AECL, Hydro, and a private-sector company, Canadian General Electric (CGE). Named the Nuclear Power Demonstration (NPD), this reactor commenced operation in 1962, supplying 20 MW of electricity to the Hydro system. NPD was followed by the ten-fold larger prototype, Douglas Point, which commenced operation in 1967. Located at what later was to become Ontario Hydro's Bruce Nuclear Power Development site on Lake Huron, Douglas Point, together with NPD, established the technological base necessary for the larger commercial CANDU units to follow.

Construction of the first two such commercial units marked the beginning of what today is Hydro's eight-unit Pickering station. These two units, with a capacity of 500 MW each, were constructed under a tri-partite capital financing arrangement between Hydro, AECL, and the Ontario government. Prior to their completion, Hydro committed a further two units as a wholly Hydro investment. The four units came into operation during the period 1971 to 1973 and quickly established an excellent performance record.

Following the construction of the first four units of the Pickering station (called Pickering-A) Hydro proceeded with the four-unit Bruce-A station. Its 800 MW units came into operation in the late 1970's and were followed by four additional units at Pickering (called Pickering-B) and at Bruce (called Bruce-B). The latest four-unit Hydro station, Darlington-A, has two units now in commercial operation.

Canada made two early entries into the international power reactor supply field. As a first entry, assisted the Indian Dept. of Atomic Energy in the construction of a 200 MW reactor Douglas Point type (RAPP-1). Subsequent assistance in the construction of a sister m .~L t~xAPP-2) was terminated in 1974 following India's detonation of a nuclear device. The second entry was the supply to Pakistan, by CGE, of a 120 MW CANDU reactor. CGE had developed this design on the basis of its earlier work in the design of NPD. Following this successful commercial sale, CGE had hoped to expand its markets for CANDU-type plants, both domestically and offshore. Despite a major effort, these hopes were not realized and CGE subsequently decided to abandon the reactor supply market and concentrate its future nuclear business on the supply of fuel and fuel handling systems for CANDU reactors.

With the withdrawal of CGE from the reactor export market, the lead role passed to AECL. In this new role, AECL inherited a CGE conceptual design for a single-unit CANDU based on the Pickering design. With its power increased from Pickering's 500 MW to over 600 MW, this new design (called CANDU-6) was adopted by Hydro Quebec for its Gentilly-2 station and by New Brunswick Power for its Point Lepreau station. AECL sold two sister units, one to Argentina (Embalse) and one to South Korea (Wolsong). These four units, when completed in the early 1980's, quickly established excellent operating histories which have continued to the present date. The four operating units are now being followed by five sister units under construction in Romania and by three sister units being constructed in South Korea.

With the successful CANDU-6 design well established, AECL is developing two further CANDU designs, a smaller (450 MW) CANDU-3 and a larger CANDU-9 in the 900]MW range. These new designs will build on well-proven CANDU technology and offer utilities significant improvements in cost, construction schedule, operability, and safety.

The foregoing major CANDU construction program saw a gradual change in the respective engineering roles of Hydro and AECL. The close working partnership which marked the early NPD, Douglas Point, and Pickering-A projects, moved to an arrangement whereby Hydro undertook, with its own staff, much of the detailed design work which AECL had earlier performed. This effectively resulted in there being two CANDU design teams in Canada. As a consequence, there was an erosion of the close technical coordination which had earlier existed between the two organizations. During the past few years, Hydro and AECL have recognized that close technical coordination would be in the interest of both parties as well as the Canadian nuclear program. As a result, they established a joint executive-level CANDU Engineering Authority to pursue this objective.

Since its outset, the CANDU program has been strongly influenced by a recognition that safety of the public and plant personnel is of paramount importance. This recognition has led to the development of comprehensive Canadian reactor safety principles which govern the design and operation of CANDU units. The Atomic Energy Control Board (AECB), licenses the design, construction, and operation of these units on the basis of demonstrated adherence to these safety principles and to detailed criteria established by the AECB.

No history of the CANDU program would be complete without reference to the vital role played by research and development (R&D) programs in establishing CANDU's underlying technological base. While the majority of these R&D programs have been carried out at AECL's Chalk River and Whiteshell laboratories, important contributions have been made by programs in Hydro's Research Division, in universities and other laboratories, and within Canadian manufacturing industries. Funding for much of the overall CANDU R&D program came, in the early years, from the federal government. More recently, however, the Canadian utilities operating CANDU units are funding a substantial share of the program through the CANDU Owners Group (COG).

From an overall perspective, the successful development of the CANDU system represents a major Canadian accomplishment. This was recognized in 1987 by the Canadian Engineering Centennial Board in selecting CANDU as one of the ten most outstanding Canadian engineering accomplishments during the past century. This accomplishment owes much to the close collaboration between AECL, Hydro, other Canadian utilities, and private sector manufacturing and engineering companies which has marked the CANDU program since its outset. Many sectors of the Canadian public have benefited from the program through lower electricity rates, through reduced emissions of acid gases and carbon dioxide, through increased markets for Canadian uranium, through reductions in purchases of foreign coal and oil, and through the creation of high technology job opportunities. CANDU technology today ranks well against the best competitive technologies in other countries. For the future, the inherent advantages of heavy water moderation offer the potential for CANDU technology to maintain its enviable position.

A Short History of the CANDU Nuclear Power System

1. Introduction

This paper provides a summary of the history of the evolution of the CANDU nuclear power system with emphasis on the role played by Ontario Hydro and by Ontario-based private sector companies in this evolution. While Atomic Energy of Canada Limited (AECL), as the federal government agency charged with responsibility for developing the peaceful applications of nuclear energy, played the central role in CANDU development, its close collaboration with Ontario Hydro was key to success. Ontario Hydro brought to the collaborative effort not only a definition of utility requirements, which subsequently shaped the evolution of CANDU, but also its extensive and successful experience in power plant engineering, construction, commissioning, and overall project management.

The paper commences with the early history of nuclear research in Canada. This research established the fundamental technological base upon which the CANDU system was subsequently founded in the 1950's. This early history is followed by sections discussing the evolution of CANDU from initial conceptual studies to the first experimental CANDU unit, NPD, followed by the first semi-commercial-scale unit, Douglas Point, and then by the first full commercial station, Pickering-A. The discussion then moves to Canada's early CANDU export projects, RAPP in India and KANUPP in Pakistan. This is followed by a section covering the CANDU-6 projects (both export units and the domestic units provided for Hydro-Quebec and New Brunswick Power). The discussion continues with a review of the recent evolution of two new CANDU variants - a smaller unit, the CANDU-3, and a larger unit, the CANDU-9. This is followed by a discussion of the Ontario Hydro CANDU projects which followed Pickering-A and of the changing roles played by Hydro and AECL in these projects. The paper continues with a summary discussion of the evolution of the Canadian reactor safety approach and nuclear regulatory process which, together, played major roles in shaping the history of CANDU. The paper concludes with a discussion of the vital role played in the history of CANDU by the supporting research and development (R&D) programs.

2. The Early History*

The start of Canada's nuclear story can be dated from 1898 with the appointment of Ernest Rutherford as Professor of Experimental Physics at McGill. Rutherford was a New Zealander and was the first of many distinguished scientists to come to Canada over the years that followed. In the book "Radio-Activity", published in 1904, Rutherford discussed much of his experimental work at McGill. He calculated that a single gram of radium would emit 876,000 calories of heat per year and commented "there is thus reason to believe that an enormous store of latent energy is resident in the atoms of the radio-elements". (1)

* Much of the text in this section is taken directly from Appendix A1 of "The Role of Nuclear Power in Ontario", a Submission by the Canadian Nuclear Association to the Royal Commission on Electric Power Planning, August, 1976.

Rutherford returned to Britain in 1907 and later succeeded Sir J.J. Thomson as head of the world-renowned Cavendish Laboratory at Cambridge. (2) It was at this laboratory that James Chadwick identified the neutron in 1932. It was also to this laboratory that Dr. Hans von Halban and Dr. Lew Kowarski took the then total world stock of heavy water (less than 200 kilograms) in 1940, when they were forced to flee from France by the German conquest.

At this early stage of the war, Dr. George Laurence was carrying out the earliest experiments in fission at the National Research Council Laboratories in Ottawa. (3) His source of neutrons was beryllium mixed with a radium compound in a metal tube about 1 inch long. The moderator (the medium for slowing down the neutrons) was 10 tons of calcined petroleum coke (a form of carbon) and the uranium was in the form of 1/2 ton of black oxide in paper sacks distributed between larger paper sacks of the coke. Much was learned from this primitive "pile" (subsequently a commonly used term for a nuclear reactor), particularly the need for greater uranium and carbon purity if a self-sustaining fission "chain" reaction was to be achieved. (4) In fact, it was just in this way that Enrico Fermi was to achieve a chain reaction in the first successful reactor on December 2, 1942. (5)

Also in 1942 the western allies agreed to move the majority of the personnel engaged in nuclear work from Britain to Canada. The first group, comprising two Austrians, two Frenchmen, two Germans, a Czech, and two Britons arrived in Canada in December. Dr. C.J. Mackenzie, then head of the NRC, said later that the deciding consideration leading to Canada's agreement to host this group and their work 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. (6) The work in Canada was part of a tripartite arrangement between Canada, Britain, and the U.S.A. The Canadian effort concentrated on (i) reactor design; (ii) how it would be shielded to protect the operators from radiation; (iii) how the used fuel would be removed and stored safely; (iv) how the operating power of the reactor would be controlled; and (v) the accumulation of scientific data for the extraction of plutonium and uranium-233 produced in the reactor fuel. This early work at Montreal was the first foundation for the highly successful United Kingdom plutonium separation plants at Windscale in the postwar years. (7)

Central to the work of the Canadian team was the choice of type of reactor to be pursued. Experiments had shown that fission of the reactive isotope contained in naturally occurring uranium, Uranium-235, could best be achieved if the neutrons striking the U-235 atoms were travelling at low velocity. On the other hand, nature dictates that neutrons produced from such fission are released at very high velocities. Hence, it was recognized that, in order for a self-sustaining fission chain reaction to be achievable, the reactor must not only contain uranium but also some medium capable of slowing down the neutrons produced from the fission process Furthermore, it was recognized that this medium, termed a "moderator", must not absorb too many neutrons while slowing them down; otherwise the fission chain reaction could not be sustained. Experiments showed that only three practical candidate media had the necessary combination of the foregoing properties. These were carbon (in the form of graphite), beryllium, and heavy water (a form of water existing in nature in which the hydrogen atoms are the "heavy" isotope, deuterium). Graphite had already been chosen by the United States for their first reactors. Hence, there seemed little point in Canada duplicating the efforts of one of its wartime allies. The second candidate, beryllium, was, at the time, little more than a laboratory curiosity; furthermore, it was known to be toxic to humans under certain conditions. The third candidate, heavy water, while in scarce supply at the time, was the best of the three candidate materials in terms of its properties as a moderator. Furthermore, since heavy water is chemically identical to ordinary water, it properties as an engineering material were well understood.

In light of the foregoing considerations, the leaders of Britain, the U.S., and Canada jointly decided that the team in Canada would proceed with the design and construction of a heavy water moderated nuclear reactor and that the project would be directed by Dr. John Cockroft, also from the Cavendish Laboratory. This was to become the NRX (National Research X-perimental) reactor. In August of 1944 a site was selected for the location of this reactor. (8) In order to study various reactor physics problems, it was also decided, at the same time, to build a zero energy experimental pile (ZEEP), under the direction of Dr. Lew Kowarski. (9) On September 5, 1945, ZEEP achieved a self-sustaining chain reaction, the first outside of the United States.

With the ending of World War II, the Canadian government was faced with the question of the future of the fledgling Canadian nuclear program. A key step in redirecting the program to peaceful applications was the passage of the Atomic Energy Control Act by Parliament in May of 1946. This Act established the Atomic Energy Control Board which would have "control and supervision over the development, application and use of atomic energy in Canada". (10) In December, 1946, the Board assumed responsibility for the recently established nuclear program facilities at Chalk River, Ontario. The Board then assigned operating responsibility for these facilities to the National Research Council, establishing what was called the Atomic Energy Project.

Also with the ending of World War II, Dr. Cockcroft was recalled to direct the post-war British nuclear program, and was replaced by Dr. W.B. Lewis, who arrived in Canada in September, 1946. Lewis had also worked under Rutherford at Cambridge and had been in charge of much of the British radar development work during the war.

On July 22, 1947, NRX achieved a self-sustaining chain reaction (criticality) for the first time. (11) NRX proved to be a most successful design of reactor and is still in part-time operation today. Near copies were later built in India (under the Colombo plan) and in Taiwan (a commercial venture).

In December, 1950, federal government approval was given to build a much larger research reactor, NRU (National Research Universal). This reactor would provide intense beams of neutrons for research and materials irradiation, for the production of cobalt-60 and other radioisotopes for the treatment of diseases and use in industry. It would also produce plutonium for sale to the U.S.A. (12) at a time when the Cold War was at its height.

NRU achieved first criticality on July 22, 1957, exactly 10 years after NRX first achieved criticality. Its neutron flux (a measure of the power and usefulness of the reactor) was five times that of NRX giving it the highest flux of any research reactor in the world at that time. The reactor was entirely designed in Canada and essentially all components were manufactured in Canada. (13) Its subsequent outstanding operating history is a testament to the quality of this Canadian enterprise. NRU, together with its elder sister, NRX, laid the vital technological foundation which paved the way for the subsequent CANDU program. Of particular note, NRU incorporated advanced technology enabling reactor fuel to be changed while the reactor remained in full operation. This ability to refuel without shutting down the reactor was a world "first" and was, subsequently, to play an important role in the success of the CANDU power reactors as described in later sections of this evidence.

3. The First CANDU Project - NPD

As early as the fall of 1949, Dr. Lewis, as technical director of the Atomic Energy Project, outlined to a group of Canadian MP's, who were visiting Chalk River, his vision for the use of nuclear fission as a source of electrical energy. (14) At that time, the NRX reactor produced a significant amount of energy (20 MW) as a by-product of its primary role as a producer of neutrons. This energy was, however, released into the reactor's cooling water at too low a temperature to be of use for producing electricity. This was also to be the case for the new NRU research reactor. To produce electricity on a commercial scale, operating temperatures of reactors would have to be greatly increased.

In early 1952, C.D. Howe, then Minister of Energy, Mines and Resources, took a key decision towards realization of Lewis's vision by establishing a new crown corporation, Atomic Energy of Canada Limited (AECL). AECL took over the assets and responsibilities of the Atomic Energy Project. (15) A second key decision by Howe was taken in June of 1954 with the separation of AECL from the Atomic Energy Control Board (AECB). (16) These decisions provided AECL with the flexibility of action necessary for the realization of Lewis's vision since, as a crown corporation, it would report directly to the Minister. At the same time, the separation of AECL from the AECB permitted the latter to devote its full attention to the independent regulation of the Canadian nuclear program.

A further important step in the launching of the Canadian nuclear power program was taken by Howe in appointing four senior Canadian utility representatives to AECL's first Board of Directors (Messrs. Dupuis, Gaherty, Massue, and Hearn). (17) Of particular importance, as events unfolded, was the appointment of Hearn since he was the Chief Engineer of the Hydro Electric Power Commission of Ontario (to later become Ontario Hydro). Hearn, together with his Chairman, Robert Saunders, were attracted to the concept of nuclear-generated electricity because Ontario was running out of undeveloped hydraulic capacity and would otherwise have to rely for future additional capacity on increasing use of coal-fired generation employing imported and relatively costly U.S.

coal. (18)

By the end of 1953, Hydro and AECL had agreed to proceed with a jointly-funded feasibility study aimed at defining a possible pilot nuclear power plant. Of particular significance was the joint decision that the team undertaking this study should be led by a senior Hydro engineer, Mr. Harold Smith (who later became Hydro's Chief Engineer). (19) In addition to other Hydro and AECL engineers, the initial team included Mr. John Foster from the Montreal Engineering Company. The makeup of this early team established the key concept of a close collaborative approach to developing nuclear power in Canada. This concept is widely recognized as having been crucial to success of the program.

On the technical front, by the time the study team was formed, the heavy water moderated, natural uranium fuelled reactor concept was considered to be the first choice. As discusssed above, Canada's reactor experience was centered on heavy water moderation. Furthermore, Canada possessed sizeable resources of uranium but did not possess uranium enrichment capabilities or the related technology. The United States had developed uranium enrichment technology during the war as one route to the atomic bomb. Uranium enrichment involves the process of artificially increasing the abundance of the U-235 isotope in uranium (less than 1% of uranium as found in nature consists of this isotope). Very highly concentrated U-235 is necessary to enable the fission process to proceed efficiently in this application. While this isotope enhancement technology was, at the time, still highly classified by the U.S. government, available information clearly showed that the costs of Canada pursuing the development of such technology solely for non-military purposes would be prohibitive. Hence, alternative reactor types requiring enriched uranium fuel, such as the light water moderated reactors, were not considered appropriate for Canada given that enriched uranium was, at the time, unavailable through normal internationally-based commercial sources.

The fundamental decision as to basic reactor type was not, however, taken solely with this consideration in mind. As a final step in the process, in late 1954, a team comprising members of the AECL Board of Directors, together with Dr. Lewis, visited key experts in both the British and American nuclear power programs to confirm the status of these programs, thereby ensuring that there would be no last-minute surprises in terms of the merits of alternative reactor concepts. (20) Subsequently the AECL Board approved, in principle, proceeding with the design and construction of a small demonstration reactor. The Board stipulated that seven private Canadian companies be asked to submit proposals for this work. AECL undertook to provide necessary nuclear-related technical data to the companies developing proposals and also undertook responsibility for subsequently supplying nuclear fuel, heavy water, and appropriate expert personnel from its staff to the envisaged project. (21)

Meanwhile, certain key features of the design concept were being firmed up by the study team under Smith. These included the basic specifications for the reactor pressure vessel, the use of heavy water as reactor coolant as well as moderator (pioneered in the NRU reactor), and the use of on-power refuelling (also pioneered in NRU). The envisaged use of a pressure vessel to contain the reactor core was a natural outgrowth of the NRU reactor design. By placing an NRU-type core inside a thick-walled steel pressure vessel and pressurizing the heavy water coolant and moderator to about 100 times atmospheric pressure, the operating temperature of the coolant could be increased from less than 100 degrees Celsius (as in NRU) to about 300 degrees Celsius. At this much higher temperature, a steam turbine could operate at reasonable efficiency in driving an electrical generator, whereas, as noted earlier in this section, the low operating temperatures of the NRX and NRU reactors made electricity generation impractical.

A further key feature of the selected design concept was the use of a zirconium alloy as the fuel cladding material. The function of the fuel cladding is to provide a strong, corrosion-resistant barrier between the coolant and the uranium fuel itself. In performing this function, the cladding must be essentially "transparent" to neutrons passing from the heavy water moderator to the uranium fuel. Zirconium is the one metallic element existing in nature which can meet this combination of requirements. Through alloying with small quantities of other elements, a highly satisfactory family of zirconium-based fuel cladding materials has evolved, called "Zircaloy". The original development of Zircaloy was the result of work by the U.S. Atomic Energy Commission and its contractors. Then-current collaborative agreements made Zircaloy available to the Canadian program.

Early in 1954, proposals were received by AECL from the private companies interested in undertaking the design and construction work. The chosen bidder was Canadian General Electric (CGE), both because of its broad-based engineering and manufacturing capability and also because of its offer to contribute significant funding to the program. Attention now turned to securing a Canadian utility partner. Ontario Hydro's offer to participate through providing the conventional portion of the power plant and undertaking to purchase the steam from the nuclear portion to power the conventional portion was accepted by AECL. The foregoing arrangements were approved by the federal cabinet on March 23, 1955. (22)

Work now commenced on the design of the reactor at CGE's offices in Peterborough. Several members of the joint study team moved to Peterborough to join the CGE team. The remainder, under Harold Smith, stayed at Chalk River to work on the conceptual design of a much larger unit (200 MWe) intended to follow the smaller unit. The smaller unit was named the Nuclear Power Demonstration (NPD) reactor. The construction site was chosen near Ontario Hydro's Des Joachim hydraulic generating station on the Ottawa River. This site was ideal in several respects, viz., access to the Des Joachim power transmission lines, access to cooling water from the Ottawa River, and close proximity to AECL's Chalk River laboratory.

By October, 1955, a further key technical decision had been taken. This involved the switch from uranium metal as the fuel material to uranium dioxide which had shown several superior properties during testing carried out for the U.S. navy in the NRX reactor at Chalk River. These superior properties included excellent dimensional stability during irradiation in the reactor core. Uranium metal, used earlier in NRX and NRU, was not dimensionally stable over the long irradiation periods required in a commercial power reactor for reasons of fuel economy. This instability could cause rupture of the fuel cladding, permitting the heavy water coolant to come into direct contact with the uranium. Since the corrosion resistance of uranium metal is very poor, the coolant would quickly become contaminated with uranium corrosion products and also radioactive fission products contained in the uranium. In this respect, the second superior property of uranium dioxide is its much greater corrosion resistance; hence, should a defect in the fuel cladding occur, for whatever reason, the rate of corrosion of the uranium dioxide would be slow. The plant operator would, therefore, be provided with ample time to locate and replace the faulty fuel before the heavy water coolant could become seriously contaminated.

While work on the detailed design of NPD proceeded, the team under Smith at Chalk River reached a conclusion of major importance regarding the larger reactor, viz., that it should be of the pressure tube type rather than of the pressure vessel type. This conclusion was driven by the fact that the pressure vessel required for the larger reactor would be far bigger and heavier than could be manufactured in Canada with any existing facilities. Even the much smaller NPD vessel had been ordered from the U.K. for this reason. The pressure vessel required for the larger reactor would have had a diameter of about fifteen feet, would have weighed several hundreds of tons, and would have required the fabrication of ring and head forgings of thicknesses in the range of ten inches. Even today, there are no manufacturing facilities capable of producing such large forgings or fabricating the complete vessel in Canada. A further major consideration was the fact that by this time in 1957, contractors for the U.S. Atomic Energy Commission had established a viable fabrication process for zirconium alloy pressure tubes intended for the Hanford New Production Reactor. The availability of zirconium pressure tubes meant that a practical pressure tube reactor could be built to use natural uranium fuel. This major conclusion then posed a vital question with respect to NPD. Should it continue as a pressure vessel reactor or should it be redesigned as a pressure tube reactor? While the latter alternative would involve a major project delay and additional costs, the AECL Board took the difficult decision to redesign NPD as a pressure tube reactor in March, 1957. (23)

Once the decision was taken to move to a pressure tube design, the question of core orientation arose. Should the reactor core be vertical, as in the case of NRX and NRU, or would a horizontal orientation prove superior i.e., one in which the pressure tubes would be horizontal in the reactor core? The horizontal orientation was selected for reasons related to the desired means of refuelling the reactor. As in the case of NRU, this was to be done with the reactor operating at full power to avoid the need for reactor shutdowns. A simple "push-through" refuelling arrangement was desired since it would avoid any necessity of mechanically tying the individual fuel assemblies (called bundles) together within the pressure tubes. The scheme called for two identical fuelling machines to be employed, one temporarily connected to each end of the pressure tube being refuelled. One of the machines would push in the desired number of new fuel bundles, displacing the same number of spent bundles into the other machine. These basic features of the refuelling arrangements have been retained in all subsequent CANDU reactors.

NPD incorporated several safety features which have been retained in all subsequent CANDU reactors. These include:

- functional and physical separation of the safety systems (those dedicated to the prevention or mitigation of accidents) from the systems utilized for normal plant operation. This ensures that failures of the latter-type systems do not disable safety functions.

- comprehensive testability of safety systems with the reactor remaining in full-power operation

- capability to remove residual heat from the reactor core, following reactor shutdown, by gravity (passive) coolant circulation

- safety shutdown of the reactor by "fail-safe" logic and gravity (passive) actuation

- capability to replace coolant in the reactor core in the event of a failure in the reactor coolant system

- provision of a containment envelope surrounding the reactor and its normal cooling system which would prevent the escape of radioactive materials to the environment following accidental releases of such materials from the reactor

The redesigned NPD was for a period referred to as NPD-II but the "-Il" was in due course dropped. NPD was completed in 1962 with first criticality being achieved on April 11. Operated by Ontario Hydro, NPD was to enjoy a long and successful operating life, providing invaluable experience to later designs and serving for many years as a vital training facility for later generations of Ontario Hydro operating staff needed for the new commercial power stations. NPD was taken out of service in 1987 when its early-generation pressure tubes had reached the end of their service life. By this time, NPD had well fulfilled its original intended purpose and the cost of retubing the reactor could not be justified in view of its small electrical generation capacity.

4. The Second CANDU Project - Douglas Point

As already noted in the previous section, the original joint concept team under Harold Smith was divided with the commencement of the detailed design of NPD. Smith and others remained at Chalk River to undertake the conceptual design of a larger reactor while the remainder joined the NPD team. By April of 1957, AECL proposed, and Ontario Hydro agreed, that the work of Smith's reformed team should be transferred to Toronto "under Hydro auspices"(24) with Smith leading what was then called the Nuclear Power Plant Division (NPPD) of AECL. In the spring of 1958, the new large reactor concept was named CANDU (CANadian Deuterium Uranium), which subsequently became the generic name for all Canadian reactors of this type. By 1959, Smith had become Chief Engineer of Ontario Hydro. John Foster, on loan from the

Montreal Engineering Company to AECL since 1953, was appointed to lead NPPD. (25) At this time, the NPPD team comprised about 30 people, with roughly half comprising AECL staff augmented by staff seconded from the John Inglis Co., Montreal Engineering, Babcock and Wilcox, Canadian Vickers, Dominion Bridge, Orenda Engines, John Thompson Leonard, Montreal Locomotive, and Dilworth Ewbank. (26) The remaining half was provided by Ontario Hydro. As would be expected, the AECL people concentrated on the nuclear portion of the work and the Hydro people on the conventional power plant side. (27) In addition to the full-time team members, representatives from the manufacturing sector assisted in equipment specification. Ontario Hydro provided expertise from its construction, project management, commissioning, and operating teams. The power output of the proposed unit was firmed up as 200 MW electric, a compromise to achieve near commercial size while representing what was thought to be a prudent scale-up from the existing experience base. AECL received approval from the federal cabinet to proceed with the project on June 16, 1959. (28)

Arrangements between AECL and Ontario Hydro called for the project to be owned and managed by AECL with Ontario Hydro providing conventional plant design, construction, commissioning, and subsequent plant operational services. Power would be sold to Ontario Hydro in accordance with a formula based on avoided costs of producing power from Hydro's Lakeview coal-fired power plant. The chosen construction site was located at Douglas Point on the shores of Lake Huron, now the location of the Bruce nuclear power complex. On June 24, 1959, Hydro decided to proceed with the acquisition of the necessary land. (29) With this step accomplished, the Douglas Point project was fully launched.

Douglas Point achieved criticality on November 15, 1966 and delivered its first electricity to the Hydro grid on the following January 7th. Not surprisingly, considering its prototypical nature, Douglas Point encountered a number of early operating problems as, indeed, did NPD before it. The most notable of these problems included excessive leakage of the heavy water coolant from certain components such as flanges and valves, inadequate facilities for the recovery of coolant leakage, and the deposition of radioactive corrosion products on the inner surfaces of the coolant system pipework. (30) Nevertheless, once these problems were overcome, Douglas Point operated successfully for many years, providing invaluable experience which benefitted the later Hydro and other commercial CANDU units. Douglas Point was removed from service in 1984 since replacement of its pressure tubes, which were nearing the end of serviceability, could not be economically justified, considering the relatively small electrical output of the unit.

5. The First Commercial CANDU Units - Pickering-A

In June of 1963, with Douglas Point under detailed design and construction and NPD in its early operating phases, agreement was reached between Ontario Hydro and AECL to commence the conceptual design of a 500 MW electric CANDU unit. (31) This was undertaken by a small team of engineers in AECL's NPPD. The unit size was chosen to match that of the 500 MW coal-fired units of Hydro's new Lambton station (comprising four such units) and represented a unit size which previous studies had indicated would permit the economics of a CANDU unit to compare favorably with those of a Lambton unit. With the smaller 200 MW Douglas Point prototype, economic comparability could not be achieved. The conceptual work, as it progressed, drew heavily on the design of Douglas Point and on the early operating experience gained with NPD. This ensured continuity in the ongoing evolution of CANDU. Since Ontario Hydro had experienced significant capital and operating cost advantages with the integrated multi-unit approach employed in the Hearn, Lakeview, and Lambton coal-fired plants, this basic plant layout configuration was adopted for the conceptual design of the nuclear units.

One major design departure was adopted for the reactor itself, relative to Douglas Point and NPD, viz., a change to the internal diameter of the pressure tubes. This was increased from approximately 8 cm to approximately 10 cm with a corresponding increase in the number of fuel elements per fuel bundle from 19 to 28. In the interest of conservatism, the size of the individual fuel elements was not changed. This change in pressure tube diameter was not undertaken lightly and was carefully considered and debated within the technical communities of both Hydro and AECL. (32) The final decision in favor of adopting the larger diameter was basically determined by the projected economic advantages, primarily in plant capital cost. This advantage was judged to outweigh the development costs and risks involved, a judgment which was subsequently proven correct.

In preparation for the commitment of a station incorporating the new conceptual design, negotiations for a commercial agreement between AECL, Ontario Hydro, the federal government, and the Ontario provincial government were commenced in September of 1963. As an outcome, Hydro agreed to proceed with two 500 MW units as the first stage of what was to become the Pickering-A Generating Station. The commitment of two units at the same time permitted economies of planning, manufacturing, and construction through the sequencing and sharing of both facilities and personnel. The financing arrangement called for Hydro to contribute to the capital cost at a level corresponding to two comparable coal-fired units (based on the Lambton plant). The federal government, through AECL, and the provincial government would provide, respectively, 54% and 46% of the additional capital funds required for the nuclear units as compared to the Lambton coal-fired units. The Agreement called for the federal and provincial governments to recover their investments through proportional sharing in the savings in total generating costs realized by Hydro as compared to the Lambton coal-fired units. (33)

By the Spring of 1964, the conceptual design work had progressed sufficiently to serve as the basis for project approval by the Hydro Board. Hydro's preferred site, immediately adjacent to the community of Bay Ridges on the eastern extremity of Metro Toronto, offered the major advantage of short interconnecting power lines to the Cherrywood Transformer Station just north of Lake Ontario. Via Cherrywood, the power would be supplied to Hydro's 500 kV transmission system feeding the major load centers in the Toronto/Hamilton/Niagara triangle. The close proximity of the preferred site to Metro Toronto did, however, raise a question of licensability by the AECB. The Hydro/AECL design team met this challenge by introducing a highly innovative containment concept - what was to become known as the negative pressure containment system. Central to the system is a large reinforced concrete building operated at a high level of vacuum (hence, the name "vacuum building"). This building is linked to the individual reactor buildings via a duct system and a number of parallel isolating valves. These valves are normally closed, permitting the reactor buildings to operate at normal atmospheric pressure. Should an accident arise, leading to a pressure rise in a reactor building, this pressure rise will actuate the isolating valves, thereby opening a flow path from the reactor building to the vacuum building. As a result, the pressure in the reactor building is quickly reduced to below atmospheric pressure, thereby positively preventing the escape to the environment of any radioactivity released inside the reactor building as a result of the accident.

Based on this novel and powerful containment system, an application for approval of the preferred site was made to the AECB late in 1964. Following Hydro's then recently adopted practice of naming its generating stations after the township in which each is located, Pickering was chosen as the name of the proposed station. Following site approval by the AECB, the preliminary safety report was completed and submitted to the AECB in support of a formal request for construction approval. This was granted in 1966.

In organizing the Pickering project, Ontario Hydro undertook responsibility for the overall project management, construction, and commissioning, together with responsibility for the design of the conventional parts of the units as well as all civil structures, including the reactor and vacuum buildings. AECL's NPPD undertook the design of the nuclear systems and the overall plant control center. NPPD continued to employ a number of senior Hydro engineers in design, development, and program management roles. Of particular note, Mr. W.G. Morison served as chief engineer for NPPD's work throughout most of the design program before his return to Hydro in early 1969. Pickering, therefore, represented a high level of technical collaboration between Hydro and AECL.

With the launch of Units 1 & 2, Hydro decided in 1965 to proceed with Units 3 & 4 of Pickering-A on a schedule that would result in the four units being completed at yearly intervals. Experience at Lambton and further scheduling studies indicated that such intervals represented a desirable optimization in the use of construction forces and equipment as well as the facilities and work forces of the equipment suppliers. In the latter case, Hydro was able to negotiate favorable extensions to the great majority of the equipment supply contracts originally placed for the first two units. This approach was also desirable in terms of ensuring identicality between all four units to the benefit of operating and maintenance efficiency. In contrast with the financing arrangements for the first two units, discussed above, Hydro itself provided full project financing for the second two units. The overall project organization and division of responsibilities amongst the participants remained unchanged, however. As would be expected, this was of great benefit in ensuring a smooth transition from a two-unit to a four-unit project.

The four units of Pickering-A came into service in the years 1971 to 1973. The reduction in completion intervals between the units resulted from the fact that most problems arose and were resolved during construction of the first unit with subsequent benefit to the schedule of the later units. In contrast to the early operating history of NPD and Douglas Point where numerous prototypical problems were encountered, the Pickering units quickly established a world-class operating record, convincing proof of the benefit of experience gained with the earlier prototypes. The four Pickering-A units achieved an overall average capability factor of 75% during the period from the in-service date of each unit (1971 through 1973) to the end of 1977. This was achieved despite the adverse effects of the shutdowns necessitated by an operators' strike in 1972 and the need to replace a number of incorrectly installed pressure tubes in Units 3 & 4 towards the end of the five year period. (34)

6. The Early Export of CANDU Reactors

The export of CANDU reactors commenced relatively early in the history of the CANDU program. Following the successful completion of the Canadian-supplied CIR research reactor at a site near Bombay in India, the Indian Dept. of Atomic Energy (DAE) was anxious to take the next step towards an indigenous Indian nuclear power program, based on the natural uranium, heavy water moderated type of reactor. India was attracted to this type of reactor because, like Canada, it did not possess its own uranium enrichment capability. Furthermore, India has very large reserves of thorium which could be utilized in this type of reactor to provide it with long-term fuel supply independence. In November of 1960, Homi Bhabha, Chairman of the Indian DAE, visited Canada to discus possible arrangements for power reactor cooperation. (35) At that time, he became interested in the Douglas Point reactor design, despite the fact that the detailed design program was still in its early stages. Following this visit, an extended series of negotiations commenced between AECL and the DAE with issues of financing and non-proliferation safeguards proving particularly difficult. (36) Finally, with the approval of the Canadian and Indian governments, an agreement was signed between AECL and the DAE in December of 1963, permitting the Rajastan Atomic Power Plant (RAPP) project to proceed. The agreement called for the design to be closely patterned on that of Douglas Point but modified, as appropriate, to maximize possible participation by Indian manufacturers in the supply of equipment since India saw this first unit as the prototype of a series of indigenously supplied reactors.

With the launching of the RAPP-1 project, the Indians wished to proceed quickly with a second unit, RAPP-2. Agreement was eventually reached between AECL and the DAE to proceed with RAPP-2 despite further difficulties regarding the non-proliferation safeguards issue, a topic of intense international negotiations at the time. The design of RAPP-2 was basically a copy of RAPP-I but incorporated some lessons of experience and certain changes to permit an even greater participation by Indian manufacturers. RAPP-1 was completed in 1973; however, the detonation, in 1974, by India of a nuclear "device" overtook completion of RAPP-2. As a result of the detonation, Canada ceased to provide India with any support of its nuclear power program. The DAE eventually completed RAPP-2 in 1981 without further Canadian support.

The second export of a CANDU reactor was to Pakistan. Pakistani interest in CANDU paralleled that of India and for many of the same reasons. In early 1961, Dr. Usmani, then chairman of the Pakistan Atomic Energy Commission (PAEC), visited Canada for discussions with AECL respecting possible collaboration in the nuclear energy field. (38) By the spring of 1962, PAEC interest became focused on an 80 MW electric version of NPD which CGE had been developing as a possible product for its entry into the CANDU export market. Ongoing negotiations between the PAEC and CGE led to increasing the power output to 132 MW to take advantage of improved size-related economics of power generation. (39) By the end of 1964, negotiations had reached the stage of a letter of intent with a formal contract coming into force the following year for the "turn-key" construction of the Karachi Nuclear Power Plant (KANUPP) by CGE. The KANUPP plant entered commercial operation in December of 1972. (40)

With the successful sale of the KANUPP plant, CGE pursued other potential international markets in countries such as Finland, Yugoslavia, and Argentina but was unsuccessful. By the late 1960's, CGE had decided to abandon the international reactor supply market, leaving AECL to pick up the leadership in the drive for CANDU exports. There were a number of reasons underlying CGE's decision, including the lack of a domestic Canadian market since Ontario Hydro did not wish to tie itself to what would have been a monopoly private sector supplier. (40) There is also little doubt that the lack of a successfully operating commercial-scale CANDU unit at the time impeded CGE's marketing efforts. This obstacle to CANDU exports was not fully overcome until the Pickering units began successful operation in the early 1970's.

7. The CANDU-6* Units

As noted in the previous section, in the late 1960's AECL inherited the leadership role in the drive to export CANDU reactors. Using an adaptation of the Pickering design in a single-unit configuration (this had been conceptually developed by CGE designers to suit the needs of most prospective international customers), AECL continued the Canadian marketing efforts in a number of countries. At the same time, AECL sought interest by Canadian utilities in such a single-unit design. On the technical side, the AECL designers continued to evolve the conceptual design so as to take advantage, not only of Pickering design and development experience, but also of the new innovations being developed for Ontario Hydro's Bruce reactors. These innovations included upgrading the power output from Pickering's 500 MW electrical to in excess of 600 MW. This was made possible by utilizing the improved fuel design then being developed for the Bruce reactors. Advantage was also taken of the development of larger steam generators and primary coolant pumps for Bruce as a means of reducing capital cost. The twelve steam generators and sixteen main coolant pumps employed in the Pickering design were replaced by four steam generators and four main coolant pumps. This resulted in a major simplification in the reactor coolant system pipework. Also following the Bruce lead, the design of the reactor itself was simplified by the replacement of the hybrid Picketing safety shutdown system. This hybrid system utilized a fast draining of the moderator (moderator dump) augmented by gravity-actuated mechanical shutoff rods (tubular elements containing neutron absorbing material). The augmentation was necessary because of Pickering's larger reactor size as compared to the smaller NPD and Douglas Point reactors. As in the case of Bruce, the new safety shutdown arrangements included two independent systems, each fully capable of handling all accident situations. The first system comprised a larger number of mechanical shutoff rods of the Pickering type whereas the second comprised a series of injection nozzles through which a liquid neutron absorbing material could be rapidly added to the heavy water moderator in the reactor core.

AECL's marketing efforts were to prove ultimately successful with the sale of four CANDU-6 units. These were Gentilly-2 (Hydro Quebec) (1973), Point Lepreau (New Brunswick Power)(1974), Cordoba (Argentina)(1973), and Wolsong (Republic of Korea)(1976). (42) A variety of different project arrangements were involved in the design, construction, and commissioning of these units. In the case of the two domestic projects, the Canadian utilities acted as overall project and construction managers with AECL providing the nuclear systems design and private-sector Canadian engineering firms providing the conventional plant designs. In the case of the Cordoba (Argentina) project, AECL originally contracted to act as the "turn-key" supplier of the nuclear portion of the plant with its Italian partner, Italimpianti, acting as the "turn-key" supplier of the conventional portion. As a result of subsequent financial instability in Argentina, the plant owner, CNEA, took over responsibility for all work in Argentina. In the case of Wolsong (Korea), AECL had overall turnkey responsibility for the entire project. Ontario Hydro provided vital assistance in the training of commissioning and operating personnel and, in the case of the offshore projects, Hydro personnel provided overall commissioning management. These four CANDU-6 units came into commercial operation during 1983 and have subsequently established excellent operating records. Their average capacity factors, since the in-service date of each unit to the end of 1991, are shown in Figure 1. In 1991 the average capacity factor for the four units was 86.2%.

**originally named CANDU-600 and subsequently renamed CANDU-6*

It should be noted that, with respect to the data summarized in Figure 1, both Gentlily-2 and Embalse have been operated at reduced power or shutdown for significant periods of time because of a lack of utility need for the power. Had the data been adjusted to reflect power generation capability rather than achieved power generation, the records of these two units would have appeared even better.

To complete the story of the export CANDU-6 units, an agreement was signed with Romania in 1978 to commence the Cernavoda project. This called for AECL to provide the CANDU-6 design on a licensing basis and certain quality assurance services. Romania contracted directly with a number of Canadian equipment suppliers to supply certain nuclear plant equipment for the first two units of what is to be a five-unit plant. Romania undertook to provide not only overall project management and plant construction but also the manufacture of much of the plant equipment. Events were to prove that these undertakings were overly ambitious; recently the new government of Romania has substantially expanded AECL's role in the project in the interests of overcoming construction quality problems and avoiding further major schedule delays.

In 1991, the Korea Electric Company contracted with AECL for the supply of engineering services and nuclear plant equipment for a second CANDU unit at the Wolsong site. This second unit (Wolsong-2) will be largely a repeat of the first unit but will incorporate a number of relatively minor modifications to meet the latest Korean licensing requirements and to reflect operating experience with the first unit and the sister units in Canada and Argentina. In September of 1992, AECL received an order for similar engineering services and nuclear equipment supply for two more CANDU-6 units (Wolsong-3&4), thus confirming Korea's previously announced long-range plan for CANDU units to provide a substantial portion of Korea's nuclear generating capacity in the future. These additional two units will be essentially identical to Wolsong-2.

Since completion of the first four CANDU-6 units, AECL has periodically revisited the CANDU-6 design to identify potential improvements which could be incorporated without necessitating major alteration of the design. The utility customers in Romania and Korea have had, of course, the final say as to which of the possible improvements would actually be incorporated in the specific units ordered to date. Romania has chosen to make essentially no changes except those necessary to suit Romanian conditions such as siting differences, differences in equipment suppliers, differences in preferred construction techniques, etc. In the case of Korea, the utility wished to limit changes to only those which it judged to be essential or at least highly desirable. By adopting this policy, the utility will ensure that it gains maximum advantage in terms of operator training, spare parts sharing, maintenance equipment and expertise sharing, etc., between Wolsong-1 and the later CANDU-6 units on the Wolsong site. This important consideration is likely to be shared by any other CANDU-6 owners who decide to proceed with a second CANDU-6 unit.

8. The CANDU-3 Program

In the mid-1980's, AECL decided to proceed with the development of a new and smaller variant of the CANDU reactor. This reflected the fact that with the downturn in demand growth being experienced by utilities in many countries, the existing CANDU-6 electrical output could exceed utility requirements in a significant market sector. Furthermore, the potential market for nuclear units in developing countries was clearly for smaller units. (43) It was, however, recognized that this potential market could only be tapped by nuclear units which offered attractive economics in comparison with available non-nuclear alternatives. The challenge clearly lies in achieving capital and operating costs which are not substantially greater per unit of generating capacity (S/kW) than those achievable with larger nuclear units (>600 MW) which have demonstrated attractive economics in utility operation. Of these costs, the capital component (termed the specific capital cost (S/kW)) is the most challenging since it is the largest single component of overall generating costs and, furthermore, is inherently subject to what is commonly referred to as the "scaling law". This empirical engineering "law" holds that as plant size increases, capital cost increases but in less than linear proportion. This relationship applies not only to nuclear plants but to large industrial facilities in general. As a consequence, nuclear plants in most countries have, to date, followed a progressively upward trend in unit size in an endeavor to improve competitive economics.

In addressing this challenge concerning the economics of smaller units, AECL designers recognized that simply "shrinking" the larger plant designs would not suffice. A more innovative approach was clearly required. At the same time, AECL designers recognized that most utilities are no longer prepared to purchase highly innovative designs, preferring designs which are based on well-proven technology. These considerations led to an approach which called for use of fewer but well proven components. For example, two steam generators instead of four, two main cooling pumps instead of four, one refuelling machine instead of two, and so on. In this way the design could be considered essentially proven while, at the same time, the "scaling law" could be substantially circumvented. (44) By incorporating the foregoing, together with a number of other considerations derived from experience and discussions with potential utility customers, AECL designers established a comprehensive set of overall design objectives for this new, smaller CANDU. (45) The most important of these can be summarized from the foregoing reference as follows:

- To enhance or improve traditional CANDU advantages including real safety, low radiation exposure (to public and staff), high capacity factor, ease of maintenance, and low operating cost.

- To reduce specific capital costs (S/kW), construction schedules, and energy costs.

- To standardize the plant design such that it would be suitable for a wide variety of potential sites, worldwide.

- To provide components which have a long life, are easily installed during plant construction, are easy to replace, and have low overall cost.

- To provide facilities and access for major equipment replacement and/or upgrading within a plant shutdown not exceeding 180 days.

- To satisfy a comprehensive set of desirable operating characteristics including:

    - Flexible power output maneuvering rates
    - Sustained operability at reduced power levels following operation at full power
    - Capability to supply internal electrical loads following disconnection from utility grid
    - Capability to rapidly return to full power operation following shutdowns

The foregoing basic approach to "downsizing", plus the noted overall design objectives, have been reflected in the design concept for the new, smaller CANDU unit, called CANDU-3. Work has now progressed to the point where the detailed generic design is now approximately 70% complete. The term "generic" refers to the fact that the design is suitable for a wide variety of potential sites and basic utility requirements such as system frequency (60 Hz or 50 Hz) throughout the world.

The key features of the generic design are described in some detail in reference (45). Of particular note, the new design incorporates extensive use of "modules". These are large, prefabricated assemblies of major blocks of plant equipment, plus associated pipework, wiring, structural supports, etc. Each such block or "module" is prefabricated in an assembly shop, then transported to the construction site and, finally, installed in the plant. This module approach is not unique to CANDU, having already been extensively utilized in Canada and elsewhere in such applications as large, offshore oil platforms. It offers several advantages. Firstly, work can proceed in parallel on several modules at the same time whereas, in many cases, conventional site construction requires work to proceed in a serial manner; major time savings are, therefore, possible. Secondly, experience has shown that the high levels of quality assurance required for nuclear plants are more readily achieved within a fabrication shop environment as compared to a construction site. Thirdly, assuming that orders for several plants are received within a reasonable time period, say at approximately one year intervals, module fabrication can move into a series-production mode with significant cost savings.

Through the extensive use of modules and reduced number of plant components (as compared to the earlier CANDU-6 design), combined with newly available very-heavy-lift construction cranes (capable of handling loads of the order of 500 tons), a major reduction in plant construction schedules can be achieved. Detailed construction planning studies indicate a site construction period of 38 months as compared to the 62 month schedule for the latest committed CANDU-6, Wolsong-2.

A first customer for this new CANDU-3 design has not yet been secured but discussions and studies are ongoing with two Canadian utilities, New Brunswick Power and Saskatchewan Power. AECL believes that the commitment of a first unit by a Canadian utility is likely to prove an essential precursor to subsequent offshore sales.

9. The CANDU-9 Program

As will be discussed in the next section, the development of the Ontario Hydro Bruce and Darlington stations was based on a larger CANDU reactor core than was utilized for the Pickering and CANDU-6 units. The number of fuel channels was increased from 380 (390 in the case of Pickering-A) to 480. This allowed the electrical output per unit to be increased roughly in proportion, making available a basic CANDU reactor design in the 900 MW class range. This, of course, has given rise to the question of whether AECL should adapt the multi-unit Bruce/Darlington design to produce a new single-unit design in the 900 MW class range. While technically this could be done without difficulty, the question has been, of course, one of market opportunity. Such a design would be too large for any Canadian utility, save Ontario Hydro and Hydro Quebec. Until recently, at least, Ontario Hydro's preference was for a continuation of its established multi-unit approach. Hydro Quebec, on the other hand, is strongly committed to continuing expansion of hydraulic generation for some years to come. Turning to the international marketplace, 900 MW class reactors have, in earlier years, been very popular in many countries; however, in recent years, new orders for any reactors have been few and far between, other than in "closed" domestic markets such as France. As a result of this market uncertainty, AECL has not, to date, undertaken the detailed design of such a single-unit 900 MW class CANDU. AECL has, however, undertaken a limited conceptual design program in order to facilitate a rapid response to future market opportunities. This new design is being called CANDU-9 to fit into the recently adopted nomenclature for single-unit CANDUs.

As defined by the conceptual design studies to date (46), CANDU-9 will employ proven component designs from existing operating CANDU units to the greatest practical extent. Certain adaptations will be required to ensure that these component designs are suitable for a broad range of possible site conditions, such as potential earthquake activity and cooling water temperatures. In addition, the design will employ advanced features, developed for the CANDU-3, to reduce the construction schedule and improve maintainability and operability. In general, the overall design objectives outlined for CANDU-3 will be adopted for the new CANDU-9 design. Reference (46) provides a descriptive and illustrative outline of the current conceptual design of CANDU-9.

10. The Evolving Role of Ontario Hydro in its Nuclear Projects

Earlier sections have described the role of Ontario Hydro in the NPD, Douglas Point, and Pickering-A projects. With the commencement of Bruce-~ the Ontario Hydro project following Pickering-A, the roles of Hydro and AECL changed from the earlier broad "partnership" arrangement. Hydro now assumed full responsibility and authority for its nuclear projects, the role of AECL becoming that of a nuclear engineering consultant and nuclear-related R&D support agency. In the case of Bruce-A, AECL's detailed engineering role generally paralleled that performed for the Pickering-A project except that CGE was assigned responsibility for engineering of the fuel handling systems. This reflected the earlier understanding between Hydro, AECL, and CGE that the latter would retain a fuel handling engineering capability following CGE's decision to abandon its earlier role as a full-scope nuclear plant supplier.

Conceptual studies for Bruce-A commenced in 1968. (47) While the design team at AECL was responsible for the overall plant layout concept, the work was led by W.G. Morison of Ontario Hydro who was also acting as chief designer for completion of AECL's work on Pickering-A, as noted earlier. By the time of Morison's return to Hydro in early 1969 to take charge of Hydro's design and development group, the basic concept for Bruce-A had been established. As would be expected, the design concept was based, in many respects, on the Pickering design. In order to achieve the desired increase in unit power output, to match Hydro's increasing load demand, the reactor power was increased by incorporating 90 additional fuel channels (from 390 to 480) and by increasing the power capability of each fuel bundle (13 per fuel channel) by increasing the number of individual fuel elements from 28 to 37 while reducing the individual element diameter so as to maintain the same overall fuel bundle diameter.

Turning to overall station layout, the basic integrated 4-unit design approach was retained as was the negative pressure containment concept utilizing a common vacuum building. The detailed containment arrangement was altered to permit a sharing of refuelling machines between units and to reduce radiation exposure to personnel during operations and maintenance work. The experience gained by Canadian equipment manufacturers from earlier CANDU projects enabled them to undertake the manufacture of larger individual components such as heat exchangers, steam generators, and pumps. As a result, the number of such components could be reduced relative to Pickering-A even though the unit output was to be essentially 50% higher. Two major safety improvements were incorporated through collaborative development between Hydro and AECL. The first was the incorporation of a second emergency (safety) reactor shutdown system patterned on a design developed by AECL for an earlier experimental reactor. This is described in detail in section 7 above with respect to the CANDU-6 design. The second major improvement was the incorporation of a new type of high-pressure emergency reactor cooling system. This provided additional assurance against severe reactor fuel damage in the event of a major loss of coolant.

The four Bruce-A reactors entered service over the period 1977 to 1979 and quickly joined their Pickering-A sisters in demonstrating an excellent early operating history. In this regard, the eight units achieved and overall average capability factor of 83% over the next five year period.

With the early success of the Pickering-A units, Hydro decided, in July of 1974, to build four more such units at the Picketing site. These additional units, located immediately adjacent to the -A units, are referred to as Pickering-B and share certain common facilities with the -A units, notably the common vacuum containment building. The design largely replicates that of Pickering-A except for the reactors themselves which are replicas of the CANDU-6 reactors. The design of the CANDU-6 reactor was provided to Hydro by AECL at no charge in the interests of furthering the historical close collaboration between the organizations. For its part, Hydro wished to adopt this newer reactor design as a means of reducing capital costs and the plant construction schedule.

Pickering-B represented a major change in the apportionment of detailed design work between AECL and Hydro's in-house engineering team as compared to the earlier Pickering-A and Bruce-A projects. Hydro decided to undertake all of the engineering work save that associated with the reactor proper and its safety shutdown and fuel handling systems which remained with AECL. Several reasons underlay this decision. Firstly, the AECL engineering team was heavily loaded with completing its work for Bruce-A in addition to its major engineering role for the CANDU-6 units. Also, at the time, Hydro had planned to assign to AECL a major role in engineering for its planned Bruce-B station as well as in developing a new, very large CANDU unit design (a conceptual study program was initiated for such a unit but did not proceed to the detailed design phase). Secondly, Hydro engineering staff were becoming available as work on the new Hydro fossil-fired units was coming to an end. Thirdly, Hydro wished to develop its own in-house capability to undertake engineering for nuclear plants on the same comprehensive basis as it had evolved for its fossil-fired plants. Basically, this limited the engineering role of AECL to the reactor proper and its safety shutdown and fuel handling systems (in the case of Pickering-B, fuel handling was assigned to AECL rather than to CGE because AECL had performed this work for the similar Pickering-A station).

Shortly after the commitment of Pickering-B, Hydro committed the second 4-unit plant at the Bruce site. Called Bruce-B, this plant is substantially a replica of the Bruce-A plant but incorporates a number of detailed improvements arising from experience gained in the design and construction of Bruce-A to that point in time. In this case, as contrasted with the Pickering-B case discussed above, Hydro decided to employ AECL and CGE engineering in the same roles as had applied in the case of Bruce-A. The determining factors in this decision were, firstly, Hydro's desire to maintain continuity in the design effort, given that Bruce-B was to follow closely on the heels of Bruce-A and, secondly, that Hydro wished to swing its available engineering resources onto the Darlington-A project which was to follow Bruce-B.

For the Darlington project, Hydro undertook an engineering role which closely followed the pattern established earlier for the Pickering-B project. AECL's assigned role also followed this pattern except that CGE was assigned the fuel handling engineering role since Hydro had decided to employ the same basic fuel handling system design as had been developed for Bruce-A and -B by CGE.

With Hydro's in-house engineering team concentrating its efforts on the Hydro multi-unit stations while the AECL team was heavily committed to the single-unit CANDU-6 projects, there was, inevitably, a diminishing of the close technical coordination which had existed earlier between the teams. This trend towards reduced technical coordination was recognized and judged undesirable several years ago by both Hydro and AECL. The outcome of joint consultations aimed at reversing this trend was the creation of a committee of senior engineering executives of the two companies, called the CANDU Engineering Authority. The first task of the committee was the establishment of a broad plan of action, called the CANDU Engineering Business Plan, issued in 1991. The basic objectives of the Plan were to reforge the close working relationship between the Hydro and AECL engineering teams, which existed during the early phases of Hydro's CANDU program, and to eliminate unnecessary differences in CANDU technology as practiced by the two engineering teams. Subsequently, good progress has been made towards realization of these overall objectives.

11. The Canadian Approach to Nuclear Safety and Regulation

The Canadian approach to ensuring the safety of its nuclear power plants has evolved on a continuing basis since the outset of the NPD project in the mid-1950's. The continuing primary objective has been to ensure that the risk to the public presented by nuclear power plants is substantially lower than that from major available and economically viable alternative sources of electrical energy. (48) In achieving this objective, an underlying principle has been that the licensee (owner/operator) bears the basic responsibility for safety while the regulatory authority, the AECB, primarily sets safety objectives and overall safety-related performance requirements and, also, audits their achievement. As a consequence of this basic approach, AECB regulatory requirements have emphasized numerical safety goals and objectives and minimized specific design and operational rules, the latter being the responsibility of the licensee. (49)

The historical background underlying the foregoing basic philosophical approach begins in 1946 with the passing of the federal Atomic Energy Control Act (Act) (as previously noted in section 2). (47) The Act declared atomic energy a matter of national interest and created the AECB to administer the Act, thus establishing the legal framework necessary to move the wartime atomic energy program onto a peacetime footing. The Act, subsequently amended in 1954, authorizes and defines the powers of the AECB. It is a body with five appointed members (the Board), one of whom is appointed President and Chief Executive Officer. Under the provisions of the Act, the Board is empowered to make regulations governing all aspects of the development and application of atomic energy. The 1954 Amendment to the Act formally transferred the responsibility for research and the exploitation of atomic energy from the Board to a Minister designated by the government. As a result, AECL was made directly responsible to the designated Minister for these functions, leaving the AECB to fulfill an unambiguous regulatory function.

In tracing the development of the Canadian approach to reactor safety, the accident involving the NRX research reactor at AECL's Chalk River Laboratory in December of 1952 played a major role. This accident resulted in what, in today's popular jargon, would be referred to as a partial "meltdown" of the core of the reactor. While health and environmental effects, even to the Chalk River site and persons employed there, were minimal and the reactor was rebuilt and returned to service successfully in the relatively short period of 15 months, the lessons learned were to prove invaluable. The essential principles, which evolved from careful analysis of the accident, recognized that even well designed and built systems fail and, therefore, that there is a need for separate, independent safety systems which can be tested on a regular basis to demonstrate their availability should they be called upon to act to prevent or mitigate an accident. These principles were recognized from the outset in the design of the first power reactor, NPD.

A next major step was defined in 1957 in a paper by E. Siddall and W.B. Lewis. (51) This paper proposed setting safety standards for nuclear power plants by comparing their economic and accidental death risks with those of coal-fired plants which they would displace. This basic approach was adopted for purposes of the safety analysis of NPD. The derived target, based on this approach, called for serious accidents to have a frequency of less than 1 per 100,000 years, based on an overall risk target of less than 1 death per 100 reactor operating years. (52) Achievement of these targets would ensure that the risk presented by NPD would, in fact, be substantially lower than that presented by the coal-fired alternative, the basic safety objective noted at the beginning of this Section.

During this period, Dr. G.C. Laurence, Chairman of the AECB's Reactor Safety Advisory Committee (RSAC), proposed that the evaluated likelihood of a "disastrous" accident at a nuclear power reactor should be less than 1 per 100,000 years. (53) Laurence concluded that achievement of such a target likelihood should prove realistic provided adequate separation was maintained between the plant's operating systems and those testable devices and systems provided to ensure safety. This reflected the basic lessons learned

from the NRX accident as noted above.
By the mid-1960's, and at the time work was commencing on the design and safety analysis for Pickering-A, the AECB formalized for the first time specific licensing criteria in what came to be known as the Siting Guide. (54) These criteria, as further modified in 1972, (55) set limits on the "frequency of serious process failures", that is, how often would a plant component or system fail during operation in a way which would require the action of any of the plant safety systems. Criteria were also established defining the required reliability of each of the plant safety systems (to be continually demonstrated through regular testing during plant operation). This concept of separation between plant operating systems and plant safety systems, both physical and in terms of demonstration of reliability, is a key tenet of the Canadian approach to reactor safety.

Within the foregoing basic framework, safety analysis is carried out at two levels. Firstly, each possible "serious process failure" is analyzed to demonstrate that its consequences, in terms of health effects arising from consequential radioactive releases, will be within AECB prescribed limits. For this level of analysis, the plant safety systems are assumed to function properly, for the second level of analysis, each possible "serious process failure" is reanalyzed, assuming, in turn, that each plant safety system fails to operate. This second level of analysis must demonstrate that the health effects would be within a second set of AECB prescribed limits. This formal methodology is unique to the Canadian approach to nuclear safety and has resulted in the fact that CANDU reactors are unsurpassed in terms of basic safety capabilities. Specifically, the fact that the safety analysis must assume complete failure of a safety system to perform when called upon required CANDU designers to develop additional safety defenses beyond those embodied in other water-cooled power reactor designs. This led firstly to the development of a completely separate, independent second reactor safety shutdown system as noted earlier in the discussion of the Bruce-A reactor design. This has been a feature of all succeeding CANDU designs and renders CANDU essentially immune to accidents involving failure to shut down the reactor when required. The second additional safety feature involved demonstrating through analysis and supporting research that the heavy water moderator contained in the reactor core and its separate cooling system are together capable of preventing a core "meltdown" in the event that the emergency core cooling system should fail to operate following an accidental loss of the normal reactor coolant water.

In the years following 1972, a new, supplementary, approach to safety analysis methodology has come into practice in Canada, and indeed in most countries. Called "probabilistic safety assessment" in Canada, this approach calls for a wide-ranging assessment of the complete plant and its many systems and components in responding to a broad range of potential accidents. This assessment is done in terms of both consequences (radioactive releases) and probability of occurrence, using various formalized "fault-tree" and "event tree" methodologies. To date, the AECB has not established specific numerical acceptance criteria relative to this methodology in terms of the regulatory licensing process. In this regard, the position of the AIECB is generally similar to that of regulatory bodies in most Western countries. The licensing of Darlington represented the first opportunity for use of the new methodology on a "trial use" basis in Canada. Notwithstanding the acceptance criteria question, both plant designers and AECB staff are in agreement that the methodology provides a powerful assessment tool for the identification of potential design weaknesses during the detailed design process and, hence, actively support its ongoing utilization and development. It is interesting to note that a probabilistic safety assessment for the CANDU-600 reactor design performed jointly with the Dutch KEMA organization demonstrated that these operating CANDU reactors meet or surpass the targets now generally established for next-generation light water reactors. (56) This assessment demonstrates the impact of the additional safety features incorporated in CANDU as noted in the preceeding paragraph.

12. The CANDU Support Research and Development Program

As was noted in earlier sections, the origin of the CANDU system owes much to the experience gained in Canada in the design, construction and operation of the NRX and NRU research reactors. Underlying this direct experience was the information gained by R&D programs at Chalk River directed to basic heavy water reactor technology in the 1940's and early 1950's. Of particular note was the technology related to reactor physics, reactor control, chemistry of heavy water systems, and reactor fuel. Without this basic, underlying technology, Canada could not have successfully developed the unique CANDU system. It is important to note, however, that the Canadian program was greatly assisted by technology made available during this early period by R&D organizations in other countries, particularly the United States Atomic Energy Commission. For example, the CANDU program benefitted from the technology developed in the U.S. for the production of heavy water (the Girdler-Sulphide process). This technology was made available to Canada and formed the foundation for the large-scale heavy water production plants built in Nova Scotia and Ontario to supply the CANDU program. Further examples include technology associated with uranium dioxide and zirconium alloys, both essential to CANDU fuel. In each of these instances, the technology served as a starting point for the ongoing R&D necessary to adapt it to the specific needs of the CANDU program. As an example of technology from non-U.S, sources, the outstanding example is the improved zirconium alloy used for the pressure tubes in Pickering Unit 3 and all subsequent CANDU units. This alloy of zirconium and niobium was evolved by AECL following a key lead provided by Soviet metallurgists.

The early period of relatively free exchange of nuclear technology, amongst western countries in particular, largely came to an end during the early 1960's. This resulted from emerging commercial considerations as nuclear power moved from the laboratory and drawing board to commercial generating stations. As a result, the CANDU program became progressively more dependent on AECL's in-house R&D program, augmented by AECL-funded R&D programs in Canadian universities and by work carried out by Hydro's Research Division in support of Hydro's CANDU units. This situation was, in some respects, fortuitous because it provided the stimulus and challenge necessary to maintain and enhance the world-class Canadian R&D capability. This was to prove invaluable as problems were encountered in the operation of CANDU units, particularly in the early period when much of the technology was still new. Experience has proven that the R&D teams, because of their broad underlying technological expertise, can respond rapidly and effectively to deal with new and unforeseen problems. As an example, reference is made in section 4 to the problem of build-up of radioactive corrosion products on the inner surfaces of pipework in the Douglas Point unit. Solving this problem required the combined talents of a number of expert technical groups, both in the AECL labs and within the station chemistry group. This expertise covered fields such as basic physical chemistry of colloids and finely-divided solids dispersed in water, corrosion of steel and other materials in the reactor coolant system, radiochemical phenomena occurring in the reactor core, and identification of the physical species contained in the depositing materials and the microstructure of the deposits. Clearly a wide spectrum of skills was called for and, fortunately, was available within AECL and the wider Canadian R&D community.

As the CANDU concept took shape in the mid-1950's, R&D efforts at Chalk River were focused on several key areas. Of particular note was the fuel for the reactors. The research reactors had utilized uranium in metallic form. This was clad in aluminum metal to prevent contact between the uranium and the cooling water, a necessary provision since uranium metal is quickly corroded by water. Such fuel would be impractical for the power reactors since aluminum could not withstand the required high operating temperatures. Furthermore, the uranium metal was dimensionally unstable under the operating conditions envisaged. Drawing on early work by the Americans, the decision was taken to develop a completely new fuel design. This called for the uranium to be in the form of uranium dioxide, a ceramic material with excellent high temperature and anti-corrosion characteristics. An alloy of zirconium was chosen as the cladding material because of its combination of desirable properties. Despite the earlier U.S. experience noted in section 3, both zirconium alloys and uranium dioxide were largely unknown as engineering materials in any application, let alone as power reactor fuel materials. Hence, a major R&D program was mounted, building on information initially provided by the U.S. This program was successfully completed in time to permit the manufacture of the first load of such fuel for NPD.

A second area of particular note involved pressure tube development specific to the needs of CANDU. Building on the American experience in fabricating zirconium alloys into seamless tubes for the Hanford N-reactor, AECL R&D worked with one of the American commercial fabricators to develop tubes in the geometry and with the properties needed for NPD. This work was continued for the longer tubes needed for the Douglas Point reactor and for the first two units of Pickering-A (longer again and of greater diameter). AECL's R&D was not simply limited to pressure tube fabrication but extended to new and improved alloys of zirconium. Following a basic direction first indicated by the Soviets, AECL developed an alloy of zirconium and 2.5% niobium which proved to have superior properties to the Zircaloy-2 alloy used in the early reactors. This was available in time for installation in Pickering-A, Units 3&4, and has been used in all successive CANDU units. The importance of this development was graphically demonstrated by evidence gathered following the failure of a Zircaloy-2 pressure tube in Pickering Unit 2 in 1983. This evidence demonstrated that after about ten years or so of service under Pickering conditions, the rate of absorption of deuterium into the Zircaloy-2 material would increase dramatically. This was a key factor leading to the failure. Fortunately, the

newer zirconium-niobium alloy has not displayed this characteristic.
In addition to R&D work carried out at Chalk River, additional component development and testing work was carried out in laboratories established at the CGE plant in Peterborough and at Hydro's Manby research center in Toronto. In 1967, the latter facilities (those specific to CANDU) were moved to AECL's new engineering site at Sheridan Park in Mississauga. Other smaller facilities were developed at other locations, generally in cooperation with private sector companies interested in the nuclear field. A great deal of specific development work has been carried out by Canadian manufacturers in evolving their products for the CANDU and other nuclear markets. For example, Babcock and Wilcox in Cambridge, Ontario, has developed a world-class nuclear steam generator engineering and manufacturing capability and is now successfully competing in the United States for the supply of replacement steam generators. It is important to note that the design of the steam generators is a Canadian accomplishment through cooperation between Babcock and Wilcox, AECL, and Hydro. This design is quite different from that developed by Babcock and Wilcox for use in nuclear plants in the United States. In the field of process heat exchangers, the engineering of units suitable for use in CANDU reactors involved the development of much more sophisticated engineering methods than previously existed in the heat exchanger industry. Canadian technology in this field can now match that available in any country. It is worth noting that this component development work has been funded through direct charges to the benefiting CANDU projects.

Canadian engineering and manufacturing technology has also been the beneficiary of codified quality assurance standards originally developed by AECL and Ontario Hydro and subsequently incorporated in the Canadian Standards Association Z.299 series of quality assurance standards. These standards are now widely utilized in many Canadian industries outside of the nuclear field and have received a considerable measure of international recognition.

During the initial phases of CANDU development, R&D efforts were directed to providing the basic technology necessary to ensure the success of CANDU as both a safe and an economic source of electrical energy. As this basic technology became established, progressively greater emphasis was placed on those aspects of the R&D programs concerned with the safety of the CANDU system. This trend has continued to the present time, reflecting both an ongoing commitment by AECL and Canadian utilities to the continuing enhancement of CANDU safety, and also, of course, reflecting public interest in risk aversion. Currently, this R&D work is directed, primarily, to providing additional assurance that the analytical methods used to assess the behavior of a CANDU reactor under severe accident conditions are sound and appropriately conservative. Several specific areas are receiving particular attention. These include the performance of CANDU fuel, and the fuel channels containing the fuel, under severe accident conditions; the transport of radioactive materials from damaged fuel into the containment building; and the ability of the containment building to withstand pressures which could be developed should hydrogen produced as a consequence of a severe accident be ignited (such as occurred in the case of the Three Mile Island accident). These individual areas are each concerned with one or more of the several sequential barriers which the CANDU design provides to separate the radioactive materials in the reactor fuel from the environment and the public. Currently, these safety-related R&D programs are funded at a level of approximately $35 million per annum which represents about 25% of the total current CANDU R&D program funding. In addition, it is important to note that the CANDU program is also the beneficiary of the results of safety-related R&D work in other countries through the IAEA, the NEA (OECD), and bilateral agreements. Fortunately, the world nuclear community generally recognizes that information relating to safety should not be subject to narrow commercial considerations and that international collaborative arrangements greatly extend the value each participant receives per dollar spent on its own internal program.

The production of radioactive cobalt in CANDU reactors represents another interesting benefit of R&D to the CANDU program. From the earliest days of Canada's nuclear program, R&D related to the production and utilization of radioisotopes for medical and industrial purposes has been a major undertaking by AECL. One of the areas pioneered in Canada was the use of radioactive Cobalt-60 for both cancer treatment and general industrial applications such as plastics manufacture and food irradiation. In the cancer treatment field, close to half a million people are treated annually using Canadian-made Colbait-60 machines. (57) Originally, this Cobalt-60 was produced by the irradiation of cobalt in AECL's Chalk River research reactors. During this irradiation, the cobalt (Cobalt-59) absorbs neutrons, becoming Cobalt-60. As the world demand for Cobalt-60 increased, the existing production capability in Canada could not satisfy the available market. AECL, together with Hydro, therefore studied the potential for commercial Cobalt-60 production in CANDU power reactors. As a result, AECL and Hydro developed the capability for producing large quantities of Cobalt-60 in several of Hydro's CANDU units. This valuable byproduct of CANDU operation has not only provided extra revenue to Hydro but has secured for Canada the position of the world's leading supplier of Cobalt-60. Canada's current share of the world Colbait-60 market is about 80%.

Since the outset of the CANDU program, there has been a progressive increase in the funding provided by Canadian utilities in support of the CANDU-related R&D program. Originally, this funding was provided by the federal government through its general funding of the AECL R&D program. As commercial CANDU projects were undertaken by utilities, costs of specific development work needed in support of these projects were included within the project capital charges. Such utility funding continued in support of specific development work required by these units once they were placed in operation. With the large number of CANDU units now in operation, and recent agreements by utilities to fund a larger portion of program costs, such utility funding has increased to the point where, today, it represents approximately 50% of the total CANDU R&D funding. In dollar terms this utility funding has increased from approximately $10 million in 1985 to a projected 1992 level of approximately $90 million. (58) While the majority of this R&D work is still carried out at the AECL laboratories, overall direction of the program is now provided by the CANDU Owners Group (COG) which includes the three Canadian "nuclear" utilities (Ontario Hydro, Hydro Quebec, and New Brunswick Power) and AECL. Participation and funding by offshore CANDU utilities is encouraged and some success has been achieved in attracting such support. It is expected that this will increase in future.

13. Overall Perspective

The successful development of the CANDU system represents a major Canadian accomplishment. This was recognized in 1987 by the Canadian Engineering Centennial Board in awarding CANDU a position amongst the ten most outstanding Canadian engineering accomplishments during the past century. (59) This accomplishment was achieved through the close collaboration of the many participants in the CANDU program. Of particular importance is the close collaboration between the Canadian utilities, which have constructed and operated CANDU units, and AECL, which has played the lead role in the development of CANDU technology. Canadian private sector engineering and manufacturing companies have also played a major role, particularly in ensuring that CANDU evolved as a truly domestic product. This could not have happened had these companies not displayed a willingness and capability to engineer and produce products of the high quality demanded by nuclear power applications. In return, these companies have not only secured a direct commercial return from their participation in the CANDU program, but have also benefited in terms of wider market opportunities through the upgrading of their capabilities.

Many sectors of the general public have benefited from the success of the CANDU program in the following ways:

- reduced electricity rates in the provinces of Ontario and New Brunswick where CANDU reactors produce a substantial portion of total electricity generation

- reduced emissions of acid gas and carbon dioxide through displacement of fossil-fired generation which would have otherwise been required

- increased markets for Canadian uranium

- reduction in adverse balance of payments which otherwise would have been made to foreign suppliers of coal and oil

- high technology job creation in the Canadian engineering and manufacturing communities.

Because much of the CANDU program has been centered, to date, in Ontario, the foregoing benefits have been particularly important to the residents of Ontario.

In the broader world scene, CANDU technology has proven competitive with other nuclear technologies. This is best illustrated by the case of Korea, the only country in the world which has purchased, installed, and is operating both light water reactors supplied from the U.S. and France, and also a CANDU unit, Wolsong-1. The recent decisions by Korea to proceed with three more CANDU units provides clear proof that CANDU technology is competitive today in the world nuclear power market. The situation with respect to competitiveness with other means of large-scale electricity generation is dealt with elsewhere in AECL's evidence. (60)

In the future, the ongoing development of CANDU technology will be centered on the following areas: (61)

Plant simplification will be a major thrust, not just to reduce cost through fewer components being required, but equally important, simplification will improve operability and maintainability and, hence increase overall plant output.

Alternative fuel cycles will be developed to further enhance CANDU's inherent advantage in low fuelling costs as compared to competitive nuclear systems. In addition to lowering costs, such fuel cycles offer the potential of further increasing the energy output available per unit of uranium consumed, an important long-term conservation consideration.

Safety enhancements will continue to be pursued.

Capital cost and construction schedule reductions are central to the question of competitiveness. As a result, and as noted in earlier sections dealing with the new CANDU-3 and CANDU-9 designs, these subject areas will continue to receive major attention.

Finally, CANDU possesses a truly fundamental advantage which cannot be overcome by competitive nuclear power technologies. This fundamental advantage lies in the unexcelled neutron economy provided by heavy water moderation. As noted in the early sections of this paper, this was a paramount reason for adoption of heavy water moderation in CANDU in the first place. The reason is likely to remain valid well into the future since neutron economy is central to maximizing energy recovery from the world's uranium resources.

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