CANDU® Development: The Next 25 Years

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Abstract

CANDU® Pressurized Heavy Water Reactors have three main characteristics that ensure viability for the very long term. First, great care has been taken in designing the CANDU reactor core so that relatively few neutrons produced in the fission process are absorbed by structural or moderator materials. The result is a reactor with high neutron economy that can burn natural uranium and a core that operates with 2-3 times less fissile content than other, similarly-sized reactors. In addition to neutron economy, the use of a simple bundle design and on-power fuelling augment the ability of CANDU reactors to burn a variety of fuels with relatively low fissile content with high efficiency. This ensures that fuel supply will not limit the applicability of the technology over the long term. Second, the presence of large water reservoirs ensures that even the severest postulated accidents are mitigated by passive means. For example, the presence of the heavy water moderator, which operates at low pressure and temperature, acts as a passive heat sink for many postulated accidents. Third, the modular nature of the core (e.g., fuel channels) means that components can be relatively easily replaced for plant life extension and upgrading. Since these factors all influence the long-term sustainability of CANDU nuclear technology, it is logical to build on this base and to add improvements to CANDU reactors using an evolutionary approach. This paper reviews AECL's product development directions and shows how the above characteristics are being exploited to improve economics, enhance safety, and ensure fuel cycle flexibility for sustainable development.

1.0 Introduction

CANDU® Pressurized Heavy Water Reactors (PHWRs) have a number of characteristics that ensure the long-term applicability and future potential of the technology. These features are summarized in Figure 1. As a result of the flexibility of the technology, evolution of the current design will ensure that any future requirements can be met, and there is no need to change the basic concept. The main reasons for this are:

- Fuel cycle flexibility: CANDU reactors were, first and foremost, designed to be highly efficient burners of fissile material and are highly efficient converters of fertile to fissile material. Combining this with on-power fuelling and a simple fuel bundle design, CANDU reactors can burn many different fuels, and fuel supply can be secured for the foreseeable future.

- Large heat sinks: CANDU reactors contain large reservoirs of water that are effective in passively removing heat from the core in the event of loss-of-cooling accidents. In addition, the presence of these reservoirs may lead to passive cooling systems for normal operation that will simplify the plants and enhance reliability. Therefore, the design can evolve to make even better use of these reservoirs.
- Replaceable components: All critical components in a CANDU reactor are replaceable, such as fuel channels. This means that CANDU plant life can be extended beyond the design life, and that components can be upgraded with the latest technology. Therefore, obsolescence is not a problem with currently operating reactors.

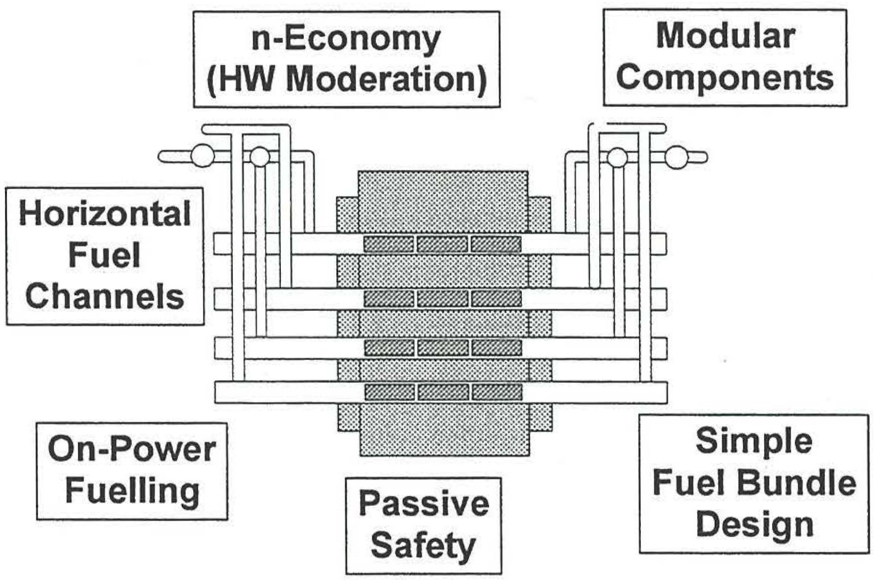

Figure 1. Essential Features of CANDU Pressurized Heavy Water Reactors

It is these features that define the CANDU PHWR as a product and that preserve flexibility in applying CANDU reactors to national requirements. Moreover, within these limits, there is considerable scope for continuing development. As a result, CANDU development over the next 25 years will focus on enhancements to the basic design. The improvements being incorporated into the design will result from an in-depth understanding of materials, processes, and systems, which will ensure that CANDU reactors continue to rest on a firm technical base. The following sections describe AECL's development programs for continuing evolution of the CANDU design and the associated underlying technology.

Evolution of CANDU Reactors

Canada has more that 50 years of experience with nuclear fission technology, which began with the ZEEP reactor at Chalk River in 1945 and eventually led to the CANDU power reactor. Over this period, CANDU reactors have evolved along two general product lines that have led to the 700 MW(e) class CANDU 6 and the 900 MW(e) class CANDU 9, as indicated in Figure 2.

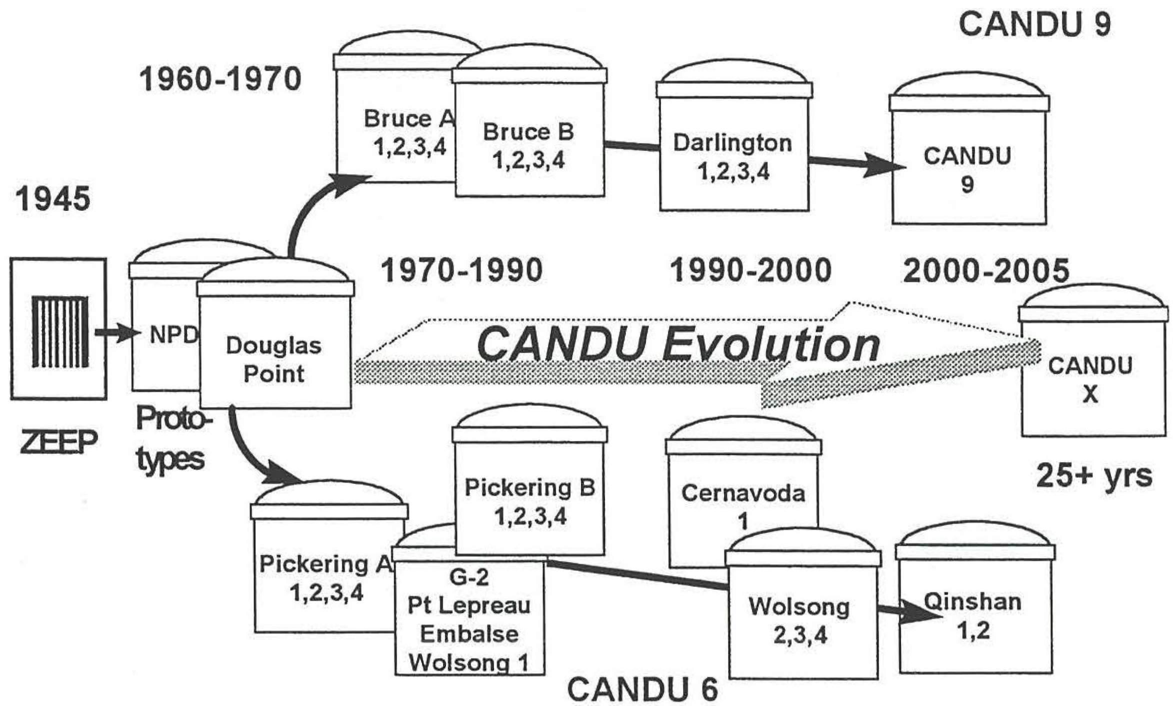

Figure 2. CANDU Evolution

The original CANDU PHWR prototype 25 MW(e) reactor, the Nuclear Power Demonstration (NPD) reactor, was built near Chalk River Laboratories by a consortium consisting of AECL, Ontario Hydro and Canadian General Electric (now GE Canada). NPD, which went into service in 1962, introduced several new features that are now characteristic of CANDU reactors, including horizontal pressure tubes, uranium oxide fuel, simple fuel bundles, and on-power refuelling.

The second prototype CANDU reactor was built at Douglas Point in Ontario and achieved first criticality in 1966. This was a 220 MW(e) power reactor which was a prototype for future commercial units. It was the first reactor in the world to use a digital control computer for data gathering and some aspects of reactor control.

The Pickering A 4 x 540 MW(e) unit plant, built at the edge of Toronto, was the first commercial CANDU reactor based on Douglas Point. Pickering included the now standard pressure tube size, and 28-element fuel bundles (compared to the 19-element Douglas Point fuel), which allowed a significantly higher average fuel channel power.

The CANDU 6 units adopted many of the features pioneered and developed for Pickering A and added some additional features from Bruce A. CANDU 6 reactors utilize fuel channels and end fitting hardware in use at Pickering, the 37-element fuel in use at Bruce, and the Bruce reactor control system (with some enhancements). Six CANDU 6 PHWRs are currently operating, and 5 additional reactors are under construction. To date, 5 countries have adopted the CANDU 6 for power generation.

The CANDU 6 reactors now in service have performed extremely well. The Point Lepreau reactor was, for a number of years, in first place for lifetime capacity factor. The other CANDU 6s are not far behind. Wolsong 1 in Korea has also achieved first place in world capacity factor ranking on an annual basis on more than one occasion. The CANDU 6, therefore, is a robust, mature design with a solid record of operating performance.

Building on the success of the Pickering Units, Ontario Hydro and AECL decided to build four larger unit stations at Bruce in the 1970s with unit outputs in the 900 MW(e) range. The Bruce site was expanded to eight 900 MW(e) class reactors in the 1980s, and four additional 900 MW(e) class units were commissioned at Darlington in the early 1990s. The latest version of these designs is the CANDU 9 reactor.

The CANDU 9 continues the basic approach adopted for the CANDU 6. The CANDU 9 is a 935 MW(e) reactor based on the multi-unit Darlington and Bruce B designs with some additional enhancements from our ongoing engineering and research programs[1]. Since one of the major risks associated with nuclear power projects is delays due to licensing activities, AECL has submitted the CANDU 9 design to the Canadian nuclear regulator (AECB) for review, and it has been confirmed that there are no conceptual barriers to licensing the CANDU 9 in Canada[2]. The CANDU 9 has been designed for a service life of 60 years at a capacity factor of 90%, and has a number of enhancements over previous plants. For example, the layout of the CANDU 9 design allows a narrow 110 meter wide "footprint" that allows several units to be constructed adjacent to each other to form a very compact multi-unit station[3].

Power increases can have a large effect on the unit cost of electricity, especially if they can be accomplished with relatively small changes in plant costs. One approach to increasing the power of PHWRs is to switch from natural uranium to Slightly Enriched Uranium (SEU) fuel containing 0.9 to 1.2% U-235. The SEU can be used to flatten the power distribution over the core to produce about 15% more power, without changing the core design. Alternatively, owing to the modular nature of the core, it is possible to add more fuel channels. For example, the CANDU 9 contains 480 fuel channels. The number of channels could be increased to 640 in a similarly sized calandria vessel, with an increase in power to 1275 MW(e). In the longer term, it may be possible to operate the primary heat transport system at much higher temperatures, thereby substantially increasing the thermodynamic efficiency. Such a change would require considerable advances to our understanding of materials at elevated temperatures under reactor core conditions, but the efficiency gains could have a significant impact on unit energy costs.

3.0 CANDU Development Program

AECL has a comprehensive product development program that is advancing all aspects of PHWR technology, including fuel & fuel cycles, fuel channels, heavy water and tritium, safety technology, components and systems, constructability, health and environment, and control and instrumentation. As discussed above, the technology arising from these programs is being incorporated into the CANDU design through an evolutionary process that emphasizes incremental improvements without changes to the basic proven design.

There are three main strategic thrusts for the development program: improved economics, enhanced safety, and fuel cycle flexibility. These strategic thrusts are being used by CANDU designers and researchers to set priorities and to provide a focus for AECL's development activities, and are translated into specific goals for each of the development areas listed in the above paragraph.

These goals are part of a 25-year development program that culminates in the "CANDU X". The "CANDU X" is not a specific design – it is a concept that incorporates our best extrapolation of what is achievable with the CANDU design over the next 25 years, and includes the advanced features arising from the R&D to be done over that time.

3.1 Fuel and Fuel Cycles

CANDU fuel cycle flexibility arises naturally from excellent neutron economy, on-power fuelling, and simple fuel design. The exploitation of this flexibility results in fuel cycles that optimize the use of uranium resources, that can exploit the natural Light Water Reactor/Pressurized Heavy Water Reactor (LWR/PHWR) synergism, and that secure long-term fuel supply even if uranium resources become scarce[4]. All these fuel cycles are part of the overall strategy for sustainable development using CANDU technology.

3.1.1 Natural Uranium

Currently operating CANDU power reactors use a once-through natural uranium fuel cycle, which avoids the need for securing a supply of enriched uranium. The low fissile content of natural uranium means that this cycle will only work for a reactor having very high neutron economy. Also, the high conversion ratio (about 0.8) provides a high fissile material production rate. In fact, about 50% of the fission energy from natural uranium fuel comes from plutonium, which contributes about 70% of the fission energy at fuel discharge. As a result, uranium resource consumption is quite low compared to the enriched fuel cycle used in PWRs (Figure 3).

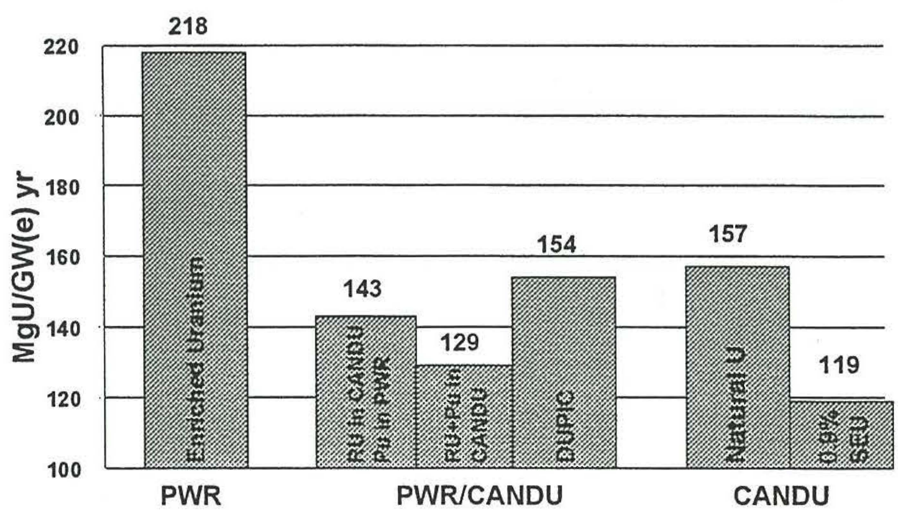

Figure 3. Uranium Utilization for Various Fuel Cycles

3.1.2 Slightly Enriched Uranium (SEU)

Even higher efficiencies can be gained by extending the fuel life by using SEU fuel, at U-235 enrichments in the range 0.9 to 1.2%. With an enrichment level of 1.2%, burnup is extended to 22000 MWd/te from about 7300 MWd/te for NU, and uranium consumption drops by about 30%. In addition, owing to the higher burnup, the volume of waste arising from this cycle is reduced by a factor of 3. More than 600 SEU fuel bundles have been irradiated in the NPD CANDU prototype reactor, and this cycle is available today for CANDU reactors.

A special sub-set of SEU, 0.9% U-235 recovered uranium from LWR fuel reprocessing, is considered in the next section.

3.1.3 LWR/PHWR Synergism

There is a natural synergism between LWR and PHWR fuel cycles that, for example, can form the basis for a "two-reactor LWR/PHWR policy"[5]. LWRs are designed to burn enriched uranium (about 3.5% U-235) fuel down to a fissile content of 1.5% (0.9% U-235, 0.6% Pu) at the end-of-life of the fuel. CANDU NU fuel starts with 0.7% U-235, which is burned down to concentrations of enrichment plant tailings (about 0.2%). Therefore, CANDU reactors are in a unique position to take advantage of the relatively high fissile content of spent LWR fuel. A number of strategies for the use of spent LWR fuel in CANDU reactors are possible. These are illustrated in Figure 4, and are further discussed in subsequent sections.

Recovered Uranium

In conventional reprocessing, uranium and plutonium are separated from the fission products and other actinides in the spent fuel. The recovered uranium (RU) from conventional reprocessing still contains valuable U-235 (typically around 0.9%, compared to 0.7% in natural uranium fuel). This can be burned as-is in PHWRs, without re-enrichment, to obtain about twice the burnup of natural uranium fuel. Also, approximately twice the energy would be extracted using CANDU reactors, compared to re-enrichment of RU for recycle in a PWR. The U-235 would be burned down to low levels (i.e., 0.2%) in PHWRs compared to PWRs (0.9%) so there may be no economic incentive for further recycle of this material. The CANDU spent fuel would then be ultimately disposed of, after a period of dry storage, in a deep geological repository.

Recovered uranium is currently a liability to many PWR owners, who have no plans to recycle it in their PWRs, because of the complications in fuel fabrication with re-enriched RU, and marginal, if any, economic benefit in PWR-recycle. Therefore, the use of RU in CANDU reactors would appear to be an extremely attractive way of dealing with a waste product while at the same time extracting additional energy.

Recovered uranium can be readily accommodated in operating CANDU reactors, with fuel performance within the natural uranium operating envelope[6]. In fact, with CANFLEX fuel (see section 3.1.5) and channel power flattening, the peak element ratings for all the fuel in the core could be reduced to below 40 kW/m, with virtually no fission gas released in the free inventory of the fuel.

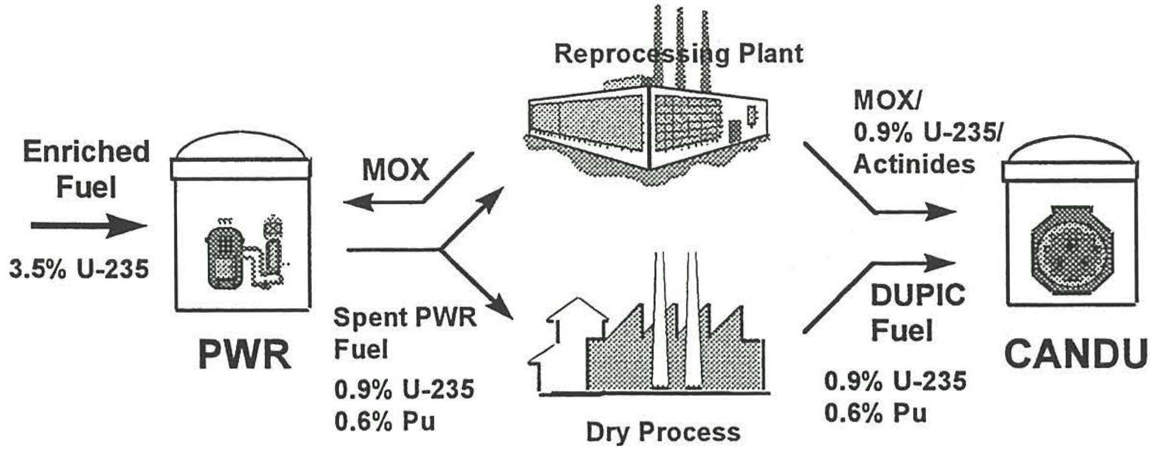

Figure 4. CANDU/PWR Fuel Cycle Synergism

Mixed Oxide (Pu, U)O_2 Fuel (MOX)

The other major product from conventional reprocessing is plutonium. Plutonium is currently mixed with depleted uranium to form MOX fuel, which is recycled by loading up to 1/3 of a PWR core with the MOX fuel. However, MOX fuel can also be used in PHWRs using a full core load. While MOX fuel fabrication will be much more expensive than natural uranium, the simplicity of the CANDU fuel bundle will result in cheaper MOX fuel fabrication costs compared to PWR MOX. A high burnup CANDU MOX fuel, therefore, has the potential of considerably lowering fuel cycle costs. Up to 50% more energy could be extracted from the fissile uranium and plutonium in spent PWR fuel through recycling in CANDU compared to recycle in a PWR. This has important advantages in improving uranium utilization, reducing enrichment requirements, and in reducing the amount of spent fuel for ultimate disposal.

TANDEM Fuel Cycle

In the TANDEM fuel cycle, the uranium and plutonium from spent PWR fuel are co-precipitated without separation. This fuel cycle uniquely takes advantage of the fact that the fissile component in spent PWR fuel (about 1.5%) can be used directly in PHWRs, without adjustment of the enrichment. Fuel burnup would be about 25000 MWd/te. This cycle is potentially much cheaper than conventional Pu separation and recycle into PWRs, since relatively simple decontamination steps can be used to remove fission products from the spent fuel.

Direct Use of Spent PWR Fuel

The Direct Use of Spent PWR Fuel in CANDU (DUPIC) involves converting the spent PWR fuel into CANDU fuel without any wet chemical processing. Only dry processes are used, in which there is no selective element removal. This, along with the high radiation fields associated with the fuel, offers a very high level of proliferation resistance. The Korean Atomic Energy Research Institute (KAERI), AECL, and the US Department of State have examined several possible DUPIC cycles. These include converting the spent PWR rods into CANDU fuel bundles with or without double cladding; vibratory packing of milled PWR pellets into fresh CANDU sheaths; and thermal/mechanical processing of the spent PWR pellets to form sinterable CANDU pellets. All options were judged to be technically feasible, and the last option, called "OREOX", or oxidation/reduction of spent PWR pellets, was chosen for further study.

The current technical feasibility study by KAERI, AECL and the US Department of State involves fabricating elements and bundles, to confirm technical feasibility of the process, to optimize the process, and to obtain technical information that would enable an economic comparison to be made with alternate technologies. A preliminary economic analysis indicates that the DUPIC cycle is economically competitive with once-through cycles in Korea[7].

Actinide Burning

CANDU reactors can be extremely efficient eliminators of nuclear waste[8]. Detailed fuel management simulations have been performed for CANDU reactors fuelled with a mixture of plutonium and actinide waste in an inert matrix carrier. Over 63% of the actinides can be destroyed in a single pass through the reactor, and over 91% of the initial fissile plutonium. Refuelling rates, and bundle and channel powers are within the natural uranium operating envelope. The high thermal conductivity of the inert matrix carrier would result in extremely low fuel operating temperatures. AECL is performing reactor physics assessments of such systems, as well as investigation of suitable inert matrix materials.

3.1.4 Beyond Uranium

All fissile material for nuclear reactors is ultimately derived from U-235. This is a finite resource that must be carefully managed over the long term. One way of extending the U-235 indefinitely is through the use of fuel cycles based on thorium.

The use of thorium as an alternative fuel to uranium could secure and extend nuclear fuel supplies indefinitely. In addition, using thorium as a breeder material may obviate the need to develop cycles based on expensive LMR (Liquid Metal Reactor) Pu breeding technology.

Since thorium itself does not contain a fissile isotope, neutrons must be initially provided by adding a fissile material, either within or outside the ThO_2 fuel material. Those same CANDU features that provide fuel cycle flexibility also make possible many thorium fuel cycle options.

One option for the "Once-Through Thorium" (OTT) cycle involves the irradiation of thorium fuel bundles separately from "driver" fuel, such as SEU. The thorium and driver fuel would be irradiated at different rates, with the thorium fuel typically residing in the reactor much longer than the driver fuel. The fissile U-233 produced reaches an equilibrium level of around 1.5%, and would be burned in-situ. The energy derived from the mined uranium used in the cycle (i.e., the uranium utilization), and fuel cycle economics of the optimal OTT cycle would be compar-able to that of SEU. Hence, a source of valuable U-233 would be produced in the spent fuel at little or no extra cost. There are various options for the driver fuel in addition to SEU, such as recycled material from spent PWR fuel (e.g., DUPIC fuel) or even natural uranium fuel.

Alternatively, the fissile material can be mixed directly with the ThO_2 fuel material. The fissile "topping" material used and the burnup define a wide range of thorium fuel options.

Even higher energy production from thorium fuel can be achieved by recycling the U-233. There is an opportunity to develop new technologies applicable to thorium fuel cycles in CANDU reactors that are more economical than conventional reprocessing, and that have a higher degree of proliferation resistance -- for example, a simple fission product decontamination process that does not produce any separated fissile material.

In the very long term, with improvements to the neutron economy (e.g., by using higher purity heavy water and lower cross section materials in the core), the Th-232/U-233 cycle can be closed and operated with total independence of external fissile material. In this cycle, as much U-233 is produced in the spent fuel as is required in the fresh fuel.

The PHWR/LMR system may also be attractive if the LMR is developed over the long term. In this system, a small number of efficient LMR breeder reactors could provide the fissile material that would fuel several lower-cost CANDU reactors. If the Pu were used to drive a thorium-based cycle in CANDU reactors, then about 9 CANDU reactors could be supported using 1 LMR. Owing to the high cost of LMRs, this could be of substantial economic benefit to countries contemplating an LMR program.

In conclusion, CANDU reactors will have a sustainable supply of fuel no matter what fuel cycle and/or advanced reactor strategy is followed in the future.

3.1.5 Fuel Bundle Design

There has been continuing evolution of CANDU fuel bundle designs since the first CANDU prototypes were built. Until recently, the major changes involved increasing the number of elements in the bundle (from 7 with NPD, 19 with Douglas Point, 28 with Pickering, to 37 with Bruce, Darlington, and CANDU 6) and decreasing the element diameters, which allowed higher channel powers. This trend has continued with the next generation of CANDU fuel, the 43 element CANFLEX bundle, which is being jointly developed by AECL and the Korean Atomic Energy Research Institute[9]. In CANFLEX fuel, the outer elements are of smaller diameter than the inner elements to facilitate the higher power generation in the outer elements. This combination of element size grading and greater number of elements, results in a fuel bundle that operates at 20% lower peak linear power rating than 37-element fuel with extended burnup capability to at least 21000 MWd/te. In addition, heat transfer in the various subchannels in the fuel has been optimized by incorporating CHF-enhancing features into the design. This has increased the critical channel power margins by at least 6%. Beyond CANFLEX, AECL is studying the use of more highly segregated bundle designs that will achieve even higher burnups.

3.2 Fuel Channels

A schematic of the CANDU fuel channel is shown in Figure 5. A fuel channel consists of a Zr-2.5Nb alloy pressure tube, surrounded by a Zircaloy-2 calandria tube, and various other components such as spacers, bellows, end-fittings, and shield plugs. The pressure tubes operate at full system temperature and pressure and are insulated from the cool moderator by a CO_2 gas gap maintained by 4 spacers.

CANDU fuel channels are based on a proven design and configuration. Nevertheless, incremental improvements at the micro-structural and micro-chemical scale are being continually incorporated. By understanding in some detail the various mechanisms affecting such phenomena as corrosion, fracture toughness, and creep and growth, we have been able to make substantial improvements to fuel channels over the past decade.

The critical component of the fuel channel is the pressure tube, since this is the component that operates under the most severe conditions of temperature, stress, and radiation field.

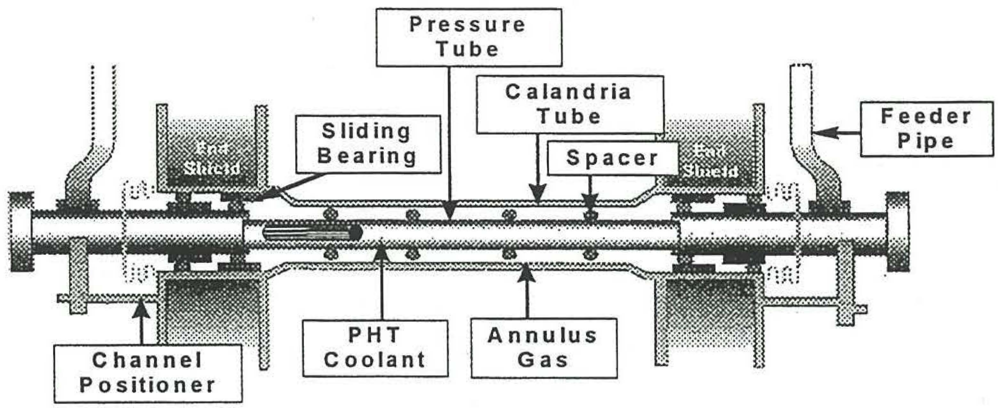

Figure 5. CANDU Fuel Channel Components

The life of a pressure tube is determined by the limits of deformation applicable to the design and the removal of causes of crack initiation and growth - such as the fracture toughness of the material and hydrogen concentrations in the tube. For example, as a result of ongoing R&D, we have specified very low levels of chlorine and phosphorous in the alloy used to make pressure tubes, which improves the fracture toughness of both the initial and irradiated tubes[10]. In addition, a careful examination of the various melting, forging, and extrusion processes has led to a considerable reduction in the amount of initial hydrogen in pressure tubes[11]. Similar developments are ongoing to decrease the rate of corrosion (and, therefore, the amount of hydrogen ingress), to control the concentration of hydrogen in the tubes, and to reduce deformation.

As a result of this work, new CANDU reactors contain pressure tubes that will have a 30 year lifetime, or more. With additional incremental improvements based on the ongoing developmental program, we believe that a 40 year fuel channel is achievable at 90% capacity factor, which represents a 33% increase in life expectancy.

Figure 6 shows how hydrogen uptake has been reduced in currently operating tubes compared to the original alloy using in the first commercial units, Pickering 1 and 2. The rates are the maximum deuterium uptake for the most affected channels - i.e., those that have the highest outlet temperatures. The Pickering 1 and 2 pressure tubes were replaced with the newer alloy, Zr-2.5Nb in the 1980s.

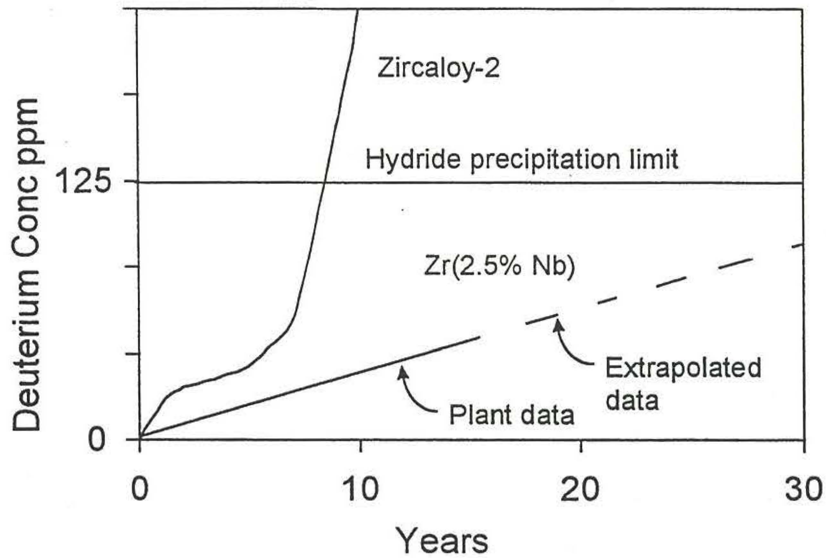

Figure 6. Maximum Deuterium Uptake in Fuel Channels

In the longer term, it may be desirable to increase thermodynamic efficiencies in CANDU reactors by increasing system temperatures (and, therefore, pressures). To accommodate such increases, AECL is developing advanced fuel channel designs that are more corrosion resistant, that transfer heat even more effectively to the moderator, and that have low deformation.

3.3 Heavy Water and Tritium

AECL is developing technologies for the production of heavy water and for heavy water management in CANDU plants, based on a proprietary wetproofed catalyst that effects rapid exchange of hydrogen isotopes between chemical species (Figure 7). This rapid exchange process can be used to concentrate deuterium in water, to upgrade heavy water by extracting H, and to detritiate heavy water.

Heavy water production technology is aimed at the extraction of deuterium from hydrogen produced by electrolysis units (CECE, Combined Electrolysis and Catalytic Exchange) and/or industrial steam reformers (CIRCE, Combined Industrial Reforming and Catalytic Exchange), and by extraction from water using a closed hydrogen loop (BHW, Bithermal Hydrogen Water)[12]. The CECE and CIRCE methods are the closest to implementation. These processes are illustrated in Figure 7.

The key to deployment of CECE technology for heavy water production is the existence of large-scale hydrogen production by electrolysis. This will depend on the ability of electrolysis units to compete with alternative means of producing hydrogen. Therefore, the cost of electrolysis cells, the cost of electricity, and the efficiency of production will all impact on the viability of CECE. Plants of the order of 100 MW(e) in size would be needed to produce heavy water at a competitive price. Nevertheless, CECE units might be an effective means to localize the production of make-up heavy water for ongoing plant operation.

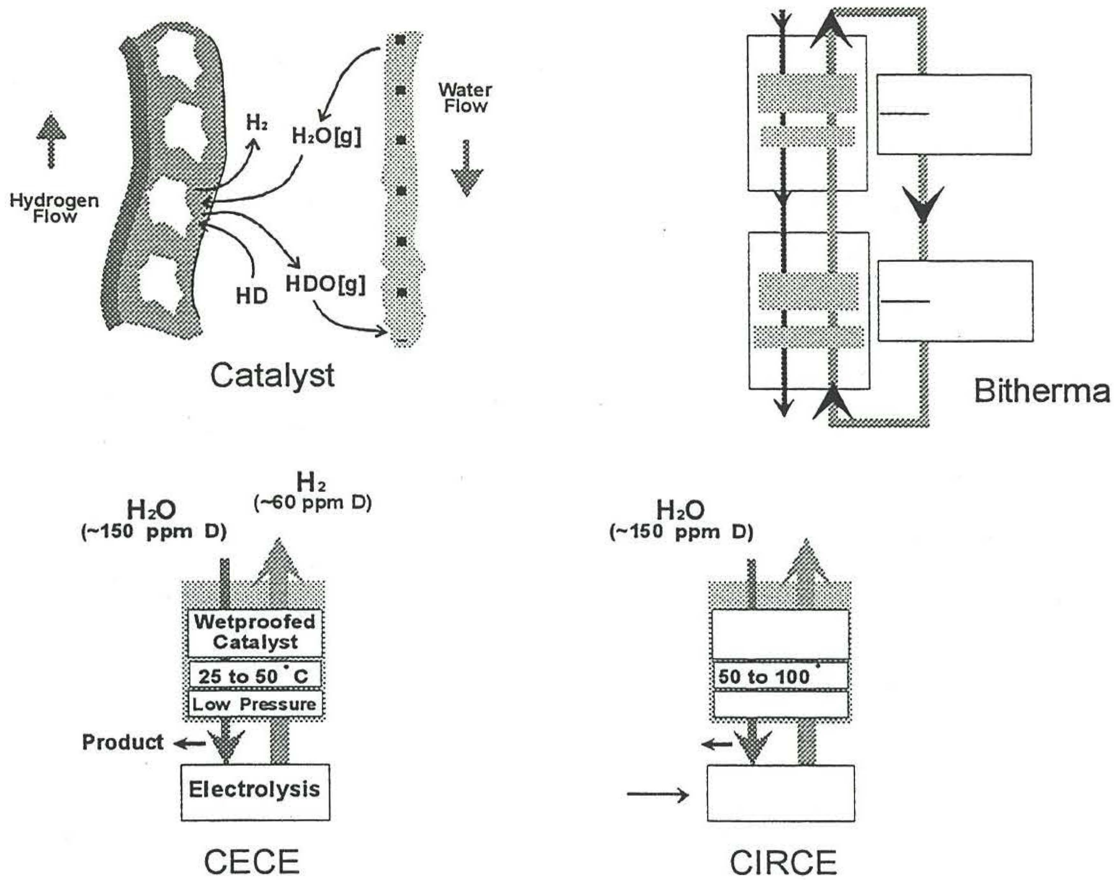

Figure 7. AECL's Heavy Water Production Technology

CIRCE technology has the potential for much larger scale heavy water production, since in most countries (including Canada), steam reforming is the dominant means of producing hydrogen. AECL's catalyst technology has now been advanced to the stage where the challenges to catalyst performance due to higher pressures and the presence of impurities in CIRCE streams have been met. Therefore, we are ready to proceed to a demonstration of the technology using a small prototype facility.

The BHW separation technology is a stand-alone process. No external source of hydrogen is needed, and the only major plant input is water. This process, which is in the early development stage, requires a catalyst that can operate for long periods of time at elevated temperatures.

Heavy water management in a CANDU reactor includes upgrading (removing H from heavy water) and, possibly, tritium extraction after a plant has operated for many years. Currently, heavy water recovered from the D_2O vapour recovery dryers and collection systems or taken from the moderator and heat transport systems, is upgraded using large water distillation columns. However, it may be possible to develop the CECE process as a cost-effective technology for both upgrading and tritium extraction that could be designed into future CANDU plants[13]. AECL is currently building a small unit to demonstrate this application.

3.4 Safety Technology

In CANDU reactors, all important safety-related systems are divided into two groups. The groups are spatially separated, and systems in one group are independent from systems in the other group. Either of the two groups can shut down the reactor, remove decay heat, prevent release of radioactivity to the public and monitor the plant status. AECL has maintained this redundancy in the evolving designs and has been continually enhancing performance via improvements to both the reliability and human factors aspects of safety-related systems. A description of CANDU safety engineering and future directions has been recently summarized by Snell and Spinks[14].

AECL has been enhancing the performance of CANDU reactors under postulated severe accident conditions that go well beyond the normal design basis for nuclear power plants. The presence of the heavy water moderator surrounding the fuel channels effectively mediates the impact of postulated severe accidents. The reason for this is that if primary and emergency coolant is lost from the system, heat is transferred out of the fuel channel and into the moderator water. From the moderator, heat can be transferred to the environment via the moderator water cooling system. This means that CANDU fuel does not melt even if both normal and emergency cooling are unavailable. In addition, the moderator is surrounded by a shield tank containing light water for biological and thermal shielding. In severe core damage accidents, where moderator cooling has also failed, the shield tank can absorb decay heat either from the moderator or from debris inside the calandria vessel, and would prevent the core from melting through to containment for tens of hours, until the water had boiled away. Therefore, in addition to the usual engineered safety systems in plants that meet international safety standards, CANDU reactors contain passive safety features that result from the inherent design of the reactor.

The CANDU 9 design has built strongly on these inherent passive safety features. For example, a large reserve water tank is located high in the reactor building and supplies water by gravity to various systems in the event of a severe accident. In particular, the tank provides severe accident prevention/mitigation by supplying water to the secondary side of the steam generators and to the primary system (in addition to the ECC), and makeup water to the moderator and shield tanks. Thus, even if the primary coolant, emergency core cooling system, and the moderator cooling system are all lost, water can be supplied from the reserve water tank to the moderator, removing decay heat for about three days via boil-off, and the severe accident would not progress to fuel melting during that time. If makeup water to the moderator and the moderator cooling system are both unavailable, then the moderator water would boil off over several hours, and the core would eventually collapse into the bottom of the calandria vessel. The shield tank water, supplied by the reserve water tank, would ensure that the debris is contained, again for about three days. Thus severe core damage accidents in CANDU 9 would progress very slowly, giving ample time for accident management and preparation of countermeasures.

Future enhancements (Figure 8) are focusing on adapting the reserve water tank to act as a passive emergency water system (PEWS) for containment cooling, for decay heat removal and/or emergency depressurization of the steam generators, and for the moderator in its role as a backup to the normal ECC system[15]. A key element of this latter concept is the development of a "controlled heat transfer fuel channel" that is capable of transferring heat to the moderator under accident conditions at lower fuel temperatures and with higher moderator temperatures than is currently the case.

The "controlled heat transfer fuel channel" uses an appropriate heat transfer material between the pressure and calandria tubes to ensure rejection of decay heat to the moderator at a low enough fuel temperature to prevent extensive fuel damage.

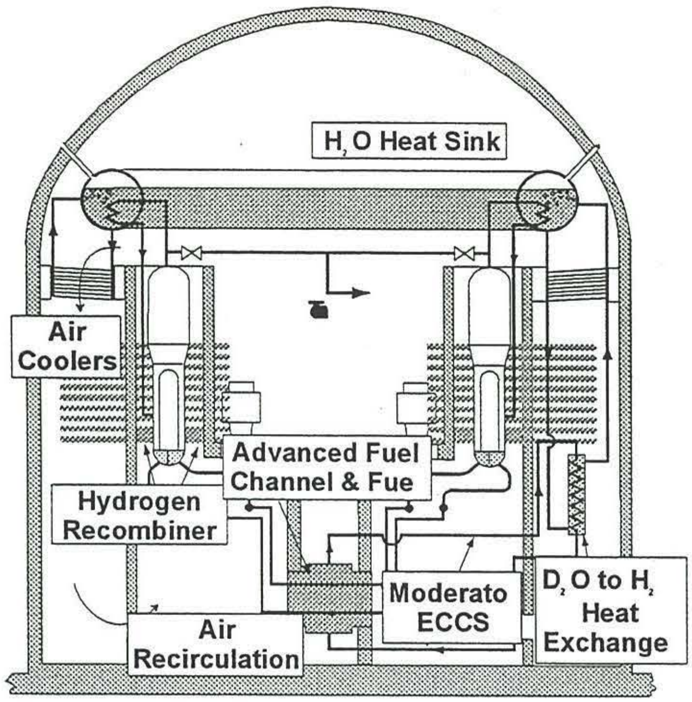

Figure 8. Advanced Safety Systems for CANDU Reactors

For this passive concept, moderator heat rejection in an accident is through a boiling/flashing natural circulation loop. It is likely that a similar system could be used for normal moderator cooling, which would eliminate the need for active cooling. The moderator would be allowed to operate near saturation temperatures to ensure effective circulation and to improve station efficiency through feedwater preheating. Analyses and large-scale tests have demonstrated the feasibility of the concept, and AECL is currently constructing a ¼ scale moderator testing facility for further development.

Other passive concepts include hydrogen recombiners, based on AECL's wet-proof catalyst, "cool" fuel concepts that lower center line temperatures by hundreds of degrees, containment heat rejection through tube banks that are cooled by natural circulation to the PEWS tank, and natural air circulation driven by the large elevation differences between the heat source and the heat sink. Some of these features are already finding their way into the current CANDU reactors. For example, passive hydrogen recombiners are specified for the CANDU 9 design.

To summarize, several passive safety concepts are being developed that will further enhance CANDU safety, even under severe accident conditions.

Components and Systems

This program is aimed at mitigating the effects of plant aging, and the development of new technologies to improve plant performance and to reduce plant capital costs. In addition, a plant life management program is being applied systematically to identify structures, systems, and components that are important for achieving the required plant performance and safety, and to determine the ease of maintaining and replacing or refurbishing them. The applicable aging mechanisms, including obsolescence, are examined for each important structure, system, and component, using various sources of experience, including feedback from operating plants[16]. The process is outlined in Figure 9.

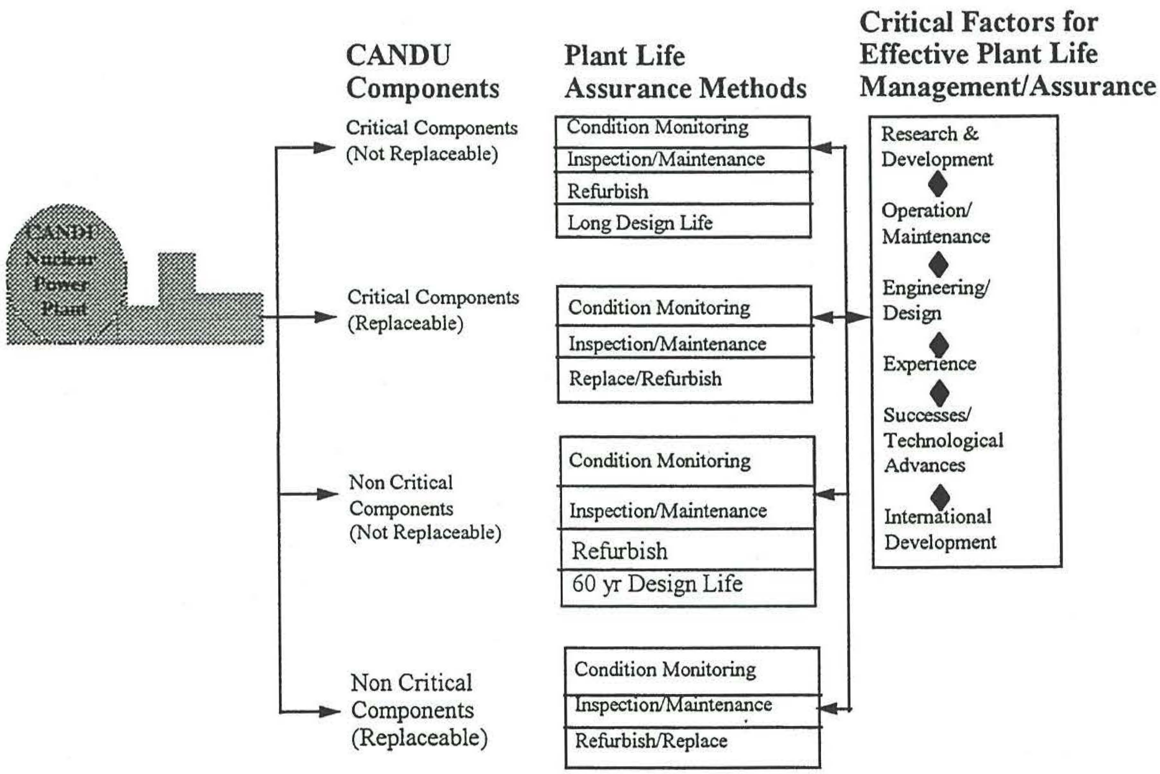

Figure 9. The Screening/Life Assurance Approach

New CANDU plants, such as the CANDU 9, are being designed for 60 years, as discussed earlier. To ensure long design life, CANDU systems and components are divided into four categories for the purposes of evaluation:

- Critical components that are non-replaceable (e.g., the civil structures)
- Critical components that are replaceable (e.g., core components)
- Non-critical components that can be designed for 60 years
- Non-critical components that may need replacement during plant life.

This initiative includes an R&D program that is directed towards the improvement of critical components (such as steam generators, heat exchangers, valves, and seals), chemistry control (heat transport chemistry and balance-of-plant chemistry), improvement to materials used throughout the station, and the minimization of emissions, waste, and operator doses. For example, one important aspect of plant monitoring is to ensure that the various chemical conditions in the plant are within specifications. AECL is developing the knowledge base and instrumentation required to continuously monitor and interpret chemistry. In the short term, information from this program will provide advice to the operators on chemistry control. In the longer term, automatic chemistry control systems may be possible.

3.6 Constructability/Project Delivery

The construction of new CANDU plants has been greatly augmented by the use of 3D CADDS to optimize sequences and configurations, the use of modular prefabricated assemblies, and the use of very heavy lift cranes to install major components through the top of the reactor building.

The design of components and reactor layout has been improved to allow many construction activities to proceed in parallel, or independently of each other. The 3D CADDS model allows us to extensively animate the assembly process to optimize the sequence and eliminate potential interferences. The model is also being used to establish improved material delivery requirements and to enhance the efficient use of site personnel. For the CANDU 9, structures have been simplified to reduce labour and shorten the schedule. Greater use is made of prefabricated structures, piping, and other skid-mounted assemblies, which are manufactured off site and put together into larger units before being lifted into place by crane.

As a result of these activities, the construction period has been shortened by at least 7 months compared to conventional construction methodology[17]. We expect to continue to optimize constructability of the plants through component simplification, advanced materials, increased use of computer applications, increased modularization, and optimization of the human resources. The overall objective is to eventually reduce project schedules to less than 60 months, as compared to the more than 70 months currently required for nuclear projects. Such a reduction will be challenging, but ultimately achievable using advanced techniques.

3.7 Health and Environment

Radiation doses from nuclear power generation are calculated using very conservative assumptions to be a very small fraction of the doses associated with natural radiation sources, and there has been a decreasing trend in the radiation doses associated with all reactor designs during the past decade. AECL is following a methodology for dose reduction that includes measurements at existing stations, examination of operational practices and data, development of improved technologies for measurement and mitigation, and rigorous review of CANDU designs to ensure that full advantage is being taken of the R&D and operating knowledge base[18]. For example, designers and researchers have adopted targets that include reducing the buildup of activation products, tritium and heavy water management processes that reduce tritium emissions, and improved waste management developments to reduce emissions during waste handling. In addition, AECL will continue to examine the more fundamental aspects of radiation and health to ensure a sound basis for any standards that impact on the CANDU product. These more fundamental programs include dosimetry, the elucidation of mechanisms underlying low-level radiation effects, and the characterization of environmental pathways. An important application of this knowledge base is to ensure that the exclusion area boundaries specified for CANDU reactors are based on sound knowledge and modeling.

3.8 Control and Instrumentation

CANDU plants have employed computerized control systems since the 1960s, and each new plant has been provided with state-of-the-art systems for optimum performance. AECL's strategy for advanced control center design is to extend the proven features of operating CANDU reactors by combining this experience base with operations enhancements and design improvements[19]. The focus for the advanced features is to improve the operability of the station, decrease the likelihood of operator or maintainer errors, and to facilitate higher production capacity factors. Since recent utility statistics show that human error is the cause of a high number of plant outages, AECL is paying particular attention to human factors in the design of our control centers and has been following a systematic design process to define requirements[20]. The human-machine interfaces, such as monitoring, annunciation, and control information, have all been verified against the design requirements to ensure that adequate and correct information is being provided for the operators[21].

The significant features of the advanced control centers include a plant-wide parameter signal database, extensive cross-checking to check similar process parameters, powerful annunciation systems with alarm filtering and prioritization, a large central overview display to present plant status, automated safety system checking, and predictive maintenance.

4.0 Conclusions

AECL has a comprehensive development program and a clear vision of how the product will evolve over the next several years. The key elements of the development program, in terms of economic improvements, safety enhancements, and fuel cycle flexibility, build on the inherent characteristics of CANDU technology. Owing to these inherent characteristics, the future potential for heavy water reactor technology is not limited by resources or evolving design requirements.

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