Key thrusts in next generation CANDU

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Abstract. Current electricity markets and the competitiveness of other generation options such as CCGT have influenced the directions of future nuclear generation. The next generation CANDU has used its key characteristics as the basis to leap frog into a new design featuring improved economics, enhanced passive safety, enhanced operability and demonstrated fuel cycle flexibility. Many enabling technologies spinning of current CANDU design features are used in the next generation design. Some of these technologies have been developed in support of existing plants and near term designs while others will need to be developed and tested. This paper will discuss the key principles driving the next generation CANDU design and the fuel cycle flexibility of the CANDU system which provide synergism with the PWR fuel cycle.

1. THE PATH TO NEXT GENERATION CANDU

The Pressurized Heavy Water Reactor (PHWR) CANDU system is a mature technology that evolved from 55 years of nuclear technology development and 30 years of commercial operation in many countries. Today thirty (30) CANDU units are operating or under construction in seven (7) countries.

The first CANDU designs were originally predicated on optimal thermal neutron utilization to enable the use of natural uranium as a fuel. However, the CANDU system, like all high technology products, must evolve quickly to meet the new requirements of the 21st century power market. The next major step in this innovative development is called the Next Generation CANDU.

This "next generation" will retain all the characteristics of the present CANDU reactor, including high neutron economy, modular design, on-power fueling, passive safety, and simple fuel design. These characteristics enable a logical and systematic approach to advancing the design through an evolutionary process. In addition, some of these characteristics allow the technology to be applied to many conceivable advanced fueling strategy without having to change the basic concept.

Thus, the main principles established for future development:

a) retain CANDU characteristics,
b) ensure every component performs at its highest level,
c) simplify and eliminate,
d) maintain safety margins,
e) improve operability and maintainability, and
f) improve the efficiency of the process and resource use.

2. KEY THRUSTS OF NEXT GENERATION CANDU

Three key goals drive the development of the next generation of CANDU plants. These are:

- *Improved Economics (Capital and Operation):* Cost reductions will result from plant optimization and simplification using "enabling technologies" which increases efficiency without compromising safety or operating margins. A key aspect of plant optimization is to ensure that all components and systems are performing at peak performance.

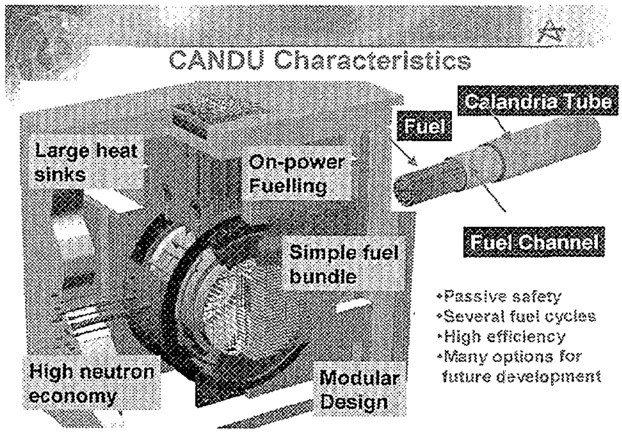

FIG. 1. CANDU characteristics.

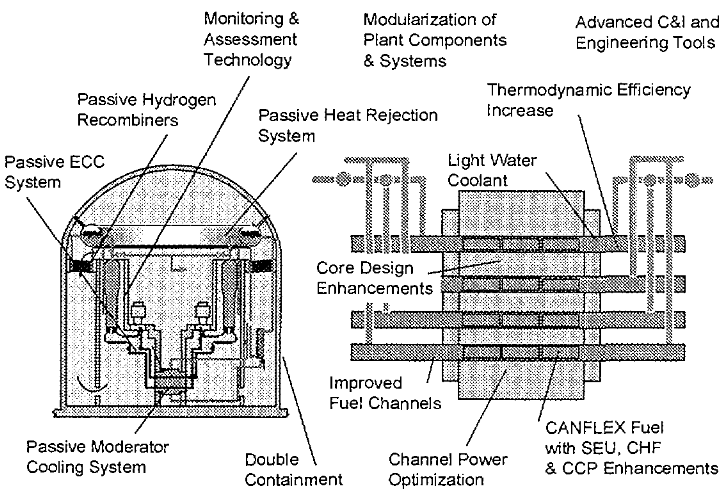

FIG. 2. Next generation CANDU enabling technologies.

- *Safety Enhancements:* The emphasis is on passive safety, which increases the reliability of safety systems while reducing design and operating complexity.

- *Enhanced Plant Operation:* The use of advanced technologies, such as "Smart CANDU" concepts to monitor and predict plant performance, will be implemented to maintain high capacity factors over the life of the plant.

To achieve these goals the next generation reactors will use new enabling technologies that are spin offs from the key characteristics of the CANDU design. Some of these enabling technologies have been developed for use in existing CANDU plants and the CANDU 9 design while other advancements will require extensive development and testing over the next few years.

2.1. Improved economics

The current CANDU reactors using natural uranium fuel are highly competitive with other commercial reactor systems. They are also competitive with fossil plants in many markets in terms of the lifetime unit energy costs, owing to the relatively low fuelling costs of nuclear power. However, it is recognized that many markets require energy systems to be competitive with low capital cost alternatives, such as combined cycle gas turbines (CCGT), even if the unit energy costs of nuclear power are lower. This is particularly true under market conditions where the long-term cost of electricity and price stability are less important than a short-term return on investment. Such market conditions would likely prevail in an open market where large centrally-controlled utilities no longer have a monopoly position. Therefore, to ensure competitiveness and diversity of supply in such markets, it is essential to seek major reductions in capital costs.

Overall, we believe that the cost of nuclear power plants must be reduced by at least 33% to meet the requirements of the coming decades. Such a cost reduction would significantly expand the market for nuclear power, particularly in emerging markets where the cost of capital is a major factor. This, in turn, would have a major effect on the reduction of environmental emissions (especially greenhouse gases) over the coming decades. In more developed markets, the goal is to provide 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 target. Since the CANDU core design is highly flexible, the initial step is to optimize the core to ensure that the maximum power can be extracted for the resources used (i.e., heavy water, fissile material, coolant flow, etc.). Once this is done, the remainder of the plant can be resized or improved, since the core characteristics drive or are tightly coupled to many of the other costs in the overall system. Core optimization starts with the fuel, which can be enhanced to ensure that the optimum energy can be extracted from the fissile material. Next, each fuel channel must be optimized with respect to channel power output. Once the output of each channel has been optimized, the entire core can be improved to provide the highest output for the smallest volume (thus, for example, improving the power to heavy water ratio). The heat transport system (HTS) and turbine-generator are then optimized based on the total core power. Finally, process systems and components are examined in detail to ensure their "fit" with the enhanced core configuration.

Every component in the plant is being examined and evaluated against both the goals for the NG CANDU while preserving the CANDU characteristics discussed above. A key element of our strategy to improve the economics is to optimize or eliminate expensive components. For example, heavy water is an essential component of the CANDU PHWR and provides moderation for high neutron economy. However, for the Next Generation CANDU opportunities to eliminate the use of heavy water where it is not strictly required for moderation, such as the coolant system, are being examined. In a similar way, every component and system is being challenged, to ensure that it is only performing its highest-level function.

2.1.1. Fuel and fuel channel optimization

CANDU fuel, owing to its simple design and location in a fuel channel with a well-characterized flow, can be optimized by improving the distribution of coolant flow and heat generation throughout the bundle. The evolution of CANDU fuel has led to progressively higher performance by segmenting the fuel into smaller elements. The latest CANDU fuel design (CANFLEX), takes this evolution a step further by using different element diameters as well as increasing the 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. Operating margins have also been enhanced by optimizing the flow properties in the subchannels of the fuel to increase the critical heat flux limits and the critical channel powers. This optimization is the result of detailed understanding of subchannel flows and heat transfer; it is yet another manifestation of the time-proven methodology of parallel experimentation and mathematical modeling, which AECL has used for several decades to develop and evolve the CANDU system.

CANFLEX fuel can reach burnups that are approximately three times the current 37-element fuel bundle. The higher burnups can be achieved by switching from natural uranium to slightly enriched fuel (SEU). For example, using 0.9% SEU fuel would double the burnup compared to the natural uranium fuel. By adopting 1.2% SEU, the burnup could be almost tripled. Such burnups would reduce the volume of spent fuel by a considerable amount, 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. At enrichments of only about 1.5% (still well below the $\geq$3.5% enrichment used in LWRs), CANFLEX enables further optimization of the CANDU core by enabling the use of light water as the HTS coolant. Such a core design would still retain the key physics advantages of the CANDU reactor. Cost analyses to date show that elimination of heavy water from the HTS more than overcomes the cost of slightly increasing the enrichment. Not only is the total cost of heavy water in the plant reduced substantially, but also the cost of auxiliary systems for heavy water recovery and treatment. 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. This reduces/eliminates the operating and maintenance costs of those support systems.

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. For the Next Generation CANDU design, we have targeted a thermal efficiency improvement to about 36% by increasing the temperature of the HTS coolant to 330°C. To accommodate these conditions, we are developing a slightly thicker and more corrosion-resistant pressure tube, with improved fuel channel components. At the same time, by using SEU and optimizing the core configuration, we can still retain the high neutron efficiency of the core despite the increase in pressure tube thickness.

2.1.2. Heavy water reduction

There are two approaches for heavy water reduction. First, as discussed above, by enhancing the power output from the core, fewer channels are needed for the same total power output. This, in turn, reduces the calandria size and the heavy water volume. An illustration of this is given in Figure 3, which compares calandria size for the CANDU 6 with the 600 MWe next generation CANDU concept discussed above. The reduction in size reduces the heavy water moderator requirement by a factor of 2.5. The second approach to reducing heavy water is the use of light water coolant in the heat transport system (HTS) and optimization of the channel pitch. This, combined with the reduction in moderator size, reduces the requirement for heavy water by more than a factor of 4. The absence of heavy water from the high pressure HTS reduces the load on heavy water systems, and reduces both capital and operating cost.

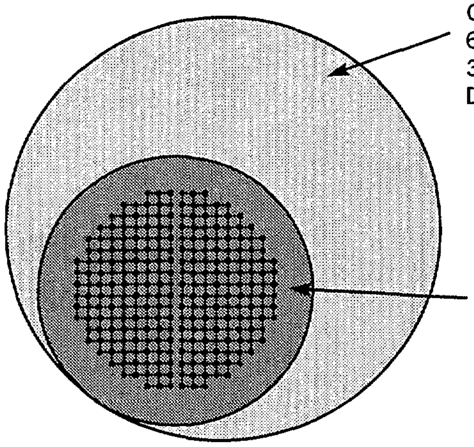

FIG. 3. Calandria reduction by core optimization.

The use of light water in the HTS also greatly simplifies the emergency core cooling/HTS interface. By trading off channel pitch and fuel enrichment, the coolant void reactivity could be reduced to any value desired (including negative). It is important to note that such changes would not affect the overall neutron economy of the CANDU reactor, and the use of advanced fuel cycles (such as the Direct Use of PWR Fuel in CANDU (DUPIC)) would not be restricted.

2.2. Enhancements in passive safety

CANDU reactors are unique in that a loss of coolant and loss of emergency core coolant does not lead automatically to severe fuel damage. The reason is the presence of the moderator, which can effectively and passively remove heat from the fuel. Over the years, we have improved the heat transfer from the fuel to the moderator under accident conditions by making small modifications to the fuel channel design. In the future, we intend to take this passive concept a step further by using thermosyphoning to remove heat from the moderator. The heat is then deposited in a large water reservoir, such as the reserve water tank used for the CANDU 9. The concept has been assessed and tested in large-scale laboratory tests for simple configurations. A similar system could also be used for normal operation, and the heat recovery used for feedwater heating to further improve the thermal performance of the plant.

Safety enhancements can also lead to reductions in complexity and cost. The replacement of valves with rupture discs in the emergency core cooling system (ECCS) of CANDU 9 design that rupture when the pressure in the HTS drops below a prescribed level have resulted in ECC reliability improvement. Such reduction in the number of valves has also reduced both capital and maintenance costs.

In addition to enhancing the various heat sinks and cooling systems, AECL is also developing other passive safety technology. A prime example of this is a passive autocatalytic recombiner, which is used to reduce hydrogen that could be released to containment. The recombiner works under cold, wet conditions by employing a proprietary wet-proof catalyst that does not require any active systems or power to operate. The recombiner maintains hydrogen concentrations below the combustion limit for some postulated accident conditions. With this recombiner design, the higher the hydrogen concentration, the more effectively the recombiner works owing to the increase in flow through the device as more heat is generated by the hydrogen/air reaction. This technology is replacing conventional igniters in AECL's future plants.

2.3. Improved operability and OM&A costs

For the Next Generation CANDU, a design goal is to enhance operating margins. Examples of improvements will include:

- Improved Regional Overpower Protection margins
- Reduced coolant void reactivity
- Lower fuel element ratings and greater margin for higher burnup
- Increased fuel critical heat flux margins
- Increased margin in pressure tube end-of-life properties.

These enhancements will be further developed and characterized in our development programs over the next few years. They are expected to have a strong impact on both plant economics and on lifetime capacity factors.

AECL is also developing 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 data bases, 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 is a general plant chemistry information tool that features automated monitoring, alarming, diagnostics, prediction, and online execution of analysis codes.

The next technology in this series, ComAND (Component Analysis and Diagnostics), will provide similar information on the critical plant components. In the future, we also plan to address thermal margins by incorporating system health monitors to measure heat transfer, flow, and other parameters affecting thermal performance. Such a system will allow plant optimization as well as avoiding potential de-rating due to premature aging effects.

These technologies would enable new business models for plant operation. A future operator may wish, for example, to 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 vendor could take on more responsibility for economic operation of the plant.

2.4. Fuel cycle flexibility

Countries with nuclear plants that wish to retain self reliance and energy independence need to explore the existing synergy between PHWR fuel cycle and that of the PWR.

The CANDU reactor is unique in that several viable fuel cycles are possible using both fissile and fertile fuel. All present and future CANDU designs will continue to accommodate these fuel cycles by maintaining high neutron efficiency, simple fuel bundle design, and on-power fueling. Even using SEU, neutron economy will still be optimized and CANDU's ability to burn a wide variety of fuels will be retained.

CANDU advanced fuel cycles (i.e., beyond the use of natural uranium and SEU) fall into two main categories. The first is the recycle of existing fissile material, such as spent PWR fuel. Spent PWR fuel represents a valuable resource for neutron efficient CANDUs, since it contains 1.5% fissile Pu and U. By reconstituting the spent fuel, using a relatively simple and proliferation-resistant dry process without Pu-U separation, to convert the fuel material into CANDU fuel pellets (DUPIC = Direct Use of PWR fuel In CANDU), an additional ~ 15000 MWd/t could be extracted from the spent fuel. In addition to DUPIC, there are a number of other fuel cycles using PWR fuel reprocessing wastes that are viable for CANDU, including the recycling of recovered uranium, plutonium, and even fissile and fertile actinides.

The second category of advanced fuel cycles concerns the extension of fissile material well into the future. For the CANDU, the development of new advanced (and expensive) technologies, such as Liquid Metal Reactors (LMRs), is not required to secure a long-term source of fissile material. One advanced fuel cycle available to CANDU reactors now is the option to burn thorium fuel. This would extend CANDU HWR applicability for the foreseeable future without having to develop a new type of reactor. A number of thorium fuel cycles are possible, including once-through cycles that do not involve fuel processing. CANDU reactors can also support LMR-based cycles, since one LMR could produce sufficient fissile material to fuel up to nine CANDU reactors. This is in contrast to the 1:1 ratio if the LMR/PWR cycle were adopted. Since the LMR will likely be an expensive commercial reactor, the CANDU/LMR synergism would be a more cost-effective option. The main option for thorium cycles that has been considered up to now is recycling ^{233}U from the spent fuel. An alternate approach is to adopt a once-through thorium cycle that does not depend on recycling of fissile ^{233}U. A "mixed bundle" approach, where elements of thorium and enriched uranium are contained in the same bundle, is the most attractive option from the perspective of fuel management and reactor control.

In the context of protection against proliferation, the CANDU is subject to International Safeguards and offers no diversion disadvantages compared to other current reactor designs. For future fuel cycles, thorium has an added advantage in that production of the fissile isotope ^{233}U unavoidably results in production of other uranium isotopes that make the fuel effectively unusable in nuclear weapons. The predominant reasons that thorium has not been used more widely to date is the fact that the ore must be 'enriched' with either ^{235}U or plutonium to start this fuel cycle, and the overwhelming advantage of experience with uranium fuels. However, at the present time there is an excess of separated fissile isotopes in the world, some of which could be used for introduction and development of thorium-based fuels for the future.

2.5. Constructability

The Next Generation CANDU will also draw heavily on past design experience with previous CANDU reactors. In recent years, considerable attention was paid to 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. Similar modularization will be 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.

These advancements along with the new features discussed above will also improve plant construction. As an example, a smaller calandria with a reduced number of fuel channels would allow a prefabricated calandria to be lifted into position with the fuel channels and reactor face feeder runs already installed. The smaller calandria size would also facilitate the installation of an integral stainless steel shield tank. The use of light water as the HTS coolant means that commissioning will be much simpler and faster – for example, there would be no need to test the hydraulics with light water, and then drain the system and refill with heavy water.

SUMMARY

The current competition from the Combined Cycle Gas Turbine (CCGT) and the emerging deregulated electricity market have defined the path for future development of nuclear generation. The PHWR-CANDU design is driven by the same market environments both in Canada and abroad. Improved economics, enhanced passive safety features and optimized constructability are some of the thrusts driving the development of the next generation CANDU.

New enabling technologies spun off from current CANDU features will form the basis of the next generation design; some have been developed for use in existing and new CANDU plants and others will require development and testing in the next few years.

ACKNOWLEDGEMENTS

Many AECL staff are aggressively pursuing the advanced knowledge in both the engineering and R&D required to take CANDU technology to the next stage of development. The degree of enthusiasm and creativity of these colleagues, who are too numerous to list here, is highly gratifying to the authors, and this paper is dedicated to their efforts.

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