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CANDU® TECHNOLOGY: THE NEXT GENERATION NOW

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ABSTRACT

We describe the development philosophy, direction and concepts that are being utilized by AECL to refine the CANDU reactor to meet the needs of current and future competitive energy markets.

The technology development path for CANDU reactors is based on the optimization of the pressure tube concept. Because of the inherent modularity and flexibility of this basis for the core design, it is possible to provide a seamless and continuous evolution of the reactor design and performance. There is no need for a drastic shift in concept, in technology or in fuel. By continual refinement of the flow and materials conditions in the channels, the basic reactor and R&D can be thermally and operationally efficient, highly competitive and economic, and highly flexible in application. Thus, the design can build on the successful construction and operating experience of the existing plants, and no step changes in development direction are needed. This approach minimizes investor, operator and development risk but still provides technological, safety and performance advances.

In today's world energy markets, major drivers for the technology development are: (a) reduced capital cost; (b) improved operation; (c) enhanced safety; and (d) fuel cycle flexibility. The drivers provide specific numerical targets. Meeting these drivers ensures that the concept meets and exceeds the customer economic, performance, safety and resource use goals and requirements, including the suitable national and international standards. This logical development of the CANDU concept leads naturally to the "Next Generation" of CANDU reactors.

The major features under development include an optimized lattice for SEU fuel, light water cooling coupled with heavy water moderation, advanced fuel channels and CANFLEX fuel, optimization of plant performance, enhanced thermal and BOP efficiency, and the adoption of layout and construction technology adapted from successful on-time plant construction projects. The development program is discussed and shown to meet the technology needs and targets. The essential features of CANDU reactors are high neutron economy (heavy water moderation), modular fuel channel design, on power fuelling, separation of the moderator and cooling systems, passive safety features, and a simple fuel design.

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These features result in a highly flexible design with respect to core layout and efficiency, safety enhancements, and advanced fuel cycles. This flexibility also means that there is no need to change these basic features, or to develop radically new designs, to advance the CANDU technology to meet evolving economic and safety goals. This paper shows how this flexibility is being applied to develop the Next Generation CANDU reactor, and how we can transition seamlessly from one reactor generation to the next.

INTRODUCTION: CANDU EVOLUTION

The modern CANDU reactor is the result of more than 55 years of nuclear technology development: 30 CANDU reactors operate or are under construction in 7 different countries. Figure 1 shows the basic configuration of the CANDU reactor core.

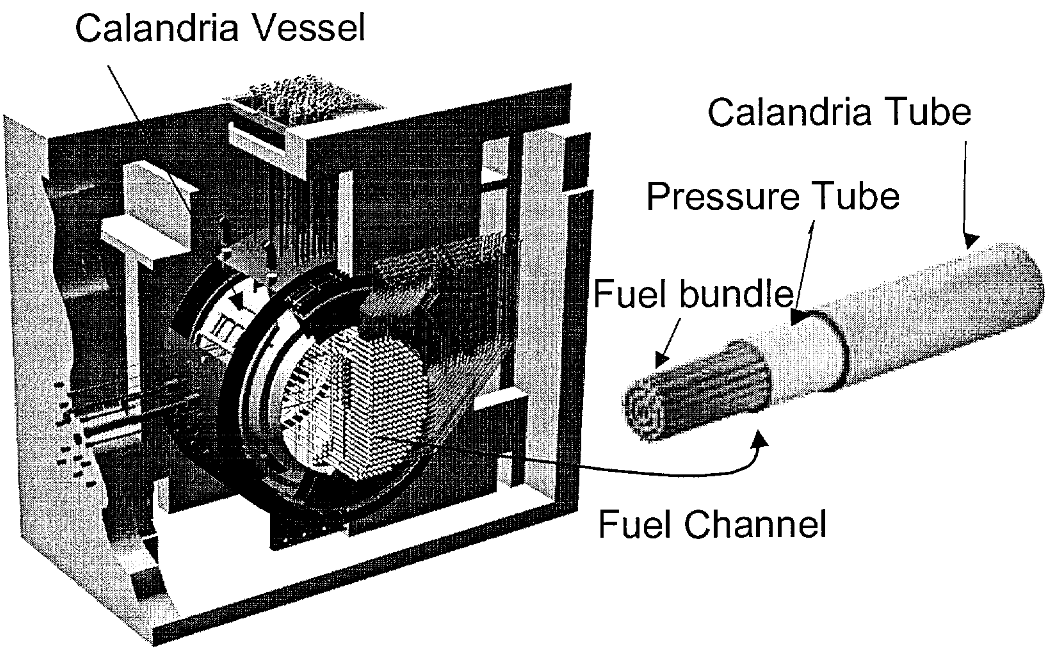

Figure 1: CANDU Reactor Core Design

The basic modular unit of the CANDU reactor is the fuel channel, containing 12 short fuel bundles. The reactor power output depends on the number of fuel channels and the chosen channel power: the 700 MWe class CANDU 6 contains 380 fuel channels, the 1000 MWe class CANDU 9 contains 480.

Another key feature of CANDU reactors is the use of a fuelling machine that pushes fuel in from one side of the fuel channel to a similar machine accepting the spent fuel bundles ejected from the other end, all while the reactor is operating at full power. Thus, there is no refuelling downtime.

The CANDU system, like all high technology products, is continuing to evolve to meet the requirements of the coming century. The next major step is called the Next Generation CANDU (NG CANDU). The essential features of the CANDU reactor enable a logical and systematic approach to advancing the design through an evolutionary process, permitting flexibility both in the design and in the application of the CANDU reactor. There is no need to depart radically from the basic design concept, or to adopt high-risk revolutionary approaches, to achieve considerable advancements to the technology.

Therefore, AECL's approach to developing advanced reactors is firmly centred on the exploitation and optimization of the existing CANDU characteristics. Following on from this, we have established the following principles for future development:

1. retain the essential CANDU characteristics;
2. ensure every component performs at its highest level;
3. simplify and eliminate components and systems where possible;
4. maintain safety margins;
5. improve operability and maintainability; and
6. optimize constructability.

The result is lower cost, increased thermal efficiency, improved safety, pre-licensed, less waste, enhanced proliferation resistance, faster construction, and competitive cost electricity.

DESIGN STRATEGY FOR IMPROVED ECONOMICS AND SAFETY

To meet the market requirements requires an integrated and effective strategy, one that is aimed at meeting the needs and satisfying the investors, owners and operators; and meets all the needs for safety and licensing as expressed by adequate operating margins, regulation and good practices.

Despite nuclear power plants being competitive on overall lifetime generating cost, in many markets any new nuclear energy systems must be competitive with low capital cost alternatives, such as combined cycle gas turbines recognizing the emphasis on short-term return on investment. Reducing the capital costs of nuclear power generation increases the rate of return on the investment while ensuring stable production costs.

We believe the capital cost of nuclear power plants must be 30 to 40% less than today's best options; which would significantly expand the application of nuclear power. The goal provides an energy mix that would allow the continuing use of hydrocarbon resources without possible restrictions due to greenhouse gas emissions.

A general methodology has been developed for meeting the economic, performance, and safety targets for the future:

a) core optimization starts with the fuel, which is being enhanced to ensure that the maximum energy is extracted from the fissile material;
b) each modular fuel channel is optimized with respect to channel power output, consistent with safety and performance limits;

c) the entire core can be configured to provide the highest output for the smallest volume (thus, for example, improving the power to heavy water ratio) while meeting safety goals;
d) the heat transport system (HTS) and turbine-generator can then be optimized to provide the highest possible efficiency for the core configuration to ensure optimal performance;
e) process systems and components can then be examined in detail to ensure their "fit" with the enhanced core configuration, and to maximize availability and optimize maintenance;
f) finally, the whole plant is engineered to optimize construction and operation, consistent with rapid quality construction.

The whole design and optimization process is paralleled by and iterates with detailed models for plant safety and costs. This overall optimization process ensures that not only are the cost targets met, but also safety is improved, and plant performance goals are met. In a sense, this is a product and development "design to market" approach, as discussed in modern business models. In fact, the whole approach requires new business model elements, as we shall discuss.

CORE DESIGN OPTIMIZATION

The plant must have a highly optimized fuel and fuel cycle, to ensure maximum resource use, minimize fuel cycle costs, assure safety and be reliable and easy to operate and control.

Key core parameters can be optimized, i.e., the lattice pitch, the calandria diameter, and the size of the heavy water reflector surrounding the core, without changing the pressure tube diameter and length. This ensures that the NG CANDU's high pressure and temperature core components, as well as the cooling system thermal hydraulics, remain firmly based on the extensive fuel and pressure tube technology that has been acquired over the years. By using slightly enriched uranium (SEU) in the CANFLEX fuel bundle, it is possible to increase the power output from the outer fuel channels, thus improving the radial power form factor. Overall fuel cycle costs can be reduced by about 30% owing to the higher uranium utilization and the reduction in the volume of spent (used) fuel.

Greater improvements could be made using slightly higher enrichments (for example, 1.5%), along with light water as the HTS coolant, retaining the key physics advantages of the CANDU reactor. By using heavy water only in the relatively low pressure and temperature moderator, then heavy water recovery and treatment systems can be reduced in size or eliminated. Of course, this also reduces/eliminates the operating and maintenance costs of those support systems.

The evolution of CANDU fuel has led to progressively higher performance by segmenting the fuel into smaller elements. The latest fuel design (CANFLEX), takes this evolution a step further by using the novel approach of differential diameters as well as increased segmentation. The result is a fuel bundle that produces the same thermal output as the current fuel design, but at 20% lower maximum linear element ratings, with subsequent thermal margins. CANFLEX SEU fuel can reach burnups that are approximately three times the current 37-element fuel bundle 1.2% SEU, reducing the volume of spent fuel and waste streams, as well as reducing load on the fuelling machines. CANFLEX SEU fuel can also be used to improve the channel power output, owing to the improved CHF margins and lower linear element ratings.

SYSTEM PERFORMANCE OPTIMIZATION STRATEGIES

In addition to improving the core thermal power output, the efficiency of electricity production can be improved by increasing the temperature of the heat transport system (HTS) coolant. We have targeted a thermal efficiency improvement to 36% by increasing the temperature of the HTS coolant.

With the core optimization, a smaller number of channels produce more energy. For example, a 240-channel reactor would have a net output of ~600 MWe; a 480 channel reactor's net output would increase to ~1200 MWe. Since the radial form factor is relatively flat, we can scale the number of channels up or down in a manner that is almost linear with output. This optimization results in a more compact core and a smaller calandria vessel, which, in turn, would drive down the costs of other systems and would facilitate construction. The NG lattice and larger calandria tube diameter reduces the moderator area surrounding the fuel by more than a factor of two. Therefore, we get a smaller, more efficient compact core, with larger thermal and safety margins, which is less expensive and more amenable to modular construction techniques, and eliminates about 75% of the heavy water.

The options discussed above serve to illustrate the very high flexibility inherent in the channel design. A new refuelling machine is being developed which is more compact and allows easy access to the tighter lattice spacing, while at the same time being simpler in design and operation. The machine concept therefore also has a lower cost, but at the same time less components for maintenance and no heavy water requirements.

The use of heavy water only in low pressure, low temperature application enables considerable simplification of the air dryer system design, revised requirements for internal shielding, and optimized equipment layout.

CONSTRUCTION AND SCHEDULE OPTIMIZATION

Another key market requirement is for a decreased construction time, to reduce the risks and costs, and enable faster and more nimble market deployment. The above design optimizations significantly improve plant construction. For example, a smaller calandria and reduced number of fuel channels would allow a prefabricated calandria and integral shield tank to be lifted into position with the fuel channels and reactor face feeder runs already installed. Commissioning will be much simpler and faster.

The Next Generation CANDU will also draw heavily on past design experience with previous CANDU reactors. In recent years, we have paid considerable attention to optimizing plant layout, materials, and constructability. A good example of this is the Qinshan project in China, where partial open-top construction techniques using heavy lift cranes are helping AECL and our partners to meet an ambitious construction schedule. This approach has been further advanced for the CANDU 9 design, where extensive modularization of components, optimal plant layout, and open top construction will lead to even shorter construction times. With modularization designed into the Next Generation CANDU, and, as a stretch target, we have established a goal of 36 months from first containment concrete to in-service.

ENHANCED AND INHERENT SAFETY

Optimization includes demonstrated assurance of licensability, adequate safety margins, and acceptable investor risk through improvements in safety. The qualitative goals are low core damage frequency, reduced emergency planning needs, and assured long term cooling for the plant. These are quantified using PSA analyses. The current CANDU reactor already incorporates passive safety as an integral and inherent part of the design. For example, the separation of the high pressure and temperature heat transport system from the low pressure and temperature moderator provides many advantages. The reactivity control devices are located in the low-pressure moderator and do not have to work against the HTS pressure. The moderator as a heat sink also effectively mediates the impact of postulated severe accidents. Even in the unlikely event that both primary and emergency core-cooling systems are unavailable, heat is transferred out of the fuel channel and into the moderator water with the result that there would be no fuel melting. Furthermore, the water-filled shield tank surrounding the calandria would contain and maintain a collapsed core in a cooled state for a long period of time if the moderator cooling system also became impaired.

The flexibility of the CANDU design also enables the further optimization and extension of these passive features and enhanced safety margins in the Next Generation CANDU. New fuel channels are being tested that can transfer even larger amounts of heat to the moderator under loss-of-coolant conditions. Looking ahead new fuels are being considered that have higher thermal conductivity, and operate at lower temperatures. These advances will result in fuel and fuel channel designs, which can withstand even severe accident conditions with minimal damage. New moderator cooling systems are being developed with highly efficient heat removal allowing natural circulation to eliminate reliance on forced convection. This enables provision at passive backup heat sink capability.

Figure 2 summarizes the optimization approach to advanced safety systems being developed for the CANDU reactor. The systems focus on passive heat transfer and coolant supply to all the critical areas of the plant. Use of PSA tools and risk-informed analyses and approaches assures that the CDF meets or exceeds requirements, and that the usually stated operator inaction time of 72 hours is easily met. Analysis of external events is also conducted to ensure the plant has sufficient seismic margin, that the EPZ zone is minimized, and that owner risk is acceptable. In addition, the rapid deployment requirement means that pre-licensing is a prerequisite, as has already been done for the CANDU 9.
Optimizing passive systems does not necessarily add cost or complexity to a reactor. For example, the CANDU 9 Emergency Core Cooling (ECC) system couples

both high reliability and simpler systems with reduced cost, using a passive burst disc system that eliminated almost 50% of the valves required. The Next Generation CANDU will take this still further.

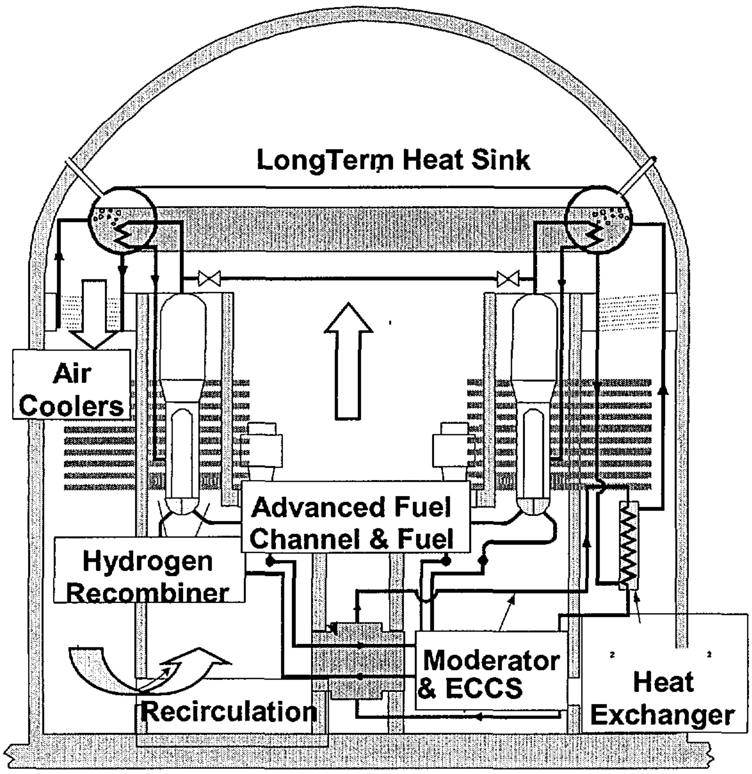

Figure 2: Advanced Safety Systems

In addition to enhancing the various heat sinks and cooling systems, other passive safety technology includes passive autocatalytic recombiners, to remove hydrogen and maintain hydrogen concentrations below the combustion limit. This technology is already being deployed in operating CANDU units in Canada.

OPTIMIZING PLANT OPERABILITY

The market requires better, cheaper and more cost-effective operation with specific targets for O&M cost, reliability and capacity factors (typically >90%).

The NG CANDU will have enhanced operating margin, including lower fuel element ratings, increased critical heat flux margins, increased margins in pressure tube performance, and improved regional overpower protection margins.

The Next Generation CANDU will also have the "Smart CANDU" suite of technologies, which will greatly enhance operability over the life of the plant. The "Smart CANDU" concept uses a combination of diagnostic probes, historical databases, state-of-the-art codes, and advanced information technology to provide operators with both the current and future status of the critical systems, structures, and components in the plant. For plant construction, the advantage of such technology is that equipment will not have to be over-specified to ensure that it operates within its design envelope over the life of the plant.

One of these technologies is called ChemAND (Chemistry Analysis and Diagnostics). ChemAND, a general plant chemistry information tool that features automated monitoring, alarming, diagnostics, prediction, and online execution of analysis codes. A prototype ChemAND system is currently operating in a CANDU 6 reactor. The next technology in this series, ComAND (Component Analysis and Diagnostics), will provide similar information covering the full range of performance-critical parameters for the critical plant components. In the future, we also plan to add system health monitors to measure heat transfer, flow, and other parameters affecting thermal performance.

These technologies would enable radical new business models for plant operation. An owner or operator may wish, for example, to also draw on external expertise to monitor the plant, and to recommend maintenance requirements and operating conditions. Such an operating model would make it easier to adopt nuclear energy without the expense and time of having to create and maintain all the expertise in-house. It could also lead to more risk/benefit sharing arrangements, whereby the partners share the responsibility and rewards for economic operation of the plant.

EFFICIENT RESOURCE USE, FUEL CYCLE FLEXIBILITY AND PROLIFERATION RESISTANCE

Another significant market requirement is that plant operators/owners wish to choose their optimal cycle to ensure low costs and stability of fuel supply. Next Generation CANDU designs accommodate fuel cycles that maintain high neutron efficiency, simple fuel bundle design, and on-power fuelling, and will use easily made and readily available SEU to achieve some of the enhancements described previously. Using the SEU cycle and thorium fuels enhances proliferation resistance and meets another perceived requirement. Next Generation CANDU flexible fuel cycles fall into two main categories:

a) the reuse of existing fissile material, such as spent LWR fuel using a relatively simple and proliferation-resistant dry process without Pu-U separation; and
b) the extension of fissile material well into the future without the development of new advanced (and expensive) technologies, using burn thorium fuel.

These cycles extend CANDU reactor applicability and resource sustainability for the foreseeable future without having to develop a new type of reactor. A number of practical thorium fuel cycles have been identified, including both once-through and recycle options, cost effectively supporting LMR-based cycles, since one LMR could produce sufficient fissile material to fuel up to nine CANDU reactors in contrast to the 1:1 ratio if the LMR/LWR cycle were adopted.

BEYOND THE NEXT GENERATION: CANDU X CONCEPTS

The Next Generation CANDU encompasses an evolutionary set of technologies that lead ultimately to the "CANDU X", also along a seamless development path. The CANDU X is a "concept vehicle" that extrapolates from current knowledge to what we believe can be achieved in our development programs over the next 25 years. Therefore, CANDU X itself is an evolving set of technologies and targets, with the overall goal of a further 50% cost reduction at any point in time. Our strategic development program is to continue to improve plant economics by increasing thermal efficiencies, developing and using materials and systems that can withstand the higher temperatures and pressures.

The ultimate goal is to improve the efficiency to about 45% by increasing the SCW coolant temperature to 625^{O}C, and operating the entire HTS under supercritical conditions. Studies so far show that the CANDU concept, with the ability to refuel on-line and place fuel reactivity where it is needed, is the ideal nuclear technology for application to high-temperature supercritical water coolant. Such a system could make use of existing and small direct cycle turbines (such as are now used with SCW boilers) located in the containment building to generate electric power, and a steam generator with an external turbine/generator outside containment to produce additional power. The CANDU X concepts illustrate that CANDU technology has several viable opportunities for continuing and seamless evolution and advancement into the long-term future.

CONCLUSIONS

New and competitive energy markets require new products, new approaches and new business models, and an integrated development strategy.

We have described the seamless development strategy leading from current designs to the NG CANDU, a reactor that is being designed now to meet the economics, performance, and safety targets associated with Generation IV reactors. All the targets for these new markets and conditions can be met using the technology pathway we have described, using technology, components and fuels that are all within today's development envelope and state of knowledge. This is a low risk and high return approach for investors, owners and operators, and is based on experience and not on extrapolation.

This strategy is possible because the CANDU design is flexible both in terms of advancing the technology to improve economics, enhance safety, and improve plant operability, and in terms of applications, such as fuel cycle choice. In the much longer term, the product will continue to evolve and include even more advances, transitioning seamlessly into the CANDU X concepts for the future.

ACKNOWLEDGMENTS

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