NEXT GENERATION CANDU PLANTS

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ABSTRACT

The CANDU® [1]Pressurized Heavy Water Reactors systems featuring horizontal fuel channels and heavy water moderator will continue to evolve, supported by AECL's strong commitment to comprehensive R&D programs.

There are three key CANDU development strategic thrusts: improved economics, fuel cycle flexibility, and enhanced safety operation based on design feedback. Therefore, CANDU reactor products will continue to evolve by incorporating further improvements and advanced features that will be arising from our CANDU Technology R&D programs in areas such as heavy water and tritium, control and instrumentation, fuel and fuel cycles, systems and equipment and safety and constructability.

Progressive CANDU development will continue in AECL to enhance the medium size product - CANDU 6, and to evolve the larger size product - CANDU 9. The development of features for CANDU 6 and CANDU 9 is carried out in parallel. Developments completed for one reactor size can then be applied to the other design with minimum costs and risk.

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.

Future CANDU designs will continue to meet the emerging design and performance requirements expected by the operating utilities. The next generation CANDU products will integrate new technologies into both the product features as well as into the engineering and construction work processes associated with delivering the products·(1) The timely incorporation of advanced design features is the approach adopted for the development of the next generation of CANDU.

CANDU DEVELOPMENT THRUSTS

There are three key CANDU development strategic thrusts: improved economics, fuel cycle flexibility, and enhanced safety operation.

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[1] (CANada Deuterium Uranium) is a registered trademark of AECL (Atomic Energy of Canada Limited)

Improved Economics

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 composite steel or structural steel modules depending on the layout and complexities of systems.

Modularization allows the manufacturing 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.

Fuel Cycle Flexibility

The excellent neutron economy gives the PHWR the ability to use different low fissile materials, and provides opportunities in continuing improvements in uranium (or other fissile materials) utilization and reactor/fuel optimization, to decrease in plant capital cost. CANDU fuel cycle flexibility arises naturally from the neutron economy associated with the use of heavy water, and the use of on-power fuelling and simple fuel design. The exploitation of this flexibility results in fuel cycles that optimize the use of uranium resources.

Light Water Reactors (LWR) 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, and the LWR can be viewed as an efficient source of fissile material for future advanced CANDU designs via a number of potential once-through combined fuel cycles. This exploitation of the natural LWR/PHWR synergism will assure long-term fuel supply even if uranium resources become scarce. Also the use of recovered uranium fuel, and the use of mixed oxide fuel with plutonium and depleted uranium, including the recycling of transuranic mix from spent fuel reprocessing, can help to reduce long lived waste. All these fuel cycles are part of the overall strategy for sustainable development of the next generation CANDU products.

Enhanced Safety Operation

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 mitigates the impact of postulated severe accidents. 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. Make up to the moderator is included in the current CANDU 6 and for the CANDU 9 design, a large reserve water tank is located high in the reactor building and supplies water by gravity to various systems.

Experience Feedback

AECL has recognized the roles of operational feedback on product. 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. AECL and Ontario have also held a number of annual Operating Experience Feedback Seminars to allow further exchange between utility operators and the designers. In recent years, there have been a total of four COG/IAEA Technical Committee on Exchange of Operational Safety Experience of PHWRs where all PHWR utilities world wide can share and exchange their operational experience and solutions to safety issues.

To complement these activities, AECL has initiated a systematic feedback process that 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. Recent examples of operational input to designs are:

- ECC performance improvements including strainer design for long term circulation of emergency coolant;
- Improvements to liquid relief valve component and system design for heat transport pressure and inventory control
- Improved safety system signal monitoring with updated digital displays, increased computerized testing for reduced operation burden and increased system reliability
- Steam generator operational improvements such as provision of additional access ports for chemical cleaning and improved divider plates for long term performance

STATUS OF CANDU PRODUCTS

Progressive CANDU development will continue in AECL to enhance the medium size product - CANDU 6, with an output of about 725MWe and to evolve the larger size product - CANDU 9, with a gross output of 945MWe. The development of features for CANDU 6 and CANDU 9 is carried out in parallel. Developments completed for one reactor size can then be applied to the other design with minimum costs and risk.

CANDU 6

The 700 MWe class CANDU 6 nuclear power plant has an outstanding operating performance record since the startup of the first four CANDU 6 units in 1983. Cernavoda-1, the most recent European nuclear plant, started operation in 1996. The most recent project to achieve startup is Wolsong-2, which achieved full power in April 1997; Wolsong 3 and 4 will go into operation in 1998 and 1999 respectively. Most recent of all is the Qinshan project, which started construction in February 1997.

For Qinshan, further improvements from the reference plants at Wolsong have been incorporated, both in plant design and in product delivery. The Qinshan design is tailored to meet stringent local requirements including tornado protection and tight requirements on emissions to allow the Qinshan site to be used for up to 5 projects. The Qinshan plant design incorporates further improvements to such auxiliary systems as fire protection (additional redundancy of water supply system). In addition, the continuing development of fuel channel design had led to the use of improved surface finish of calandria tubes. This has the added advantage of increasing heat transfer margins if the moderator were to be required as an emergency heat sink. Consistent with the 40-year design life target, improvements in feeder material selection, using trace addition of chromium, will enhance resistance to long-term corrosion effects. Similarly, careful attention has been paid to specifications of key components such as the steam generators to allow in-service inspection and cleaning to ensure their capability for a 40-year design life. Specifications are optimized to ensure design fully meets requirements, without placing unnecessary restrictions on manufacturers.

Building on the successful application of CADDS models for CANDU 9 design engineering and for Wolsong 2, 3 and 4 construction support, the Qinshan project will be based on a comprehensive set of 3-D CADDS models. These will be linked to electronic databases covering wiring (INTEC) equipment specifications (TeddyBase) and materials management (CMMS). This will improve the effectiveness of engineering and procurement processes, and in particular will minimize plant design inconsistencies such as physical interferences, material or performance interface errors etc. As a result, the construction and installation stages of the project will be subject to much less schedule or cost risk. Constructability has been further improved by the adoption of open-top techniques for work within the reactor building. This is based on the use of a very-heavy-lift crane to install major equipment before completing the reactor-building dome. Specific equipment items were installed this way for Darlington NGS. Full scale application of this technique has allowed an ambitious project schedule of 72 months from contract effective to first unit in-service to be committed; this despite an extremely restricted site, and the natural additional challenges inherent in the first project in a new environment.

Future CANDU 6 projects build upon the latest version of the product under construction in Qinshan, China. Design enhancements being considered are in the areas of capital cost reduction, improved licensability, elimination of obsolescence and improved operability.

CANDU 9

The CANDU 9 is a stand-alone version of the successful integrated multi-unit units at Darlington and Bruce Nuclear Generating Stations operating in Ontario, Canada. Added to the advantages of using proven systems and components, CANDU 9 offers a higher output, better site utilization, improved station layout and a control centre with better operability.

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 been confirmed that there are no conceptual barriers to licensing the CANDU 9 in Canada.(2)

Proven Systems, Equipment from Operating Stations

The CANDU 9 employs the standard CANDU lattice design and fuel channel arrangement with the same neutronic characteristics as the other operating CANDU reactors including the CANDU 6. The calandria design, with 480 fuel channels, and the design and arrangement of reactivity control devices are the same as for Bruce B and Darlington. The design of the CANDU 9 calandria and shield tank assembly is based on the Darlington reactor design with improvements incorporated from the CANDU 6 design to meet a 0.2g seismic requirements. The fuel channel of the CANDU 9 reactor is similar to the CANDU 6 design.

There are 12 fuel bundles in each fuel channel as in CANDU 6. CANDU 9 uses standard CANDU fuel consisting of 37 elements of uranium dioxide sheathed in Zircaloy and held together as a bundle by end-plates. CANFLEX fuel, which has many advanced features can be used in CANDU 9.

The CANDU 9 heat transport system is essentially the same as the single loop Bruce B heat transport system. The major heat transport system equipment including steam generators and pumps, are of the same design as equipment now in operation at Darlington. The design parameters established for the Darlington heat transport system are applicable to the CANDU 9. As a result, heat transport system conditions are the same.

Better Site Utilization

Site area requirements for nuclear power plants is a strong function of the Exclusion Area Boundary (EAB) radius which is a licensing requirement, and the site layout arrangements of the various buildings. CANDU 9 has been designed to require a small EAB radius and to have a narrow 110 metre wide “footprint” that allows several units to be constructed adjacent to each other forming a compact multi-unit station.

The use of a “large dry" containment design (pre-stressed concrete building with a steel liner) gives lower design leakage and therefore greater margin in meeting the requirement of a reduced Exclusion Area Boundary.

Using siting requirements typical of light-water reactors, adapted to CANDU, the CANDU 9 can meet an Exclusion Area Boundary of less than 500m. AECL's calculations have shown that to achieve an EAB of 500m; a containment design leakage rate of 0.6% per day at design pressure is required. Since the design leakage rate of CANDU 9 is 0.2% volume per day about a factor of three less than that used in the analysis, an EAB of 500m is clearly achievable for CANDU 9.

In addition to the Containment Isolation System, provision of a redundant independent, diverse Ventilation Isolation System to isolate the ventilation lines, will provide further defense-in-depth for CANDU 9.

CANDU 9 building arrangement has benefits both from the construction, operational and maintenance viewpoint, as well as from the site utilization viewpoint. The buildings are arranged to allow replication of the initial unit with minimum spacing between units while retaining all the necessary access for the construction of subsequent units. The common services for the units are located in the station service building.

Control Centre With Better Operability

A formal human factors engineering plan defines the process of incorporating human factors into the design of CANDU 9 systems and equipment.(3) All aspects of plant design for which there is an interface with plant personnel will incorporate consistent human factor considerations. Underlying this approach is a refined engineering design process that cost-effectively integrates operational feedback and human factors engineering to define operations staff information and information presentation requirements. Based on this approach, the CANDU 9 control centre will provide utility operations staff with the means to achieve improved operations.

As part of the CANDU 9 design strategy, a physical, full-scale mock-up of the control centre panels and consoles is being used for conceptual evaluation, rapid prototyping, design decision-making, and then for the verification and validation of the design features, displays and operator interactions. The functionality of the simulation supported control centre mock-up provides a dynamic mechanism for the on-going verification and validation design activities by system designers.

The CANDU 9 control centre provides plant staff with improved operability capabilities. A major evolutionary change from previous CANDUs is the separation of the control and display/annunciation features formerly provided by the digital control computers (DCC). This improved function separation provides control in the distributed control system (DCS) and display/annunciation in the plant display system (PDS). This strategy allows powerful computers, without application memory constraints or execution limits, to provide extensive control, display or annunciation enhancements within an open architecture.

NEXT GENERATION CANDU DEVELOPMENT

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(4) 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. It has been planned to have in-reactor testing in a CANDU 6 reactor in New Brunswick in order to demonstrate its in-reactor performance, within the same basic plant configuration.

Currently operating CANDU power reactors use a once-through natural uranium fuel cycle, which avoids the need for securing a supply of enriched uranium. 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. 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.

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.

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.

Future Enhancements

Safety Improvements

For future CANDU products, further systematic review of severe accidents and features to facilitate severe accident management will be made to achieve a balance between preventative and mitigation measures. Due the important role of containment in severe accident scenarios, particular attention is required in meeting 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

Future designs need to address requirements for accident management to limit accident consequences and/or reducing the probability of such accidents, based on systematic evaluation methodologies such as Level 2 PSA. As a result the necessary structures and systems can be hardened with additional margins to ensure sufficient monitoring and control capability and accident management following seismic and other external events, as well as accident conditions.

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, 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.   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.

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.