EVOLUTIONARY CANDU 9 PLANT IMPROVEMENTS

IAEA-SM-353/28

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Abstract

The CANDU 9 is a 935 MW(e) nuclear power plant (NPP) based on the multi-unit Darlington and Bruce B designs with additional enhancements from our ongoing engineering and research programs. Added to the advantages of using proven systems and components, CANDU 9 offers improvement features with enhanced safety, improved operability and maintenance including a control centre with advanced man-machine interface, and improved project delivery in both engineering and construction. The CANDU 9 NPP design incorporated safety enhancements through careful attention to emerging licensing and safety issues. The designers assessed, revised and evolved such systems as the moderator, end shield, containment and emergency core cooling (ECC) systems while providing an integrated final design that is more passive and severe-accident-immune. AECL uses a feedback process to incorporate lessons learned from operating plants, from current projects experiences and from the implementation or construction phase of previous projects. 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. The CANDU 9 Control Centre provides plant staff with improved operability and maintainability capabilities due to the combination of systematic design with human factors engineering and enhanced operating and diagnostics features. The use of advanced engineering tools and modem construction methods will reduce project implementation risk on project costs and schedules.

1. INTRODUCTION

The evolution of the CANDU® family of heavy water reactors (HWR) is based on a continuous product improvement approach. Proven equipment and systems from operating stations are standardized and used in new products. As a result of the flexibility of the CANDU technology, evolution of the current design will ensure that any new requirements can be met, and there is no need to change the basic concept. CANDU reactors have evolved along two general product lines the CANDU 6 and the CANDU 9. [1]

Building on the success of the 4-unit stations at Bruce B which began commercial operation in 1980s, four additional 900 MW(e) class units were commissioned at Darlington in the early 1990s. 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 [2]. Reduced project implementation risk for CANDU 9 has been assured by up-front engineering and licensing prior to contract start.

Added to the advantages of using proven systems and components, CANDU 9 offers improvements providing enhanced safety, a control centre with better operability and a design enabling improved project delivery in both engineering and construction. Enhanced competitiveness of the CANDU product is assured by incorporating improvements based on updated technologies, including safety technology, the rapidly advancing information technology and modern construction methodology.

2. 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 engineering program was a 39 month program started in January, 1995 and was concluded at the end of March, 1998. The scope included performing up-front design engineering and the completion of a licensability review of the CANDU 9 NPP by the Atomic Energy Control Board (AECB) to reduce project implementation risk. In 1997 January, the two year licensing review by the AECB was completed. The CANDU 9

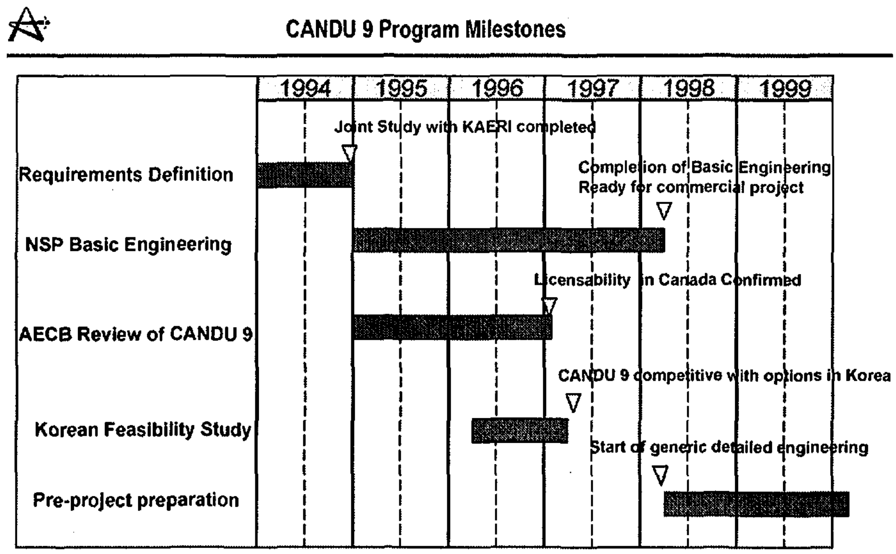

FIG. 1 Major milestones of CANDU 9 program

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. [3] The overall program milestones are shown in figure 1.

In 1996, a Korean feasibility study comparing CANDU 9 with other NPP options was carried out. AECL has submitted many documents in response to questions from the feasibility study team as well as providing inputs to the technical and economic evaluations. The feasibility study concluded that CANDU 9 is competitive with other reactor options in Korea.

We have identified the generic detailed work to be done as part of the pre-project preparation. This program 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 the CANDU 9 project delivery.

The preparation of the preliminary safety analysis report is progressing. The licensing interactions with the AECB are continuing in order to resolve most of the additional work items raised in the Statement of Licensability.

3. SAFETY ENHANCEMENTS

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

- 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 and
- a reactor coolant system with a larger pressurizer and analysis shows a lower power pulse following a large LOCA
- improved layout and separation between steam & water systems and electrical systems, together with the seismic qualification of the Main Control Room
- better provisions for mitigating severe accidents by use of the reserve water system including improved provisions for steam relief from the shield tank

- significant new features include the replacement of conventional valves in the emergency core cooling system with simple rupture disks and floating-ball isolation valves.

The CANDU 9 NPP design work provided the opportunity to enhance safety, through improvement of safety performance and through careful attention to emerging licensing and safety issues. The designers assessed, revised and evolved such systems as the moderator, end shield, containment and emergency core cooling (ECC) systems while providing an integrated design that is more passive and severe-accident-immune. These safety enhancements are highlighted in the following brief descriptions:

3.1 Containment

Previous CANDU containment system designs included pressure suppression systems utilizing high-flow water sprays and, in multi-unit plants, vacuum buildings. These systems have proven to be very reliable. However, customer requirements have evolved, so that newer CANDU designs now will incorporate the large dry containment concept utilizing a steel liner in a conventional post-tensioned concrete building. While the overall severe accident program ensures a balance between preventative and mitigative measures, the role of containment as a mitigation measure is important.

The CANDU 9 reactor building is a steel-lined, pre-stressed concrete structure which 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 without a dousing system 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.

The containment free volume is sufficiently large so that no pressure suppression system is required in the short term to maintain the post LOCA peak pressure below the design pressure. The long-term containment atmosphere heat sink is provided by the reactor building air coolers. Judicious layout of equipment inside containment results in large, open volumes, with good potential for natural circulation and no apparent hydrogen traps.

The CANDU 9 containment system automatically closes (i.e. buttons-up) all reactor building penetrations open to the containment atmosphere when an increase in containment pressure or radioactivity level is detected. 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. Higher ventilation air flow rates promote better mixing, backed-up by hydrogen igniters/recombiners carefully located at strategic possible accumulation locations. Passive catalytic recombiners are provided to control hydrogen concentration in the long term period after a LOCA; short-term control is accomplished by igniters (the same as those used in current CANDU 6 units).

3.2 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 feeders 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 minimizes the positive reactivity insertion as a result of a large pipe break in the HTS. 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°C. This enhances the natural circulation capability of the HTS after transients or accidents causing loss of forced flow, (including a steam line break combined with loss of Class IV electrical power,) by ensuring that full reactor coolant inventory in the HTS can be maintained at any time during cooldown.

3.3 Grouping Redundancy and Additional Seismic Qualification

The concept of grouping and separation of safety related systems has been an integral component of CANDU plant designs for many years. This concept provides physical and functional separation of safety related systems to ensure that common cause events do not impair the capability of all systems to perform essential safety functions. Through this concept, the plant can be shut down, decay heat removed, and the plant conditions monitored from systems and components of one of two groups known as Group 1 and Group 2. For the CANDU 9 design, this concept has been enhanced through additional redundancy and diversity in the provision of cooling water and power supplies. In addition, the emphasis has been placed on plant monitoring and management to ensure that the necessary controls needed to monitor and maintain the controlled shutdown and cooldown condition.

A Group 2 feedwater system has been engineered to supply emergency water to the steam generators automatically, for decay heat removal, for approximately 10 hours. This Group 2 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 Group 1 Feedwater Systems. The new system is seismically qualified and is capable of full steam generator pressure operation so as to cope with all the possible operating conditions in the steam generators. The available operator response times, generally 8 hours, have been attained for accident conditions requiring steam generator heat sinks.

In addition, the main control room and the secondary control area are designed to meet the safety grouping and separation design requirements. 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. Both control locations are qualified to remain functional during design basis and external events, and the necessary structures and systems have been appropriately hardened and qualified.

3.4 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.

The reserve water tank is also connected to the normal end shield cooling circuit. During normal reactor operation, the reserve water tank acts as the head tank for the end shield cooling system using circulation pumps. However, in the event of process failures, such as a loss of forced circulation in the end shield cooling circuit or a loss of cooling water to the end shield heat exchanger, the reserve water tank with the large water inventory acts as a passive heat sink. The layout of the equipment and the piping connection between the end shield of the reactor core and the reserve water tank are designed to facilitate enhanced thermosyphoning for heat removal from the end shield. Due to the large heat capacity of the reserve water tank inventory, the rate of heat-up of end shield coolant and the calandria and end shield tubesheet is slow. This increased time interval will ensure fuel channel integrity for a long period before requiring any operator action. An analysis has been carried out confirming the adequacy of the cooling by thermosyphoning after a loss of flow in the end shield system. [4]

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 and 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.

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. This capability is provided by the cool, low-pressure moderator system surrounding the fuel channels and about 1cm. away from the fuel. In such a severe accident, the fuel would collapse inside the fuel channels, the pressure tubes would either balloon or sag into contact with the calandria tubes, and decay heat would then be transferred to the moderator water. The separate moderator cooling system would remove this heat.

In the event of an even more severe accident in which other failure results in the moderator cooling system not functioning, the moderator water would boil-off slowly. Channels would sag, then collapse progressively to the bottom of the calandria tank. Decay heat would be removed by conduction to the shield tank water. The shield tank with water make-up 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. The essential safety advantage of this design is the long time taken before fuel might penetrate the calandria tank, allowing mitigation actions to be taken. In the worst case only a small amount of fuel would reach the molten state during this time.

Significant work has been also done for the input to the design of the post-accident management system. Operator Response Guidelines (ORGs) have been prepared for several abnormal events, including LOCA with ECCS available, steam line break, and loss of Class IV electrical power. ORGs for additional abnormal events are under preparation.

3.5 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 has increased the reliability target for this special safety system over that of previous designs. Elimination of the isolation and injection valves avoids all the problems that can be encountered during ECC valve testing due to excessive leakage of the isolation valves and spurious core by-passing due to errors in valve testing sequence at operating stations. 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.

3.6 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 very careful design of the in-containment vapor-recovery system.

To reduce the external exposures of workers during shutdown conditions, the layout has been improved; shielding has been enhanced and corrosion-product activity transport has been reduced. Examples are:

- CANDU 9 carriage maintenance can be carried out in the fuelling machine (F/M) Lock while the reactor is still on power
- Strategically placed shielding on the carriage will allow maintenance to be carried out with reduced dose from the F/M.

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. Examples are:

- New fuel storage has been moved from inside containment to outside the reactor building.
- The fuelling machine (F/M) discharge ports for gravity drain-down of the F/M have been eliminated to reduce potential heavy water loss.
- F/M snout blowdown is to be incorporated to reduce D2O spillage each time a F/M disengages from a channel.
- Vent ports on the transition section between the irradiated fuel transfer mechanism and the fuel transfer port includes a closed loop condenser circuit which will condense and collect D_2O vapour evaporating or boiling from the fuel bundle surface as it is being transferred.

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 Wolsong 1 experience.

4. OPERATIONAL AND MAINTENANCE IMPROVEMENTS

AECL uses a feedback process to incorporate lessons learned from operating plants, from current projects experiences and from the implementation or construction phase of previous projects. 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. The CANDU 9 Control Centre provides plant staff with improved operability capabilities due to the combination of systematic design with human factors engineering and enhanced operating and diagnostics features.

In the CANDU 9 design, emphasis is placed on improving the reference plant design. The following sections provide some highlights of CANDU 9 plant improvements based on lessons learned from operational experience.

4.1 Reduce Potential Of Process Failures

The CANDU 9 NPP is designed to reduce the frequency 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. The pressure and inventory control system design and the associated procedures identifying necessary operator actions following an LRV failure event minimize the risk of excessive re-pressurization of the bleed condenser which caused the relief valves to open in the Pickering event. 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. An independent assessment analysis will be performed to confirm partitioning of control systems implementation on the DCS. As well, an independent hazards impact assessment is conducted to ensure that unexpected fault propagations will not occur.

4.2 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, establishing an HFE design process basis and integrating this HFE process into the project design to interface all designers from all disciplines.

CANDU plants have employed computerized control systems since the 1960s, and each new plant has been provided with then 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.

For improved operational capabilities, the CANDU 9 design has incorporated an advanced control centre.[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 operation staff awareness of the plant situation in a very legible and recognisable format. A powerful and flexible annunciation system will provide extensive alarm filtering, prioritising 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 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.

An advanced annunciation feature in CANDU 9 is the provision of special safety system impairment levels and potential operating policy violation alarms (i.e. which could occur, for example, in a maintenance mode) with a display/report capability which details the resultant system unavailability or margin encroachment under the prevailing failure or configuration changes. The utilization of a flexible navigation system for the visual display unit (VDU)-based plant display system allows custom information displays 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. The design of each system of the plant is reviewed against human factors requirements to ensure that the needs of the plant personnel for the monitoring, annunciation and control of the system are appropriately addressed.

4.3 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.[6] In advance of the formulation of the integrated approach described in the PLIM paper, 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 NPP, 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.

4.4 Enhance Maintainability and Inspection

The following improvements have been made to CANDU 9 equipment for maintenance and inspection:

4.4.1 Fuel Handling Equipment

- Torlon spacer balls have been added into the CANDU 9 ballscrew assembly to reduce ball wear and increase the number of channel visits between maintenance.
- Use of oil has been reduced in the CANDU 9 system which will minimize leakage and in turn reduce the potential for fire hazard.
- The fuelling machine carriage use more common commercial equipment and sub-assemblies have bolted connections for easy removal and replacement.
- F/H Process equipment layout has been arranged to provide more ready access for maintenance, removal and replacement
- New fuel transfer equipment for CANDU 9 are outside containment which is more readily accessible for maintenance. By transferring the irradiated bundles directly into basket modules, manual bundle handling is considerably reduced later, when preparing for dry storage.

4.4.2 Reactivity Control Units

- Vertical RCU guide tube tensioning springs at the reactivity mechanisms deck facilitate any required re-tensioning and reduces maintenance radiation exposure.

- Horizontal flux detectors will be tensioned by spring and not bellows, this avoid cutting and re-welding bellows for re-tensioning to reduce maintenance radiation exposure.
- Offset LISS nozzles allow more adjustment to avoid contact with sagged calandria tubes due to creep thus eliminating the need for replacement.
- Horizontal RCUs access from outside vault wall will reduce maintenance radiation exposure.

4.4.3 Steam Generators Inspection And Cleaning

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

5. 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 are modified to access 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.

Construction, installation, and layout design considerations have resulted in a shorter construction schedule for the CANDU 9 NPP. The ability to reduce the construction schedule was possible due to the adoption of sequence efficient 'open-top' reactor building construction technology utilizing a very heavy lift crane. Other techniques employed to reduce the construction schedule includes parallel fabrication and construction activities, eliminating or reducing construction congestion, providing adequate access and transportation corridors, providing flexible equipment installation sequences as well as reducing material handling requirements.

In addition to these layout improvements for construction improvements, 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.

6. SUMMARY

The CANDU 9 is a 935 MW(e) NPP evolved from the multi-unit Darlington and Bruce B designs, with some additional enhancements from ongoing CANDU engineering and research programs. The Basic Engineering program has been successfully completed. AECL has submitted the CANDU 9 design to the Canadian nuclear regulator (AECB) for review, and it was confirmed that there are no conceptual barriers to licensing the CANDU 9 in Canada.

The CANDU 9 NPP engineering work provided the opportunity to enhance safety, through improvement of safety performance and through careful attention to emerging licensing and safety issues. The CANDU 9 designers have made evolutionary improvements to plant safety features matching current requirements.

Feedback from operating experience leads to improvements for improved operability and maintenance including a control centre with advanced man-machine interfaces. Information from PLIM programs underway with operating utilities will assure protection against degradation mechanisms.

The use of advanced engineering tools and modem construction methods will improve project delivery in both engineering and construction, and hence reduce project implementation risk on project costs and schedules.

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