THE DEVELOPMENT OF CANDU

by

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ABSTRACT

The CANDU (Canada Deuterium Uranium) pressurized heavy-water reactor type is successful in several countries and is being installed in several countries today. The concept was developed in Canada with cooperation from many other countries, notably the US, UK, Japan and Italy. This is one of the very few reactor types that have successfully reached full maturity in the world.

The fundamental starting point of the concept was the use of natural uranium fuel. This choice determined several other positive choices, such as heavy water moderator, on-power fuelling, and computer control. The use of heavy water moderator and the need for large power output determined the choice of a channel-type configuration. Power plants utilizing this concept are now operating in various sizes up to 935 MWe.

Development of CANDU began, and continues today, as a 100 percent civilian project with the broad participation of local industry and strong support from CANDU owners. By policy choice, export of the system is accompanied by technology transfer and industrial localization.

This section briefly describes the history and technical development of this power reactor concept, its present status in the world market, and its unique advantages for power generation.

THE DEVELOPMENT OF CANDU

1. INTRODUCTION

Canada is one of the few nations that have successfully developed economical nuclear power plants, an achievement by no means to be expected, considering the extremely large scope of development for a single country.

This document briefly describes the history and technical development of this power reactor concept. It also includes notes on the associated development planning and strategy and some of the lessons learned from this unique development achievement.

2. IN THE BEGINNING

2.1 ZEEP

It may be surprising to some, to learn that Canada has been in the nuclear energy business for more than 50 years. In 1945, a 10-Watt research reactor, called “ZEEP” (see Figure 1) was built at laboratories in Chalk River, Ontario. (The name stood for Zero Energy Experimental Pile.) A small device, (under 3 metres in height) ZEEP was the catalyst to Canada's future in the nuclear age. It was in ZEEP that the first controlled chain reaction outside the U.S took place.

2.2 NRX and NRU

Other research reactors followed --among them, the 42 MW NRX in 1947, and the 200 MW NRU in 1957, also at Chalk River. These two research reactors were among the most powerful in the world. They used vertical fuel string orientation, with a variety of water coolant loops for fuel, materials testing and irradiations.

In 1952, the Canadian government formally established AECL to develop the peaceful uses of nuclear energy, and a program to develop a nuclear power reactor for the production of electricity was initiated.

At the same time, the Canadian utility Ontario Hydro had become interested in the prospects of nuclear power as an alternative to coal for electricity production for the province of Ontario, which had little domestic reserves of fossil fuels. In early 1952, the premier of Ontario, and the chief engineer of Ontario Hydro, federal minister responsible for National Research Council and the recently created AECL met to plan for the introduction of nuclear power in Ontario. Thus, the stage was set for the long and productive period of cooperation between the designer AECL and the utility Ontario Hydro, a cooperative effort became one of the essential elements in the successful development of CANDU.

While heavy water was strongly favoured as the moderator, the choice of coolant was less clear; options initially considered included light water, heavy water, steam, gas, organic liquid and liquid metals. It was proposed that the construction of a small demonstration power reactor would provide some of the answers. This demonstration CANDU reactor was known as NPD (Nuclear Power Demonstration). The development of the key CANDU concepts and their adoption in NPD over competing options is the key part of the technical development of CANDU.

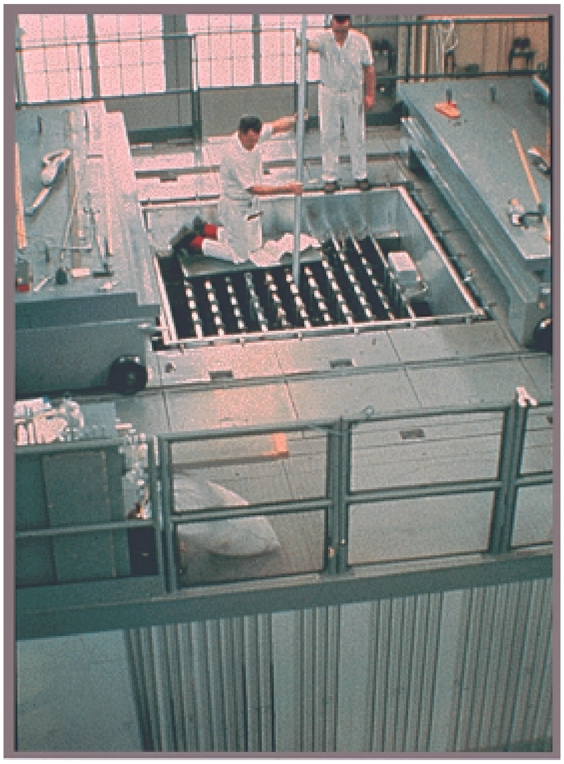

Figure 1: Zero Energy Experimental Pile (ZEEP) Reactor

2.3 NPD (20 MWe Class)

The CANDU nuclear power reactor development program started in 1954 even though the name CANDU was not adopted until several years later. At that time a study team, called the Nuclear Power Group, was established at Chalk River laboratories. Their aim was to develop a small - scale demonstration of nuclear power reactor design that could compete economically with coal-fired stations. Although the reactor power was not specified, a maximum capital cost was defined. Initial designs to meet the cost target were limited to about 10MW (electrical).

In the early stages of the Nuclear Power Group's program a number of important "givens" were assumed by the team as the basis for design. These included the use of vertical reactor core geometry - a logical choice given the experience base established by ZEEP, NRX, and in the design of NRU. The use of a steel pressure vessel was assumed since high coolant temperatures (and therefore high pressures) would be necessary in order to achieve a useful thermodynamic efficiency for the conversion of thermal energy to electricity. Heavy water was assumed as both the moderator and coolant in order to permit the efficient use of natural uranium as the fuel. This was considered essential since Canada did not have facilities for the production of enriched uranium. For the same reasons of efficiency, on-power fuelling was assumed (this capability was earlier included in the design of NRU). Mechanical control rods were assumed for regulating and shutdown functions, also as in the case of NRU. In effect then, this early concept represented a direct evolution from NRU, i.e., an NRU reactor configuration, contained within a pressure vessel to allow reasonably high operating temperatures.

The question of the geometry and metallurgy of the fuel received particular early consideration given the necessity for relatively high operating temperatures. The team chose bundles of round rods as the most conservative approach for use with uranium metal fuel - the only "proven" form of uranium available at the time. Since aluminum alloys as used in NRX and NRU were not suitable for the desired fuel operating temperatures, zirconium was chosen as the reference fuel cladding material because of its strength and corrosion resistance under the desired operating conditions and its low capture of neutrons.

Another key question was the choice of materials for the reactor coolant system piping, coupling the reactor pressure vessel to the steam generator. While U.S. designers had chosen austenitic stainless steel for boiler tubing and coolant system piping for their early PWR's, the NPD designers and Chalk River metallurgists were concerned about stress corrosion cracking with this material. They therefore decided to use ordinary carbon steel for the pipework and nickel alloy for the boiler tubes.

By August 1955, AECL had decided to increase the demonstration plant power from 10 MW to 20 MW, so that fuel performance information would be produced more quickly and the peak fuel ratings would be closer to future commercial plant conditions. A short seven-element cylindrical fuel bundle had been selected, but with the increase in fuel rating, it became necessary to further subdivide the fuel, and a 19-element bundle design was selected. This early decision on a 19-element bundle configuration, 80-mm in diameter set the pattern for CANDU fuel development. Current fuel bundles have 37 or 43 elements (see Figure 2). A 50 cm length was recognized to be extremely convenient to make and handle, and has proven to be very reliable and sufficiently efficient. This offers several advantages: ease of manufacture, handling, shipping, facilitates bi-directional on-power fuelling to maximize burn-up; and simple compact irradiated fuel transfer and storage. The same 50 cm length is used for CANDU fuel today. The choice of fuel-sheath thickness is another prime example of the influence of the CANDU design pioneers on the project. The early designers were determined to minimize the non-fuel materials within the reactor core that waste neutrons and thereby limit the total heat output from the fuel. The goal was a fuel irradiation of 240 MWh/kg, which would result in an attractively low fueling cost for commercial reactors. Early experiments of thin fuel sheaths performed well and ever since all CANDU fuel has been sheathed with 0.4mm thick Zircaloy tubing, which has achieved an outstanding low defect rate.

Figure 2: CANDU Fuel Bundle

At about the same time, the fuel material was also changed. Originally, Zircaloy-clad uranium metal had been chosen, although some priority was also given to developing a high-temperature aluminum alloy as sheathing, because of the high cost of zirconium. Work on uranium oxide as a fuel had also begun to generate results. Because of the high-temperature stability and resistance to oxidation of UO_2 ceramic, this was selected as the fuel material - and remains so to this day. By early 1957, the design of a pressure - vessel reactor or NPD was progressing, but cost estimates were rising considerably. An in-depth reappraisal of the design program was carried out, looking ahead to the application of the NPD concept to a commercial size power plant.

In the spring of 1957, the nuclear power branch reported the conclusions of this review as follows: power output had the largest effect on unit energy cost and for a commercial reactor, at least 200 MW output was required to compete with a coal-fired power station. The size of pressure vessel required for such a reactor would be much larger than an equivalent enriched uranium light-water reactor vessel, and would be beyond prevailing manufacturing capabilities in Canada. At the same time, Zircaloy pressure-tube technology was being developed in the United States for the Hanford N Reactor so a pressure-tube design was now considered to be practicable, and it was recommended by the review. Since a thirty-year amortization period would be needed to achieve a low unit energy cost, the station life was set to be at least thirty years. Another requirement was that the core should be replaceable and this would be only possible with a pressure-tube design. A horizontal orientation of the pressure tubes simplified the support of the reactor and its fuel, and made bi-directional on-power fueling practicable. This fueling system was a major and essential innovation. Short fuel bundles would be inserted in one end of a fuel channel and would be moved progressively through the channel as each new bundle was added and an irradiated one removed from the other end. By fueling adjacent channels in opposite directions, a more uniform neutron flux could be obtained throughout the reactor. The higher net neutron production from fresh fuel would offset the neutron losses by absorption in the fission products within fuel nearing the end of its irradiation in the adjacent channel. All the fuel could be discharged from a channel at roughly the same total irradiation, which would be about twice that achievable with unidirectional fueling or with full core-length fuel bundles. The higher average fuel irradiation achieved with this fueling scheme helped to compensate for the extra neutron loss by absorption in the pressure tubes. However, the one disadvantage of the pressure-tube design was its higher capital costs due to increased heavy water volume in the moderator system relative to a pressure vessel design. This was because a wider spacing between channels was required to accommodate feeder pipes at each end of each channel and the head of the fuelling machine.

This program set the main conceptual design features of CANDU reactors. Most of these have been retained to this day. The choice of a pressure-tube reactor design removed any limit on the reactor size, so that the same basic design could be used as progressively larger units were required.

By August 1957, a conceptual design that incorporated most of the familiar features of the CANDU reactor was produced. These features included, in particular, the horizontal “calandria” reactor vessel, stainless steel end fittings and their rolled joint connection to the pressure tubes, and the associated fuel channel closure seal plugs. The material selections for the fuel, reactor coolant system piping and the boiler tubes were carried over from the earlier design.

These major new features had to be designed, developed and tested.

For reactor control, an ingenious system was proposed of using moderator level variation to adjust core reactivity. This was combined with a means of rapidly dumping the moderator into a dump tank below for reactor shutdown.

A major concern with any heavy-water reactor is to avoid losses of this valuable material. Extensive leakage-collection systems were installed. However, these could not be applied to the many joints and valves in the high-pressure, heat transport system, where small leaks of heavy water might occur. Here, the leaked heavy water would immediately vaporize. The answer was to isolate the reactor vault and the boiler room so that large air driers could recover the bulk of this leakage.

NPD ran well throughout its operating life till 1985 and provided early experience with CANDU components, systems and materials. NPD was also a test bed for new fuel-bundle design, for alternative pressure-tube materials, new instruments and other components, despite the fact that its neutron flux was considerably lower than that in large CANDUs.

2.4 DOUGLAS POINT (200 MW Class)

In 1957, AECL and Ontario Hydro decided to proceed with a detailed design assessment and development work for the 200 MW prototype commercial station named Douglas Point. At the time, a power of 200 MW was considered to be a commercial station.

To achieve the ten-fold increase in power output from NPD to Douglas Point required a higher coolant temperature to increase steam-cycle efficiency, a doubling of the maximum power rating of the fuel, a higher average to maximum fuel power rating (flatter neutron flux distribution), a 5 m (rather than 4 m) channel length, and 306 fuel channels instead of 132. There were also many changes in the details of material selection, component and systems design from NPD. Zircaloy calandria tubes and a stainless-steel calandria were selected for greater strength and better corrosion resistance than aluminum as used in NPD. These materials became the norm for all future CANDUs. The reactor and its auxiliaries were housed in a containment building with radiation shielding and pressure retention provided by 1-m thick walls, rather than in an underground vault. A more elaborate water spray dousing system was provided to control pressure in the building in the event of a major release of steam.

A major innovation was the use of extensive computer data processing and a limited degree of computer control. Douglas Point was the first reactor in the world in which a reactivity-control element was positioned by a stored-program digital computer.

Douglas Point was declared in-service in September 1968. Initial operation included many challenges, - from which important lessons were learned for the development of later CANDU’s. For example, the main coolant pumps had to be modified; valves required frequent maintenance. Heavy-water leakage was also excessive. Much development work on valve, rotating equipment and piping joint seating was required to bring this under control and keep losses within an acceptable range.

Radiation fields were high. This problem was the result of poor water chemistry control, resulting in the movement of radioactive corrosion products, generated in the core, into the steam generators and other out-reactor components. This was remedied by developing a chemical process for removing the corrosion products, and improving the chemical control procedures.

It also demonstrated that the standard engineering quality accepted for many conventional components was not sufficient for nuclear application. This caused AECL to expand its R&D effort to take an in-depth look at many out-reactor components (for example, pump seals, valves, steam generators and heat exchangers), and to develop much more rigorous specifications for them.

3. THE INTRODUCTION OF COMMERCIAL CANDU's

3.1 PICKERING A (500 MW Class)

By 1964, studies by Ontario Hydro showed that a 500 MW reactor series would be needed to compete with the newest coal-fired stations, which consisted of multiple 500 MW units. Also, the high expected rate of expansion of the Ontario Hydro electrical system required the addition of large blocks of power to serve Ontario's booming economy.

As a result, design work started on Pickering "A", a 4 X 550 MWe unit plant, built at the edge of Toronto. This was the first commercial CANDU and was designed by a joint AECL/Ontario Hydro team. Many features were based on Douglas Point, incorporating the lessons learned from its construction and operation. Pickering included the now standard pressure tube size, and more highly -subdivided 28-element fuel bundles, allowing significantly higher average fuel bundle and channel power. In the early years, the performance of the Pickering A units was outstanding and these units consistently showed in the "top 10" performing units worldwide. Unfortunately, at the time of construction, some design issues had not yet been fully understood. In particular, Units 1 and 2 had pressure tubes made of Zircaloy 2. This is now known to be subject to high rates of hydrogen (deuterium) pickup and consequent hydride cracking. Also, creep elongation rates of pressure tube material proved to be greater in service than had been anticipated. After some 10 years of service, the Pickering A units were taken out of service in sequence for retubing using the more hydrogen resistant Zr - 2.5% Nb alloy. This alloy has proved effective for long-term service in all subsequent CANDU's. The replacement pressure tubes have performed well, and lessons learned from the replacement program will help faster replacements of fuel channels in future.

The scale-up in power to 550MW from Douglas Point's 200 MW was achieved by adding 27 percent more channels, increasing the channel diameter to 103 mm, with a corresponding 50 percent increase in allowable fuel bundle power, and achieving a flatter flux distribution to raise the average bundle power.

At Pickering the next step in automation of reactor control was also taken. All major plant processes were to be controlled by the central computer. Since failure of the computer would shut the reactor down, a second identical computer was added on standby and was designed to take over at any time. This arrangement has worked well, and has been used in successive CANDUs with increasing levels of sophistication.

An important feature of on-power fueling is the ability to remove failed fuel bundles before they can deteriorate and seriously contaminate the heat-transport system. Thus, in CANDUs, fission products make only a minor contribution to radiation fields around steam generators or piping after shutdown. Instruments that measure gaseous fission products and radioiodine in the coolant are used to detect any failures. Two methods were developed to locate the channel containing the failed fuel bundles. One is to scan the gamma radiation from each of the outlet feeder pipes during shutdown, to detect accumulated solid fission products (e.g., zirconium-95, niobium-95 and lanthanum-140) that deposit on the walls. The other is to measure the amount of two short-lived volatile fission products, which emit delayed neutrons (bromine-87 and iodine-137), in a sample of coolant from each channel using an on-line delayed-neutron monitoring system. The latter are used at both Bruce stations and the CANDU-6 reactors, while gamma scanning is used at both Pickering stations and Darlington.

3.2 BRUCE (745 MWe)

In 1968, Ontario Hydro committed four 745 MW units to be built adjacent to Douglas Point, and this became the Bruce A plant, which first entered service in 1977. They were the first units to have large coolant circulating pumps of only four per unit. Steam generator size was more than doubled from Pickering, so that only eight per unit were required. The increased reactor power output was achieved by a combination of additional fuel channels and the introduction of the 37-element fuel bundle in which the diameter of the individual elements was reduced by 15 percent. This fuel bundle design was a successful optimization of durability, moderate fuel rating and low cost and it has been used on all subsequent CANDU's. Each Bruce A reactor was designed for a net electrical output of 745 MW.

Some significant improvements over Pickering were also included in the Bruce design. For example, the reactor control system made extensive use of self powered "in core" flux detectors made of platinum and vanadium wire coils. These "Hilborn" detectors (a Canadian design) allowed for a sophisticated mapping of reactor neutron flux which in turn made it possible to control the reactor flux more precisely using liquid zone control rods. These detectors were also used in the shutdown systems to provide safety monitoring to prevent overpower in any region of the core. The Bruce design was also notable as the first reactor design with 2 fully independent diverse shutdown systems, employing both gravity-driven absorber rods and liquid injection of neutron poison into the moderator. The Bruce design, with the higher core power, also included a high-pressure emergency core coolant system. For Bruce, this could be backed up, for severe accidents, by the cool, low-pressure moderator as an emergency heat sink for the fuel channels, since the emergency moderator dump was now not needed.

4. TODAY'S CANDU PLANTS

4.1 LATER ONTARIO HYDRO UNITS

Subsequent to Bruce A, a series of three 4-units stations were built by Ontario Hydro, incorporating changes of a more evolutionary nature:

- Pickering B - sister units to the Pickering A design, but with safety systems and reactor and coolant systems design similar to the CANDU 6 (see below)
- Bruce B - sister units to Bruce A, but again settling on standard reactor control concepts as for the CANDU 6.
- Darlington - retaining the 900 MW class Bruce-type reactor design, but introducing the application of the four - boiler, two - loop coolant system concept to the larger size. Darlington pioneered the increased application of digital computer control to all safety system functions for the two shut down systems.

4.2 CANDU 6 (700 MW Class)

Starting in the early 1970's, AECL developed the single-unit station design, now known as CANDU 6. CANDU 6 utilizes fuel channels, end fitting hardware and fuel handling machine in use at Pickering, the 37 element fuel in use at Bruce, the Bruce reactor control system (with some improvements), and a single boiler and heat transport pump for each of the four quadrants in the 2-loop coolant system.

More allowance has also been made for pressure tube creep in the CANDU 6 design, allowing axial creep to be accommodated over its full life. The choice of low cobalt steel for the heat transport system piping, equipment and valves has also reduced its radiation fields, due to corrosion product activation.

The CANDU 6 has also adopted the use of a steel-lined concrete reactor vault filled with light water, as the primary reactor shielding and support structure. It is notable that, as attention to severe accidents has increased, this has been recognized and confirmed as an inherent emergency heat sink for a degraded core.

As a single-unit design, the CANDU 6 established a distinctive containment design. The reactor building is of pre-stressed concrete with a water-spray dousing system for pressure suppression.

The CANDU 6 design has evolved continuously over the years since the original four units (Pt. Lepreau and Gentilly-2 in Canada, Embalse in Argentina, and Wolsong-1 in Korea) went into service in 1983 and 1984. The most recent units entering service in 1996 - 99 include Wolsong 2, 3, and 4, and Cernavoda in Romania. Units are also under construction at Qinshan, Zhejiang Province, in the People's Republic of China. Figure 3 shows Unit-4 at Wolsong.

Figure 3: Wolsong Unit-4, Republic of Korea

Recent innovations in CANDU 6 design have included the extension of the plant design life to 40 years; improved reactor building atmospheric control system for reduced emissions; extended use of qualified software for shutdown systems; the inclusion of advanced operator display systems in the control room; the use of hydrogen igniters for severe accident mitigation.

AECL continues to examine further innovations for the CANDU 6 design series, to identify those which offer advantages for the owner, and are sufficiently proven to be incorporated into the design.

For shorter-term development, AECL has embarked on a program of significant enhancements to the CANDU 6 design. The objective here is to improve economics, and streamline licensing while retaining the operating CANDU 6 experience base.

An example of innovation which is successfully undergoing proof - testing is the next - generation CANFLEX fuel bundle design. The advanced CANFLEX fuel bundle is the logical evolution from current CANDU bundle designs. With 43 elements (where the current CANDU fuel bundle designs have 37 or 28) and two element sizes, CANFLEX provides enhanced reactor performance, increased safety margins and a greater spectrum of fuel cycle options. Because it achieves reduced ratings for high burnup, it is the optimal fuel carrier for CANDU while yielding additional benefits of natural uranium fuel.

4.3 CANDU 9 (900MW Class)

The CANDU 9 is a larger single - unit design, based on the 900 MWe class reactor with 480 fuel channels. Just as CANDU 6 evolved from Ontario Hydro's Pickering four-unit stations, CANDU 9 is an evolution of the larger integrated four-unit Darlington (see Figure 4) and Bruce B nuclear stations.

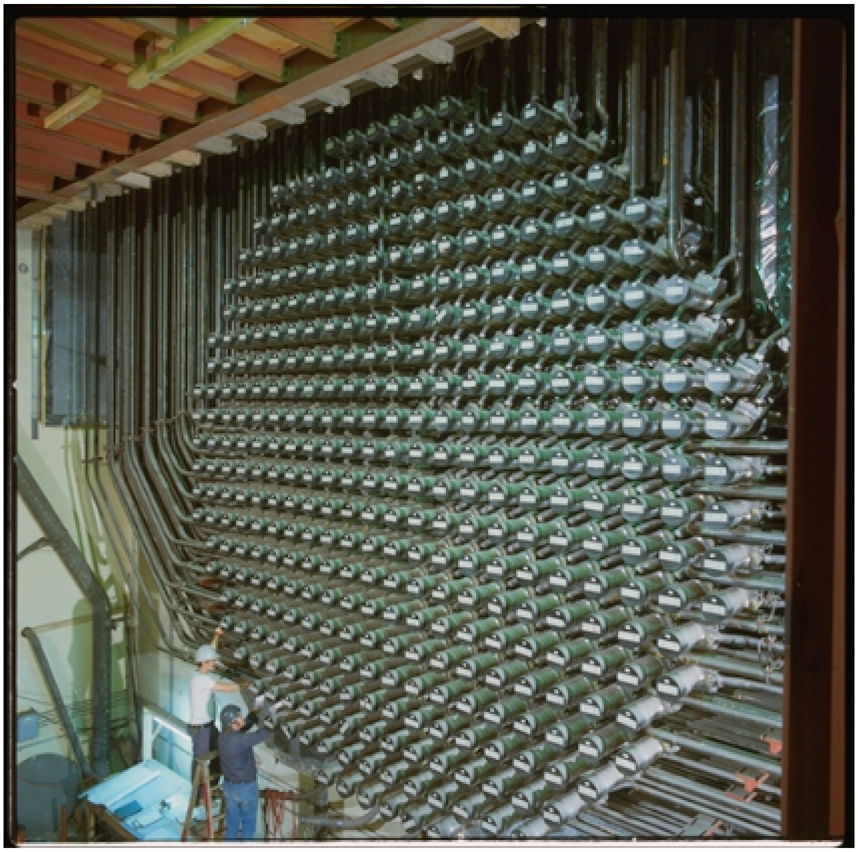

Figure 4: Darlington Calandria, 480 Fuel Channels

The CANDU 9 is a 935 MWe reactor design with some significant additional enhancements from ongoing engineering and research programs. Reduced project implementation risk has been assured for CANDU 9 by up-front engineering and licensing prior to contract start. In addition, the CANDU 9 design, from the beginning, has used state-of-the-art information technology such as 3D-CADDs plant wide modeling linked to material management and equipment databases. The CANDU 9 design has been developed emphasizing constructability (such as optimization for modular construction and open-top construction) and maintainability (such as ensuring ample space for equipment access).

Added to the advantages of using proven systems and components, CANDU 9 offers improvements providing enhanced safety, a control centre with better operability via CRT computer based operator interface, and sophisticated alarm processing.

CANDU 9 design includes a number of safety enhancements, such as a containment which is simplified by the elimination of the dousing system and has a lower design leakage rate, more reliable isolation, better hydrogen mitigation; a reactor coolant system with a larger pressurizer, capable of accommodating volume changes from full power to the cool (100^0C) shutdown condition; improved layout and separation between steam and water systems and electrical systems, together with the seismic qualification of the Main Control Room; better provisions for mitigating severe accidents by use of a reserve water system (supplied by a high level emergency water tank in the reactor building) including improved provisions for steam relief from the shield tank; the replacement to conventional valves in the emergency core cooling system with passive one-way rupture disks and floating-ball isolation valves.

A Group 2 feedwater system, engineered to supply emergency water to the steam generators automatically, for decay heat removal for approximately 10 hours.

The main control room remains functional for all design basis accidents, including external events such as an earthquake, whereas the secondary control area is only required for an event such as a major fire or hostile takeover which may require an evacuation of the main control room.

For improved operational capabilities, the CANDU 9 design has incorporated an advanced control centre (see Figure 5). The control centre features standard panel human-machine interfaces that provide an integrated display and presentation philosophy. A large, central overview display presents immediate and simplified plant status information for operation awareness of the plant situation in a very easily read format. A powerful and flexible annunciation system provides extensive alarm processing.

Figure 5: CANDU Advanced Control Centre

A major evolutionary change from previous CANDUs is the separation of the Control and Display/Annunciation features formerly provided by the digital control computers. The CANDU 9 plant monitoring, annunciation, and control functions are implemented in two evolutionary systems: the Distributed Control System (DCS) and the Plant Display System (PDS). The DCS implements most of the plant control functions on a single hardware platform while PDS similarly implements the main control room display and annunciation functions. This permits extensive control, display or annunciation enhancements within an open architecture, providing great flexibility.

And, as with CANDU 6, the CANDU 9 incorporates all the proven features of CANDU, such as high neutron economy, proven safety, fully automated plant control and on power fuelling capability. In addition, by making changes in fuel, the number of fuel channels and the size of the other components, the CANDU 9 design is capable of being adapted to increased output for future market energy requirements of 1300 MWe and beyond.

5 CONCLUSION

Just as the NPD reactor was the first demonstration of CANDU's unique ability to refuel on-line, each new project advances the CANDU design, while keeping proven features. The on-line fuelling capability chosen at the outset is still a strong benefit for the reactors. CANDU's unequaled neutron efficiency is a direct result of the reactor being designed specifically to produce electricity.

The CANDU design will continue to evolve. The objective is to constantly enhance reactor economics by lowering costs and improving performance, to further enhance reactor safety, and to contribute to sustainable development by fully exploiting CANDU's fuel cycle flexibility. This is based on collaboration between designer, partners and utilities.