A Brief Introduction to CANDU9 – A New Generation of Pressurized Heavy Water Reactors

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1. Introduction

The evolution of the CANDU® family of Pressurized Heavy Water Reactors (PHWR) featuring horizontal fuel channels and heavy water moderator is based on a continuous product improvement approach. Proven equipment and system concepts from operating stations are standardized and used in new products. Due to the modular nature of the CANDU reactor concept, product features developed for one product size, say the CANDU 9, can easily be incorporated in other CANDU products such as CANDU 6. The product evolution is supported by AECL's strong commitment to comprehensive R&D programs. Therefore, CANDU reactor products will incorporate further improvements and advanced features that will utilize results from our CANDU Technology R&D programs in areas such as fuel channels, heavy water and tritium, control and instrumentation, fuel and fuel cycles, systems and equipment, safety technology and constructability.

The CANDU development future extends many decades ahead, because of the flexibility of the PHWR concept. The family of CANDU-type plants 25 years into the future is represented by the "CANDU-X" development program. This program extends the pressure tube, D_20 moderated reactor type to high-efficiency, low-cost conditions.

2. CANDU development Thrusts

There are three key CANDU development strategic thrusts: improved economics, fuel cycle flexibility, and enhanced safety operation. These thrusts coupled with Experience Feedback lead to enhanced products with low implementation risks (Reference 1).

2.1. Improved Economics

CANDU design development focuses on improving economics by simplifying systems and equipment design, by improving plant energy efficiency, and by reducing operating costs. In addition, cost reductions are being achieved by product delivery improvements. Economic benefits from delivery improvements are particularly significant in today's advanced designs such as CANDU 9.

CANDU designs utilize advanced engineering tools, such as 3-Dimensional (3-D) Computer Aided Design and Drafting System (CADDS) tools and advanced construction methods, for better economics and reduced risks to future owners. The 3-D CADDS model is used to establish the layout configuration, optimization of the fabrication sequence and construction, and the choice of prefabrication modules depending on the layout and complexities of systems.

Modularization allows the manufacturing and installation of modules in parallel with the structural concrete work at site. This not only reduces the construction schedule and costs, but also improves the accessibility for system installation within a module, therefore improving the work quality.

2.2. Fuel Cycle Flexibility

The excellent neutron economy gives the PHWR the ability to use different low fissile materials, as well as natural uranium in present-day units. This provides opportunities to improve uranium (or other fissile materials) utilization to reduce plant fuelling costs. By design adjustments to optimize reactor and fuel designs, capital cost per MW can also be reduced in future CANDU's. CANDU fuel cycle flexibility arises naturally from the neutron economy associated with the use of heavy water, the use of on-power fuelling, and the simple fuel design (Reference 2).

2.3. Enhanced Safety Operation

CANDU has many inherent and passive safety features. This type of reactor has been proven safe in operation around the world.

Among the distinctive CANDU safety features are: the extensive use of digital plant control, with an advanced control centre designed to minimize operator error and to provide easily understood information displays; two independent shutdown systems which are automatically tested; natural circulation of the primary system following loss of power; and the passive emergency heat sinks provided by the cool, low pressure moderator and shield cooling system. In adapting CANDU for the future, greater development of passive, natural systems for emergency cooling can be achieved.

2.4. Experience Feedback

AECL has for a long time recognized the importance of operational feedback in product improvement. AECL has been active in the CANDU Owners' Group on Information Exchange program where good operating practices are exchanged, events are reported, and data relevant to safe plant operation is collected screened, and distributed to COG members. COG has also held a number of annual Operating Experience Feedback Seminars to allow further exchange between utility operators and the designers.

To complement these activities, AECL has initiated a systematic feedback process which incorporates regular, formal review of lessons learned from not only operations, but also from construction, commissioning, regulatory activities as well as incorporating R&D results.

3. CANDU 9

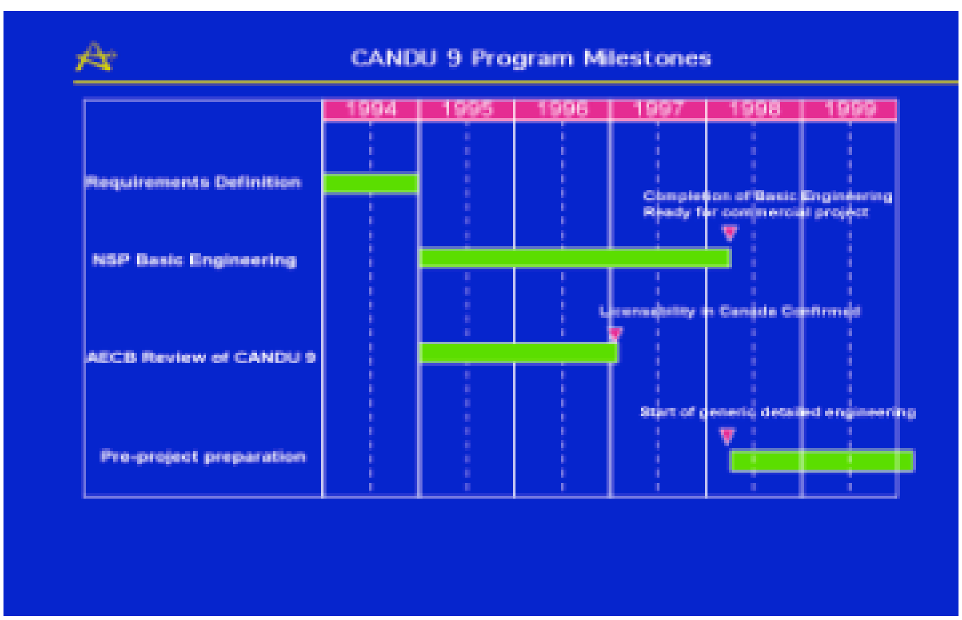
3.1 Summary

Building on the success of the 4-unit station at Bruce B which began commercial operation in the 1980s, four additional 900 MW(e) class units were commissioned at Darlington in the early 1990s, and have operated successfully. The latest, single-unit design of this type is the CANDU 9, a 935 MW(e) reactor based on the multi-unit Darlington and Bruce B designs with additional enhancements from ongoing AECL engineering and research programs (Reference 3). Reduced project implementation risk for CANDU 9 has been assured by a thorough program of up-front engineering and licensing prior to contract start.

Added to the advantages of using proven systems and components, CANDU 9 offers a number of well-proven improvements providing enhanced performance and safety, and a control centre with better operability. The design is based on state-of-the-art information technology, enabling improved project delivery in and/or both engineering and construction.

3.1. CANDU 9 Program

The basic engineering work for CANDU 9 followed the product design requirement definition work and conceptual studies, which were started in 1993. The basic 39-month engineering program started in January, 1995 and was concluded at the end of March, 1998.. In 1997 January, a two year licensing review by the AECB was completed. The CANDU 9 licensability report by the AECB noted several improvements in the design and confirmed that there are no conceptual barriers to licensing the CANDU 9 in Canada (Reference 4). The overall program milestones are shown below:



The on-going pre-project preparation will complete the CANDU 9 design work that is required to support a shorter project schedule, to evolve and progress the CANDU 9 product and to further enhance CANDU 9 project delivery.

3.2. Safety Enhancements

In their licensability statement, Atomic Energy Control Board (AECB) staff commented favorably on the key features of the CANDU 9 plant that they considered to be improvements over earlier CANDU plants.

The CANDU 9 NPP design work provided the opportunity to enhance safety, through improvement of safety performance margins and through careful attention to emerging licensing issues. These safety enhancements are highlighted in the following brief descriptions:

3.2.1. Containment

The CANDU 9 reactor building is a steel-lined, pre-stressed concrete structure that provides biological shielding and an environmental boundary (i.e. a pressure boundary in the unlikely event of a loss-of-coolant-accident (LOCA)). The improved CANDU 9 containment system uses a ‘large dry’ cylindrical steel lined containment (which needs no water sprays for pressure suppression) to achieve enhanced containment integrity with increased simplicity. The design leak rate is 0.2 % volume/day at design pressure. Because of the lower design leak rate from containment, the exclusion area radius for the siting of CANDU 9 can be as small as 500 meters, significantly reducing site area requirements for CANDU 9 plants. This is an important advantage in the context of meeting siting requirements and land availability.

Automatic isolation of the ventilation lines penetrating the containment structure has been enhanced and is provided by two separate and independent systems for increased reliability. The containment ventilation system provides enhanced atmospheric mixing within the reactor building following a postulated loss-of-coolant-accident, backed-up by hydrogen control. Passive catalytic recombiners are provided to control hydrogen concentration after a LOCA.

3.2.2. Reactor Coolant System

Two improvements were made to the principal process system of the CANDU 9, the Heat Transport System (HTS), relative to the reference design (Bruce B). One improvement consists of interlacing the fuel channel feeder pipes so that adjacent channels are alternatively connected to separate inlet and outlet headers. In this way the fuel channels served by each inlet header are uniformly distributed throughout the core. This interlaced arrangement provides a more even distribution of coolant density through the core. The second improvement is the provision of a larger pressurizer capable of accommodating changes in volume of the reactor coolant in the HTS from full power to shutdown condition at 100^{o}C. This enhances the natural circulation capability of the HTS after transients or accidents causing loss of forced flow.

3.2.3. Safety Related Systems Redundancy and Seismic Qualification

A safety grade auxiliary feedwater system has been engineered to supply emergency water to the steam generators automatically, for decay heat removal, for approximately 10 hours. This feedwater system provides back-up to the diesel driven auxiliary feedwater pump in the event of a loss of normal redundant feedwater pumps in the normal Feedwater Systems. This system is seismically qualified and is capable of full steam generator pressure operation.

In addition, the main control room remains functional for all design basis accidents, including external events such as an earthquake. 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. Both control locations and the necessary structures and systems are qualified to remain functional during design basis and external events.

3.2.4. Reserve Water System and Severe Accident Mitigation

The CANDU 9 design provides a large reserve water inventory in a torus shaped tank located at high elevation in the reactor building, above the steam generators. The reserve water tank, provides an emergency water supply for several low pressure cooling loads such as the low pressure emergency coolant injection and the backup feedwater supply, as well as providing a make-up source for the shield tank, moderator and heat transport systems.

CANDU reactors contain large reservoirs of water that are effective in passively removing heat from the core in the event of severe accidents. The fuel channels are surrounded by normally cooled moderator in the calandria vessel. A unique feature of the CANDU design is the capability to prevent fuel channel melting following a loss of coolant accident, even if the emergency coolant injection system does not function, provided by the cool, low-pressure moderator system surrounding the fuel channels.

In addition, the moderator in CANDU 9 is surrounded by a shield tank containing light water for biological and thermal shielding. The CANDU 9 shield tank with improved provisions for steam relief, provides a very large inventory of cooling water to contain overheated core components within the calandria shell and extend the time available before accident management measures are required. A further level of passive heat removal for CANDU 9 is achieved by providing gravity-fed inventory to the calandria and shield tank from the reserve water storage tank.

3.2.5. Emergency Core Cooling System

The CANDU 9 emergency core cooling (ECC) system design has been simplified to improve the reliability and performance of the system, to enhance system operation in the event of a Loss of Coolant Accident (LOCA). The key improvements and simplifications made in this special safety system includes the following:

- Replacement of D2O isolation valves by one-way rupture discs to separate the heavy water reactor coolant from the light water used for ECC;
- Elimination of high pressure injection valves;

- Location of ECC water tanks inside containment;
- Shorter ECC water injection lines.

These simplifications for the ECC have further increased the reliability for this special safety system over that of previous designs. These improvements also reduce the capital cost as well as significantly reducing the operating and maintenance costs for testing, inspection, maintenance and repair over the lifetime of the NPP.

3.2.6. Radiation Protection

The CANDU 9 plant has been designed to comply with ICRP-60, the recommendations of the International Commission on Radiological Protection issued in 1991. Further, as design targets, the CANDU 9 plant has been designed so that total worker exposures will be less than 1 person-Sv/a and the maximum exposure to a member of the public will be less than 50 μSv/a. The approach taken to reduce the internal exposures of workers and tritium emissions to the public has been to reduce tritium-in-air levels by careful design of the in-containment vapor-recovery system.

To reduce the external exposures of workers during shutdown conditions, the layout has been improved to improve equipment access, shielding has been enhanced, and corrosion-product activity transport has been reduced. For example, the CANDU 9 fuelling machine carriage maintenance can be carried out while the reactor is still on power, with strategically placed shielding on the carriage to allow maintenance to be carried out, in low radiation fields.

Relatively easy access to the reactor building during plant operation always has been a hallmark CANDU advantage. By careful attention to segregation of possible high activity water vapor from areas with lower activity from tritium, this access can be retained while achieving stringent targets for total worker exposure. In addition, fuel handling operations have been reviewed and design features improved to reduce heavy water loss, and further reduce tritium emissions.

In order to reduce tritium emissions from CANDU 9, a dryer is provided at the reactor building ventilation system air exhaust. Early analysis indicates that there will be at least a three-fold reduction in tritium emissions relative to early CANDU 6 plant experience.

3.3. Operational and Maintenance Improvements

Most of the requirements for design improvements are based on a systematic review of current operating CANDU stations in the areas of design and reliability, operability, and maintainability as part of AECL’s design feedback process. Features such as the CANDU 9 Control Centre provide plant staff with improved operability capabilities, due to the combination of systematic design with human factors engineering and enhanced operating and diagnostics features.

3.3.1. Reduce Potential Of Process Failures

The CANDU 9 NPP is designed to reduce the potential for of the heat transport system liquid relief valve (LRV) failures and bleed condenser relief valve opening. Its components are specified and designed to ensure adequate relief valve performance in case LRV's fail. Also the CANDU 9 plant reduces reliance on operator action following an LRV opening incident.

The control instrumentation and electrical design in CANDU 9 are coordinated and checked so that logic changes will provide expected response and that failure effects are known. Distribution of the control systems amongst the various partitions, stations and modules within the distributed control system (DCS) is done so that a DCS module failure will not cause multiple system failures and that the scope of the failure is limited and distinct.

3.3.2. Improve Plant Operability

Recent statistics show that high numbers of plant significant events have been directly attributable to human errors. Consequently, special attention has been given to human factors engineering (HFE) during the design of the CANDU 9 nuclear power plant, integrating HFE into the project design to interface all designers from all disciplines.

For improved operational capabilities, the CANDU 9 design has incorporated an advanced control centre (Reference 5). The control centre features standard panel human-machine interfaces that provide an integrated display and presentation philosophy; and includes the use of a common plant display system for all consoles and panels. A large, central overview display presents immediate and simplified plant status information to facilitate staff awareness of the plant situation in a very legible and recognizable format. A powerful and flexible annunciation system will provide extensive alarm filtering, prioritizing and interrogation capabilities to enhance staff recognition of events and plant state.

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 the plant control functions while PDS similarly implements the main control room display and annunciation functions. This permits extensive control, display or annunciation enhancements within an open architecture. A flexible navigation system for the plant displays allows selected information to be accessed in a simple, direct, convenient and logical manner by operations or maintenance staff

The reactor shutdown computers for CANDU 9 include automated system testing and on-line neutronic trip calibration capabilities. One specific benefit of on-line calibration is the provision of an improved "margin-to-trip" thus eliminating unnecessary spurious trips. Safety system monitor computers will provide automated safety system testing, resulting in shorter test duration with reduced opportunity for human error.

A full-scale mockup of the main control centre panels and consoles has been built and is being used for conceptual evaluation, rapid prototyping, design decision-making, and then to allow verification and validation of the interactions between the operator and the annunciation/ monitoring/control interface features of the plant.

3.3.3. Protection Against Degradation or Ageing Mechanisms

A Plant Life Management program is being undertaken by both the utilities and AECL to safeguard the operating plant investment, and to incorporate the improved knowledge into AECL's latest CANDU 6 and CANDU 9 products. Preliminary results from a number of ageing studies for critical components were incorporated into CANDU 9 to achieve design life as described below.

For the CANDU 9, feeder material has been specified at a minimum of 0.2 wt% of Chromium content and chemistry control has been specified to achieve a tighter and lower pH operating range. This will reduce concerns with flow accelerated corrosion on the heat transport system side, and particularly in outlet feeders. For CANDU 9, AECL has also adopted strict velocity limits for high energy piping.

An ultrasonic inspection program of the wall thickness in the secondary side piping to monitor thickness variations is recommended as an added assurance against incidents such as feedwater line breaks which occurred in the US. In addition, copper alloy material is avoided in the secondary side; velocity limits are adhered to in the steam and feedwater system design; and alloy steels (whereas 2.25% Chromium and 1% Molybdenum) are used where high erosion is anticipated.

Most piping vibration has been associated with high pressure drops across pressure reduction orifices. Multiplate orifices used in CANDU 9 have been reviewed to eliminate cavitation and to avoid vibration, such as those used in heavy water feed pump and ECC pump by-pass lines, and in the heat transport system balance line.

Additional inspection ports are added near the tubesheet for CANDU 9 steam generators to provide increased access for cleaning, inspection and water lancing. Additional inspection ports are added at each tube support plate on the secondary side to facilitate inspection and cleaning.

3.4. Improved Delivery

CANDU designs utilize advanced engineering tools, such as 3-Dimensional (3-D) Computer Aided Design and Drafting System (CADDS) tools and advanced construction methods, for better economics and reduced risks to future owners. The 3-D CADDS model is used to establish the layout configuration, optimization of the fabrication sequence and construction, and the choice of pre-fabricated structural assemblies depending on the layout and complexities of systems. AECL has developed additional tools to extract component properties directly from the model to carry out necessary analyses. Data are also used to carry out further design detail work such as locating electrical cable runs, specifying pipe hangers as well as conducting stress and seismic analyses.

The computerized engineering tools utilized a common project database. For example, the design is progressed using a standardized material database catalogue so that a correctly qualified component is easily specified in a traceable manner for an application. This use of an integrated database will enhance standardization, reduce inventory stocking costs as well as eliminate costly incorrect specifications requiring rework while providing a tool for the utility for on-going configuration management. Parts lists can be taken directly from the model at procurement time for a given project.

The construction schedule for CANDU 9 has been reduced due to the adoption of sequence efficient 'open-top' reactor building construction technology, and by parallel fabrication and construction activities, eliminating or reducing construction congestion and providing adequate access and transportation corridors.

The building layout of the CANDU 9 design results in 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 for better site utilization.

3.5. Summary

The CANDU 9 NPP engineering program has provided the opportunity to enhance safety, through improvement of safety performance and through careful attention to emerging licensing issues. The CANDU 9 designers have made evolutionary improvements to plant safety features matching current requirements. The basic engineering program has been successfully completed, and a Canadian licensing review has confirmed no conceptual obstacles to licensing. The CANDU 9 is an advanced CANDU design, proven and available today.

4. Next Generation CANDU Development

4.1. Use Of Slightly Enriched Core

Future development of the larger size CANDU includes the development of designs with an increase in reactor output. With a modular fuel channel design, a higher reactor output can be achieved without the introduction of new technology while maintaining the same reactor channel licensing and safety limits. The increased output can be achieved by using a new fuel design and/or by using slightly enriched uranium fuels in the same reactor core as the current CANDU 6 and CANDU 9.

By using the new CANFLEX fuel bundle with 43 elements which has improved thermal margin, and by adjusting and optimizing core and heat transport design and overpower detection system design, a modest increase in channel power can be accommodated. The development of the design of this fuel is complete.

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.

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.

4.2. Larger Size CANDU

Owing to the modular nature of the CANDU 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 the current CANDU 9 reactor shield tank assembly. This larger reactor will be capable of generating about 1200 MW to 1400 MW, depending on the fuel used, with higher power output being produced with slightly enriched fuel such as recovered uranium fuel.

4.3. Safety Improvements

Due to the important role of containment in severe accident scenarios, particular attention is being paid to the following key requirements for future designs.

- Containment structure with larger design margins and low leakage rates
- Redundant heat sinks for long term decay heat removal
- Good isolation provisions and means of post-accident cleanup
- Hydrogen mitigation systems that allow systematic and timely dispersion and reduction of hydrogen concentrations.

Future enhancements are focusing on adapting passive emergency water systems 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.

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.

4.4. 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. 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, and development of improved technologies for measurement and mitigation. 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, low-level radiation effects, and the characterization of environmental pathways.

4.5. 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. The focus for the advanced features is to improve the operability and maintainability of the station, decrease the likelihood of operator or maintainer errors, to reduce capital and operating costs, and to facilitate higher production capacity factors. The significant features of the advanced control centers include a plant-wide database, extensive cross-checking of similar process parameters, additional operational aids such as automatic procedure call up, configuration management assistance, automated system performance checking, and predictive maintenance.

4.6. CANDU X Program

To extend the CANDU design concepts for a design for 25 years ahead, a development program under the title CANDU X has been established.

The current goals of the CANDU X program are the definition of overall concept options and the establishment of the technical and engineering feasibility of advanced and modular concepts by:

a. Increasing the performance and design limits for the CANDU channel, using a high-temperature insulated channel concept to provide increased lifetime and safety margins;
b. Simplifying the primary system flow conditions (natural versus forced circulation), addressing stability limits, and improving heat exchanger lifetime and design;
c. Improving the operational and safety constraints, including the response to severe accidents, enhanced fuel performance, and improved hydrogen management;
d. Optimizing the balance-of-plant sufficient to ensure continued technical and economic feasibility;

e. Conducting basic programs in safety, thermalhydraulics, and chemistry to provide the knowledge essential for the definition of the innovative reactor concepts, advanced materials and chemistry specifications, and extension of operating conditions to high temperatures and pressures.

5. Summary

CANDU 9 is a single unit version of the integrated 4-Unit designs in operation at Bruce B and Darlington in Canada. This product contains the latest CANDU technology and has been given licensing approval by the Canadian Regulator.

The CANDU 9 can be enhanced to give rector outputs up to 1400 MW. While CANDU by its very design contains many passive safety features; further passive safety enhancements are under active development.

The CANDU family of products is capable of extensive development for many decades ahead. An advanced design approach under the title of CANDU X is being used to establish design concepts to be successful 25 years from today.

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