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THE NEXT GENERATION CANDU 6

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Abstract

AECL's product line of CANDU 6 and CANDU 9 nuclear power plants are adapted to respond to changing market conditions, experience feedback and technological development by a continuous improvement process of design evolution. The CANDU 6 Nuclear Power Plant design is a successful family of nuclear units, with the first four units entering service in 1983, and the most recent entering service this year. A further four CANDU 6 units are under construction. Starting in 1996, a focused forward-looking development program is under way at AECL to incorporate a series of individual improvements and integrate them into the CANDU 6, leading to the *evolutionary development of the next-generation enhanced* CANDU 6. *The* CANDU 6 *improvements program* includes all aspects of an NPP project, including engineering tools improvements, design for improved constructability, scheduling for faster, more streamlined commissioning, and improved operating performance. This enhanced CANDU 6 product will combine the benefits of design provenness (drawing on the more than 70 reactor-years experience of the seven operating CANDU 6 units), with the advantages of an evolutionary next-generation design. Features of the enhanced CANDU 6 design include:

- Advanced Human Machine Interface - built around the Advanced CANDU Control Centre.
- Advanced fuel design - using the newly demonstrated CANFLEX fuel bundle.
- Improved Efficiency based on improved utilization of waste heat.
- Streamlined System Design - including simplifications to improve performance and safety system reliability.
- Advanced Engineering Tools, -- featuring linked electronic databases from 3D CADDS, equipment specification and material management.
- Advanced Construction Techniques – based on open top equipment installation and the use of small skid mounted modules.
- Options defined for Passive Heat Sink capability and low-enrichment core optimization.

1. INTRODUCTION

AECL's CANDU 6 NPP product line is based on the foundation of a successful series of operating power plants and current build projects. Using the continuous improvement approach, incremental design improvements have been incorporated in successive projects. By extending this approach to incorporate the benefits of AECL's product development programs, a series of improvements can be mapped out for the future, leading to a next-generation enhanced CANDU 6.

In practice, AECL's approach for CANDU 6 is to incorporate design improvements based on: provenness; incremental change; benefit to plant performance and safety; benefits to plant economics. Design changes are thoroughly evaluated to ensure these objectives are achieved. As developments meet the criteria of provenness and readiness for implementation, they can be seamlessly incorporated into the next CANDU 6 build project, offering customer benefits with very low implementation risk. This approach has already been followed in design upgrades for current projects at Wolsong, in the Republic of Korea, and Qinshan, in China.

In addition, AECL's design evolutionary approach emphasizes systematic design response to feedback from operating plants, build projects, from R and D programs and from worldwide experience. In this way, the design is maintained up-to-date and is fine-tuned to minimize operating problems. Design "provenness" is maintained, not by freezing the design, but by a continuous, "living" design improvement process.

The CANDU 6 design has led to a successful family of units, with the first four units entering service in 1983 (Point Lepreau and Gentilly-2 in Canada; Embalse in Argentina; and Wolsong-1 in the Republic of Korea. More recently, further CANDU 6 units are under construction, and three units have recently entered service (Cernavoda-1 in Romania, in 1996; Wolsong-2 in 1997; and Wolsong-3 in 1998). In addition, units are under construction at Cernavoda-2, Wolsong-4 and Qinshan 1 and 2.

In 1996, a focused CANDU 6 improvements program was started, with the objective of identifying and developing successive design improvements to establish the next generation, enhanced CANDU 6 design. This program includes all elements of an NPP project in its scope. This includes not only design improvements, but also engineering tools improvements, design for improved constructability, scheduling for faster, more streamlined commissioning, and improved operating performance. This enhanced CANDU 6 represents the outcome of the natural evolution of the CANDU 6 design, incorporating design feedback in conjunction with the design improvements from this development program. The enhanced CANDU 6 NPP design combines the benefits of design provenness (drawing on the more than 70 reactor years experience of the seven operating CANDU 6 units), with the advantages of an evolutionary, next generation design. The principles behind AECL's approach to evolutionary improvement are shown on figure 1.

In this paper, examples are given of the key incremental design features included in successive CANDU 6 NPP's together with a summary description of the improvements in the next-generation enhanced CANDU.

2. CONTROL CENTRE DESIGN EVOLUTION

The original CANDU 6 control centre and human-machine interface incorporated a high degree of automation and digital control. From the beginning, the CANDU 6 design philosophy emphasized provision of extended operator decision and action time for upset and accident conditions.

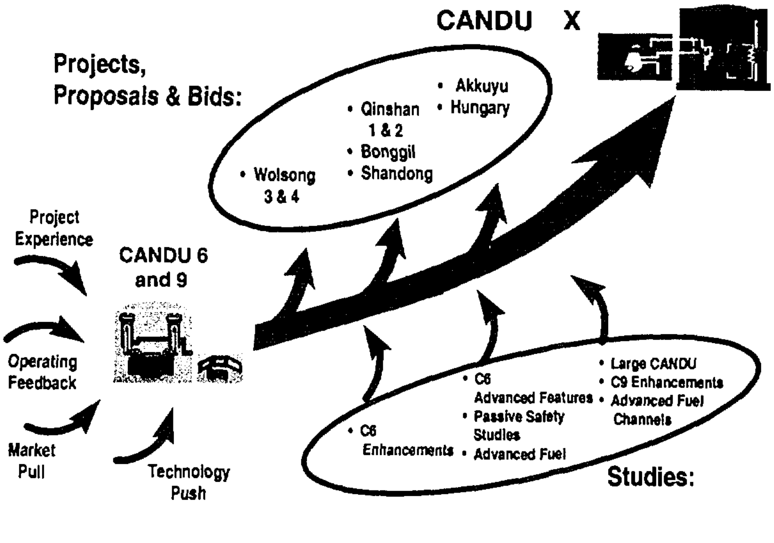

FIG. 1 CANDU Product Evolution

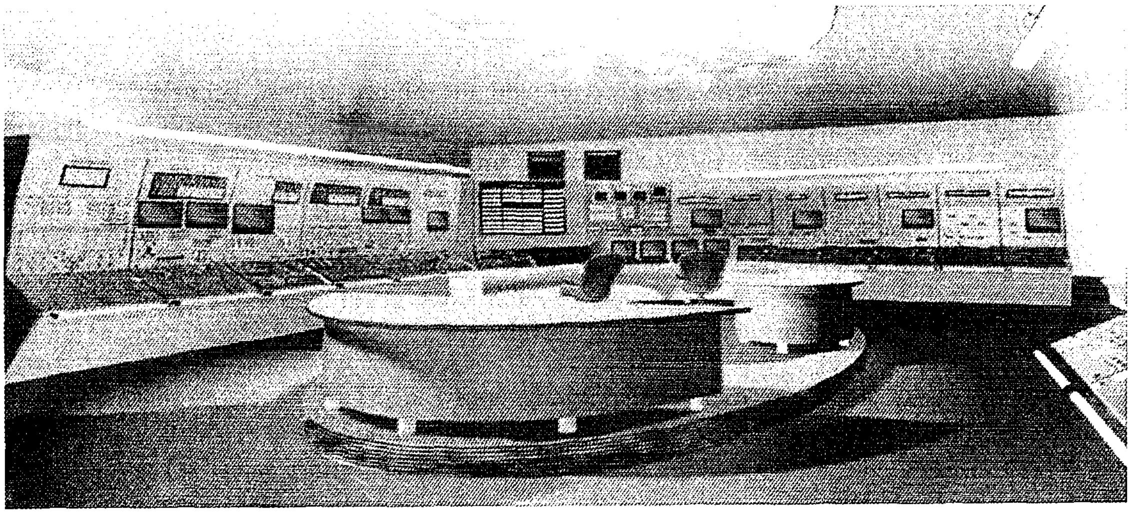

FIG. 2 Advanced Control Room

The original control centre design for the CANDU 6 plants completed in the 1980's, included plant control and display functions carried out by dual-redundant computers, with extensive use of CRT displays. Refinements for the Wolsong 2, 3, and 4 projects included redesigned emergency core cooling system (ECCS) panels, to reflect the complete automation of all stages of ECCS operation. For Qinshan, the Safety Parameter Display System has been integrated into the design, and the control room panels have been simplified and re-oriented based on human factors principles. Most notably, the operator interface has been streamlined by inclusion of extensive CRT-based control and information display at the central operator sit-down console, and by the inclusion of the advanced CANDU messaging system to provide "intelligent" annunciation during upset conditions. Operator situation awareness and analysis is enhanced by the use of two large-screen plant overview displays.

The next CANDU 6 projects will implement the Advanced CANDU Control Centre (Figure 2). In addition to the enhancements noted above, this will feature:

- Real time plant information, and historical data, communicated throughout the plant via Local Area Network.
- Extended automation of safety system on-line testing and calibration.
- Touch-screen context-sensitive CRT's as the first-line operator interface.

These improvements respond to utility expectations to have an operator interface based solidly on human factors principles, and which simplifies operator management of accidents Reference (1).

Finally, the future enhanced CANDU 6 will adopt plant control by a distributed microprocessor based system for both NSSS and BOP equipment. This is readily incorporated due to the separation between the digital control and display functions in the control equipment architecture. The use of multiplexed distributed control, in combination with the separation of control and display functions, will greatly reduce the effort and schedule duration required to complete wiring during project construction. For example, this allows the elimination of the complex Control Distribution Frame of the original CANDU 6 units, with resulting savings in on-site critical path wiring activities.

3. FUEL DESIGN EVOLUTION

The CANDU 6 reactor core is designed around the highly-proven, economical 37-element CANDU fuel bundle. The CANDU 6 core design allows fuelling with a variety of low fissile-content fuels, in particular natural uranium. Up to the present time, the natural uranium fuel cycle has been used in all CANDU 6 units, to take advantage of its simplicity, and of the independence from fuel enrichment. 37-element CANDU fuel has achieved excellent performance in CANDU 6 and other CANDU power plants. The average fuel defect rate is less than one in 100,000 fuel pins. Because CANDU plants refuel on-line, any fuel defect which does occur can be located and removed promptly. This contributes to the very low activity levels typically seen in CANDU coolant circuits.

AECL has carried out a development program with KAERI of Korea, to make available an advanced 43-element fuel bundle, (Figure 3), the CANFLEX fuel bundle, which will enable a flexible choice of fuel cycles to suit utility strategy. By the choice of two carefully selected fuel pin diameters in the fuel bundle, the CANFLEX bundle achieves 20% lower fuel ratings than 37-element fuel, based on the same overall bundle power. This leads to lower fuel temperatures and free fission-gas release, which allows much higher burnups, and hence opens up the competitiveness of alternate fuel cycles. In addition, the CANFLEX fuel bundle is designed to achieve significantly higher thermal margin, which gives flexibility to optimize the core design, while providing greater flexibility to the plant operators to vary core conditions.

Demonstration irradiation of CANFLEX fuel bundles in a CANDU 6 reactor began in September of this year at Point Lepreau NGS in New Brunswick, Canada. After successful irradiation and post-irradiation of the demonstration bundles, transition to full-core CANFLEX fuel at Point Lepreau is anticipated.

The present CANDU 6 design is optimized for 37-element fuel. The enhanced CANDU 6 plant includes the same core design, with flux detector configuration adjusted to optimize the reactor for CANFLEX fuel. The reference fuel management scheme and fuel channel flow designs are also adjusted to complement this, allowing up to 6% increased thermal output from a natural uranium-fuelled core, while establishing higher thermal margin for greater operational flexibility. The future CANDU 6 design will allow the option of power plant optimization for slightly enriched uranium fuel (0.9% to 1.2% b.w. U-235), to permit a further 5% output increase, in combination with significantly extended burnup (a factor of 2 or more higher). The CANDU 6 core design is readily adapted to optimization for variations in fuel cycle (in fact, existing CANDU 6 plants can be fuelled with slightly enriched fuel with no back-fit requirements except flux detector re-calibration). Therefore such designs will provide future opportunities to take advantage of fuel cycle options for the future to reduce fuelling cost, improve uranium utilization, or make maximum use of alternate fuel sources

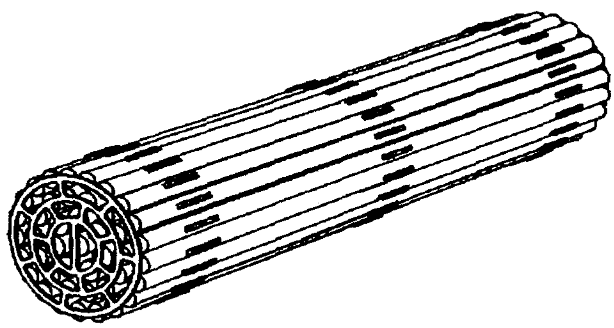

FIG. 3 CANFLEX Fuel Bundle

such as Recovered Uranium (RU), MOX, or thorium. Reference (2) describes the range of fuel cycle options which can be considered for CANDU in the future.

4. SAFETY DESIGN EVOLUTION

The CANDU 6 has, from the start, included safety design features which are familiar as standard parts of the CANDU family of designs:

- Two separate, diverse, fully redundant shutdown systems.
- All reactivity devices contained in the cool, low-pressure moderator.
- All safety systems designed for on-line testing to demonstrate 10^{-3} system unavailability continuously during operation.
- Moderator D_20 available as an emergency heat sink in the event of coolant loss coupled with assumed failure of emergency core cooling (ECC).

As the CANDU 6 design has evolved, the fundamental approach to safety design has not changed, but incremental improvements have been made. Incremental changes so far include:

- Automation of transfer from medium-pressure to low-pressure ECC, establishing full automation of all ECC functionality.
- Use of qualified, licensed, safety-critical software for digital control and testing of each shutdown system.
- Duplication of ECC heat exchanger and key isolating valves for easier testability and greater demand availability.
- Separate safety system monitoring display computer and console in Control Room.
- Dual-redundant, seismically-qualified fire suppression sprays.

Features under development for the enhanced CANDU 6 design include:

- Improved fuel thermal margin through the use of CANFLEX fuel and improved core flow and temperature monitoring.
- Reactor shielding vault cooling system design optimized to enhance inherent emergency heat sink capability for severe core damage accidents.
- Simplified, high-pressure design containment, eliminating requirement for fast-acting dousing pressure suppression sprays.
- Emergency core cooling system gas / H_20 / D_20 isolation using simplified, passive components.
- Increased redundancy and operating flexibility of both auxiliary and emergency feedwater systems.

5. POWER SYSTEMS DESIGN EVOLUTION

The CANDU 6 Primary Coolant System and associated systems use a well-established equipment configuration (2 coolant loops, each with two steam generators and two coolant pumps). Detail improvements to power systems design, implemented in current plants, include:

- Improved fuel channel piping materials, with higher chrome content to enable 60-year effective operating life.

- Steam generator design including improved access for inspection and cleaning.
- Fuel Channel design with greater seismic margin for more site flexibility, and featuring pressure tube design and material selection for longer life.
- Moderator system design with optimized core D_20 flow distribution, to allow higher temperature operation and save on heat sink equipment cost.

The CANDU 6 product optimization program has established a series of design improvements to improve performance, operating life, and safety margin:

- Moderator waste heat recycle via low-pressure feedwater heating, allowing over 1% improvement in output while achieving equipment cost reductions.
- Heat transport system purification optimized for precise control of pH and related chemistry parameters.

In addition, important improvements have been included for the next CANDU 6 in design of plant service systems. For example, the reactor building and service building ventilation and vapour recovery systems have been simplified and optimized so as to reduce emissions of tritium by a factor of four in comparison to the original CANDU 6 units.

Similarly, the use of the AECL-developed CECE catalytic exchange process improves effectiveness of heavy water in-house upgrading.

6. ENGINEERING METHODS EVOLUTION

Recent CANDU 6 build projects have incorporated successive advances in the use of advanced engineering tools. The Wolsong 2, 3 and 4 projects were based on use of 2-D CADDS to produce a reference plant design model through a series of linked CADDS databases. This enabled successes in project implementation through reduced design rework and field changes. This evolution has continued to the Qinshan project where a full 3-D CADDS model is used as the basis for CANDU 6 design. Electronic data transfer to engineering tools for such activities as support design, and stress analysis, has streamlined project execution. One result is a dramatic reduction in the number of field interferences, with benefits in reduced installation rework.

In wiring design, AECL introduced the InTEC wiring software for the Wolsong 2, 3, 4 project. This software links the design, engineering, procurement and installation processes.

For future CANDU 6 projects, AECL's suite of software tools such as 3D CADDS will be fully linked, with the inclusion of key functions of equipment specification (through TeddyBase the Tagged Equipment Database, and CMMS project (CANDU Material Management System), along with intelligent databases for document and other deliverable control.

At this point, AECL has developed, and gained real-world project experience with, a comprehensive suite of engineering tools, which enable efficient, timely generation and communication of engineering information throughout the project team, and throughout the duration of project execution.

7. PROJECT DELIVERY EVOLUTION

Project delivery for CANDU 6 units has also been improved through a continuous process of evolution. In particular, the use of open-top construction with equipment installation using heavy lift cranes, and the application of small, skid mounted modules, will streamline and shorten total project schedules. The Qinshan CANDU 6 project is currently using open-top methods extensively for major equipment installation. Future CANDU 6 projects will build on this experience to enhance the application of open top techniques. In addition the CANDU 6 improvements program has identified and designed 8 selected system modules which can be pre-fabricated and lifted into position "over-the-top", in addition to structural modules and rebar prefabrication. These delivery improvements will lead to further project schedule reductions. Currently CANDU 6 projects have achieved on-time completion in as low as 69 months from Contract Effective Date (CED) to in-service (Wolsong-3). For the immediate future, a target 66 month schedule has been established.

8. OPERABILITY EVOLUTION

The advancement of plant control, instrumentation and monitoring (section 2 above) is part of an evolution towards making operations and maintenance simpler, less time-consuming and more effective. This is recognized to be a key utility desire, and is an objective in all areas of design improvement. It is considered both for hardware design and for the provision of support information, for example linking operations and maintenance manuals to design basis and plant detailed configuration information.

The comprehensive, linked use of engineering tools, as described in section 6 above, allows a much more accurate, organized, and easily retrievable body of operating support information. The inclusion of plant operational history storage, available on the station LAN to both operations, helps maintenance and technical support staff to make effective maintenance planning decisions. AECL is carrying out studies in partnership with CANDU utilities to identify how this improved information availability can be used to generate and implement Condition-Based Maintenance (CBM) procedures for key systems. Condition Based Maintenance optimizes preventive maintenance and inspection plans, to reduce maintenance staff burden while at the same time improving equipment reliability. In support of this, additional Equipment Status Monitoring instrumentation is being included in the design for key plant equipment. In addition, AECL's development programs have established and tested equipment improvements in instrumentation self testing and signal noise analysis, which improve equipment status knowledge.

9. PASSIVE HEAT SINK CAPABILITY FOR CANDU 6

The CANDU 6 plant design has emphasized the use of passive systems, features and components to maximize reliability. Safety systems such as the two shutdown systems and the emergency core cooling systems use stored energy from high-pressure gas, or gravity, as part of the poised state, requiring the minimum of signal and valve response to act. The fully automated emergency core cooling together with the design for dual redundant trips on each shutdown system for all events, means that for design basis events, the enhanced design will allow an operator a grace period of ~ hours before safety-critical action is required.

AECL's development program has included several years of conceptual and detailed design and proof testing of further passive heat sink features. The objective is to take advantage of these features to improve system reliability, further simplify operator response and improve maintainability by minimizing the safety-critical requirements for active components and support systems. The introduction of passive features is planned as an evolutionary process. It is not considered necessary to define systems as fully "passive" or "active". The benefits of passive features are measured in overall design outcomes such as system availability on demand, long term reliability, or degree of dependence on operator action. Passive heat sink features from this program are scheduled to be included in the longer term development of the CANDU 6.

The AECL program of passive heat sink development is described in Reference 3. The conceptual design of a linked group of passive heat sinks for CANDU 6 is shown in figure 4.

The centrepiece of the passive heat sink approach is the Passive Emergency Water Supply (PEWS) tank, a porous-shaped tank located at a high elevation in the reactor building.

The basic requirement is to supply cooling water for decay heat removal for an extended period, and the PEWS tank can supply water for various systems and functions, dependent on the initiating event and whether any subsequent system failures have occurred. The two heat sink designs planned for early implementation in the CANDU 6 include the use of natural circulation moderator cooling (enhanced by forced circulation at full reactor power) and natural circulation containment atmosphere cooling. In both cases, the heat sink is a passive backup to the existing engineered system, Emergency Water Supply (for failures of normal steam generator heat removal).

10. DESIGN OVERVIEW FOR ENHANCED CANDU 6

The CANDU 6 Improvements Program is based on developing and implementing a series of incremental improvements while maintaining the proven nature of the design. In this way the project risk of implementing change is kept low. Also there is strong assurance that the good operating performance shown by the existing CANDU 6 plants will be repeated or exceeded. Each improvement is selected to be practical when implemented on its own, but also to complement other planned design changes.

AECL's design direction is based on responsiveness to utility and regulatory requirements. For example, the CANDU 6 design has been reviewed in comparison to the EPRI Utility Requirements Document, and found to meet the high-level requirements (the URD was developed principally for LWR's, so one-for-one comparison at a detailed level is not practical). The CANDU 6 development direction is to maintain compliance with the principles of major utility requirements, and to respond to utility expectations, such as the use of human factors principles in the human-machine interface design. Similarly, with regard to regulatory expectations, the direction is to maintain and enhance the ability to carry out timely plant licensing in a diverse range of national jurisdictions. The enhanced CANDU 6 design will continue to comply with IAEA safety guides and with evolving Canadian

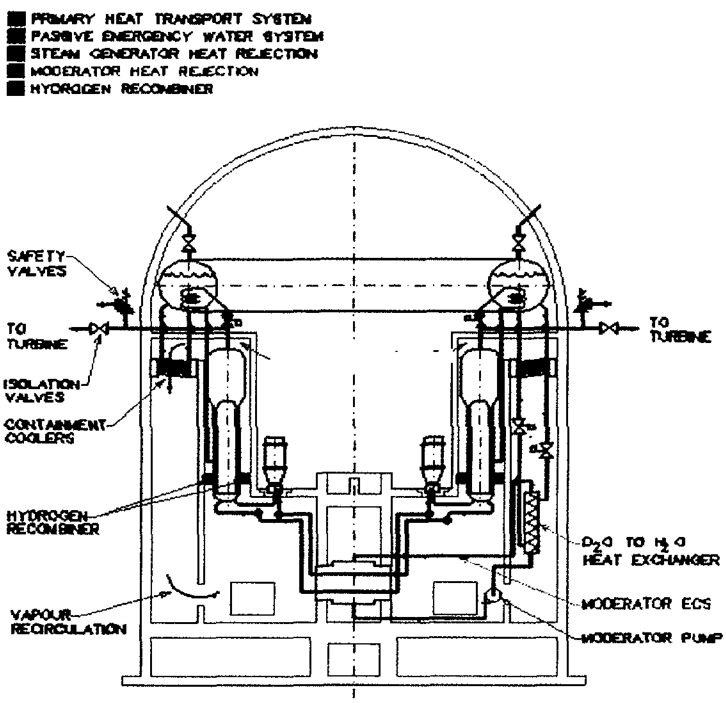

FIG. 4 Illustration of passive CANDU 6 system

licensing regulations, and will maintain a continuous link with established licensing approvals, for example regarding safety critical software methods.

The process of improvement selection, definition and implementation follows a careful review path establishing that individual changes are: proven (development testing is complete); incremental (limited cascading effect on rest of plant); beneficial to performance (e.g. capacity factor improvement; lower maintenance burden; lower risk of operator error, etc); beneficial to safety (improved margins; improved safety-critical system reliability); and / or beneficial to economics (reduced supply cost, construction cost, schedule, operating cost). In this way, change implementation occurs with very low risk to the customer.

The outcome of the CANDU 6 improvement program represents an evolutionary plant design incorporating state of the art features appropriate to 21st century projects, while maintaining provenness via the high degree of design continuity from the existing CANDU 6 plants and current projects.

The enhanced CANDU 6 will incorporate the following key features.

- Advanced control centre.
- Distributed digital control for both safety, process systems.
- CANFLEX fuel.
- Uprated output.
- Improved thermal margins.
- Improved Thermodynamic efficiency via moderator waste heat recycle.
- Simplified containment design and emergency core cooling design.
- Operator grace period of ~ hours.
- Improved equipment status monitoring.
- The use of electronic engineering tools to enhance operator capability to manage plant configuration and plan maintenance.
- Streamlined delivery to achieve short 66 months project schedule.

AECL's development of passive heat sink features will lead to the further stage of CANDU 6 development. This advanced version of the CANDU 6 will include:

- Moderator heat removal using natural circulation for high-reliability accident heat sink.
- Containment heat removal using natural circulation heat exchangers to minimize support system requirements and maximize long-term containment heat removal reliability.
- Optional core design optimized for low-enriched fuel for increased output and fuel burnup.

11. CONCLUSION

This paper outlines the evolutionary future of the CANDU 6 design. A great deal of potential exists to complete the development of the design, generating improvements in plant safety, operability and economics. The result of the AECL design improvements program can be envisaged as an evolutionary, enhanced CANDU 6 design. The next step is already under development, to adapt the design for the inclusion of passive heat sink features, and make available a core design optimized for low-enriched fuel.

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