Reducing the Cost of the CANDU® System

David F. Torgerson
Vice-President, Research & Product Development
Atomic Energy of Canada Limited

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Abstract

The high-level strategy for developing the next generation CANDU reactors consists of three main thrusts:

- Cost reductions via plant optimization and simplification
- Safety enhancements with an emphasis on passive safety
- Enhanced Plant Operation using "Smart CANDU" concepts

The next generation CANDU reactors will retain all the essential characteristics of the CANDU reactor. These include high neutron economy, modular design, on-power fueling, passive safety, and simple fuel design. However, we believe that the extensive knowledge base that has been developed over the last 50 years can be used to achieve considerable plant optimization and simplification. The cost reductions that result from optimization and simplification would significantly expand the applicability of nuclear power, particularly in emerging markets where the cost of capital is a major factor. This, in turn, would have a major impact on the reduction of environmental emissions over the coming decades. Some of the enabling technologies being considered for the next generation CANDU plants are outlined in this paper.

Introduction

Environmental concerns have led to a re-examination of the role of nuclear power with respect to the reduction of greenhouse gases and other emissions. Nuclear power does not produce greenhouse gases, acid rain, particulates, or other emissions that could have widespread environmental impact. In addition, the waste produced by reactors is small in volume and is contained for ultimate disposal. However, for extensive application of nuclear power in the future, reactors must also be able to compete effectively in open energy markets.

Deregulation, privatization, and open competition are all reshaping the global electricity market. For example, some emerging markets have adopted privately financed and operated Independent Power Projects (IPPs) to meet their growing energy needs. For the most part, these IPPs are Combined Cycle Gas Turbines (CCGT), owing to their low capital costs, rapid construction times, and low regulatory risks. The expansion of CCGT plants is obviously not compatible with reducing greenhouse gases. However, for nuclear power to have a major impact in these emerging markets, similar conditions need to be secured – particularly low capital cost and low risks associated with plant operation and performance.

It is instructive to examine the differences in CCGT and nuclear plant economics in more detail. Taking data from the OECD-NEA/IEA publication "Projections of Electricity Generating Costs, 1998 Update", it is possible to compare the levelized unit energy costs (LUEC) of a nuclear plant and a CCGT unit. The data for a 676 MWe CANDU 6 and a 350 MWe CCGT plant have been used to generate the relationship between the LUEC and the discount rate shown in Figure 1.

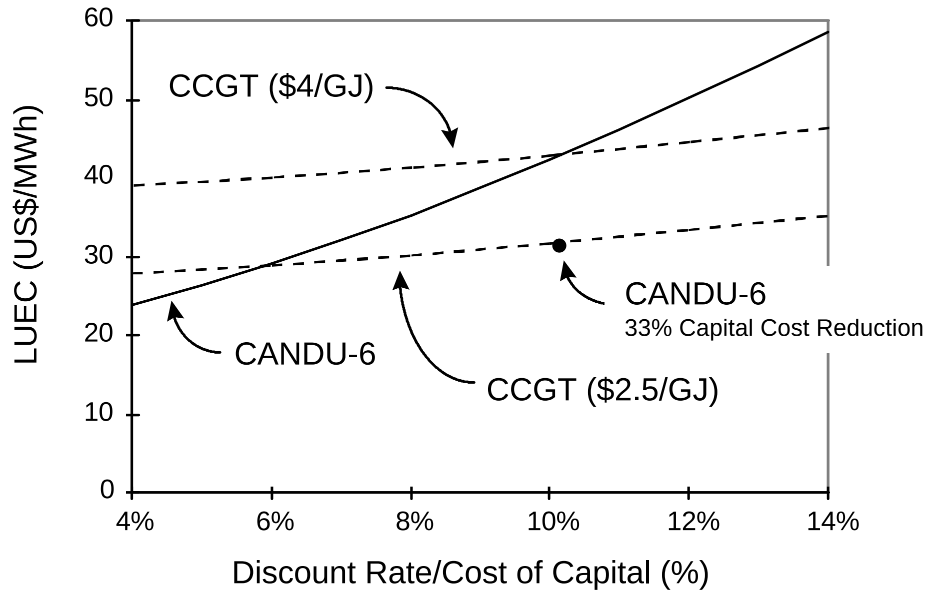

Figure 1: Levelized Unit Energy Cost vs. the Discount Rate for typical CCGT and CANDU 6 Costing Parameters

The competitiveness of nuclear power is dependent on both natural gas prices and on the cost of capital. Natural gas prices vary from about US$2.5/GJ in North America to US$3-4/GJ in Europe and some areas of the Asia Pacific. A discount rate of 5% is typically used for economics analyses by national utilities in developed countries. However, developing countries have higher borrowing costs, and have used discount rates of up to 10%. In an open market, the cost of capital would be at least 10% for private utilities. The relatively sharper dependence of a nuclear plant LUEC on the discount rate reflects the higher initial capital cost (the overnight capital cost per unit energy is about a factor of 3 higher for a nuclear plant compared to a CCGT plant).

Overall, the levelized unit energy cost associated with nuclear plants is very competitive at lower discount rates and/or higher natural gas prices. Also, nuclear power is relatively unaffected by fueling cost fluctuations, since fueling costs are only ~5% of the LUEC. By contrast, fluctuations in natural gas prices over the life of the plant will have a large effect on the cost of power, since more than 50% of the LUEC is attributable to the cost of fuel. For these reasons, nuclear power is very attractive to national utilities who wish to establish steady, competitive electricity prices over several decades of operation. However, in open, deregulated markets, capital cost and shorter-term rates of return are likely to be more important than long-term levelized energy costs. Therefore, AECL is placing particular emphasis on capital cost reduction, while at the same time enhancing safety margins and plant operability. For example, as shown in Figure 1, if the capital cost of a CANDU 6 is reduced by 33%, then CANDU reactors are competitive at the lowest natural gas price for a 10% discount rate.

This paper outlines some of the enabling technologies that AECL is developing and/or assessing for the next generation CANDU design. The intent is not to outline the entire scope of AECL's development work, but to illustrate that there is considerable flexibility within the CANDU design for further enhancements. This flexibility results in several viable options for achieving significant capital cost reductions. Our goal is to develop the enabling technologies over the next 5 years required to achieve a cost reduction of at least 30%. Longer-term enhancements could lead to additional cost savings, and we have established an aggressive stretch target reduction of 40%. While the next generation design will retain all the essential features of the CANDU system, it will be a significant step from the current system. However, as the enabling technologies are established and tested, they will be considered for incorporation into the current design. Therefore, the next generation CANDU program will also result in improvements to the current CANDU design, which will continue to be developed through evolutionary steps.

Principles for CANDU Development

The high-level strategy for developing the next generation CANDU reactors consists of three main thrusts:

- Cost Reductions. 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.

- 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.

The next generation CANDU reactors will retain all the essential characteristics of the CANDU reactor. These include high neutron economy, modular design, on-power fueling, passive safety, and simple fuel design. However, the extensive knowledge base that has been developed over the last 50 years can be used to achieve considerable plant optimization and simplification, while preserving these characteristics. Therefore, there is no need to consider large changes to the CANDU design to achieve the next generation product.

Enabling Technologies for The Next Generation CANDU Reactor

Enabling technologies for the next generation CANDU reactor are based on existing features of the CANDU reactor, plus enhancements to be developed over the next few years. In some cases, the enabling technologies were initially developed to improve the performance of existing CANDU reactors -- such as CANFLEX fuel which is currently being irradiated in Pt Lepreau. The application of CANFLEX to the next generation design is a logical step in the evolution of AECL's fuel technology. Thus, many of the enabling technologies can be applied to improve the performance of existing operating reactors and new projects. Other advancements will require extensive development and testing, and would only be applied to the next generation plants.

An overview of the enabling technologies under development or assessment is summarized in Figure 2.

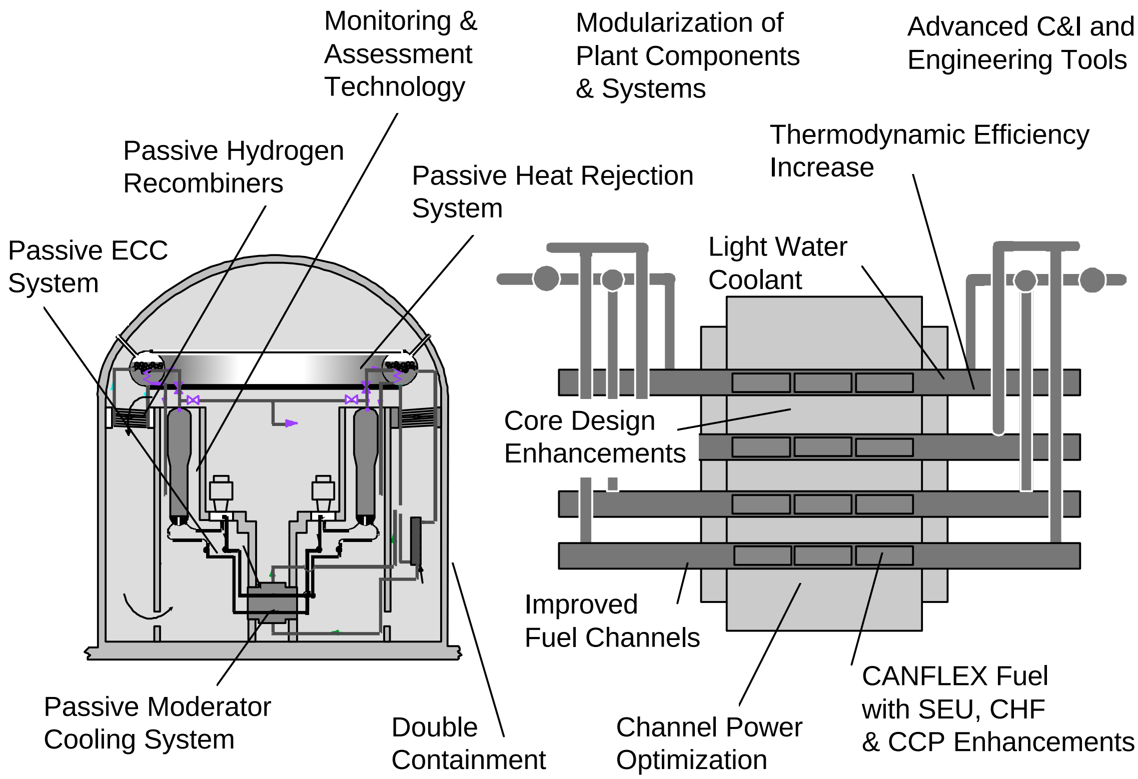

Figure 2. Next Generation CANDU Enabling Technologies

Some of the specific enabling technologies being assessed and developed are summarized in the following sections.

General Approach to Cost Reduction

The fundamental characteristics of the CANDU reactor are high neutron economy, modular design, on-power fueling, passive safety, and simple fuel design. These features will be preserved in the next generation design. Nevertheless, there is considerable latitude for enhancing the design, while preserving these characteristics.

The basic modular unit of the CANDU reactor is the fuel channel. The CANDU core was developed for optimal neutron economy to accommodate natural uranium fuel. However, the core can be further optimized for power output without compromising neutron economy. Once the core is optimized, it is possible to simplify the ancillary systems. For example, if the core design is optimized to maximize the power/heavy water ratio, then the load on several other systems would be reduced, such as heavy water recovery and upgrading. The systematic reduction in the size and complexity of systems, in turn, leads to reductions in other components. Eventually, this could lead to reduction in the size of containment and other civil structures. Therefore, we are taking a "systems approach" to plant enhancement, whereby improvements to the fuel channel modular units are cascaded through the entire plant.

An additional goal is to preserve and enhance plant safety margins and plant reliability. Passive safety features, such as heat transfer to the moderator under accident conditions, would be further developed to replace active systems.

Finally, it is essential to ensure that plants operate with consistent and high capacity factors over the life of the plant. We believe that this "certainty" can be accomplished by building in extensive monitoring and predictive technology into our plants, and by adopting new business models for plant operation.

Fuel Development

The starting point for core optimization is the fuel. CANDU reactors currently use 28- or 37-element natural uranium fuel bundles. These designs have performed well over the last few decades and are effective carriers for natural uranium fuel. The next generation CANDU fuel, CANFLEX, contains 43 elements and uses two element diameters to reduce the peak element ratings from 37-element fuel by about 20%. CANFLEX was developed to accommodate several different fuel options, such as slightly enriched uranium (SEU), thorium, recycled LWR fuel, etc. An important feature of CANFLEX is the ability to achieve burnups that are about a factor of 3 higher than current values.

In addition, CANFLEX elements contain appendages that improve the critical heat flux (CHF). Since the pressure drop across CANFLEX fuel is similar to 37-element fuel, the improved CHF performance results in a significant increase in the critical channel power (CCP). This feature can be used, along with SEU, to extract higher powers from the fuel while maintaining or enhancing operating margins. The importance of this feature is further developed in the next section.

Fuel Channel Power Enhancements

The use of CANFLEX fuel, with higher margins to dryout, would allow improvement to the fuel channel power output. For example, CHF/CCP data for CANFLEX fuel indicate that the power limit could be increased substantially by replacing 37-element fuel with CANFLEX.

One way to exploit this improvement is to develop a core that uses SEU with the CANFLEX bundle. For such a core, it would be possible both to increase the average channel power, and to smooth the radial power distribution across the core. This would eliminate many of the "underperforming" fuel channels (which use the same resources as a "high-performing" channel). For example, a 240 channel core with CANFLEX/SEU could generate about 600 MWe, compared to 676 MWe for a 380 channel CANDU-6 core fueled with natural uranium. The time-averaged peak channel power in the 240 channel core with CANFLEX/SEU would be well below the limit. In addition, the lowest power channel would generate ~6.2 MWt compared to ~3 MWt for existing CANDU reactors. The reduced number of channels would require less heavy water, and would result in a large reduction in calandria size, as discussed in the next section.

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.

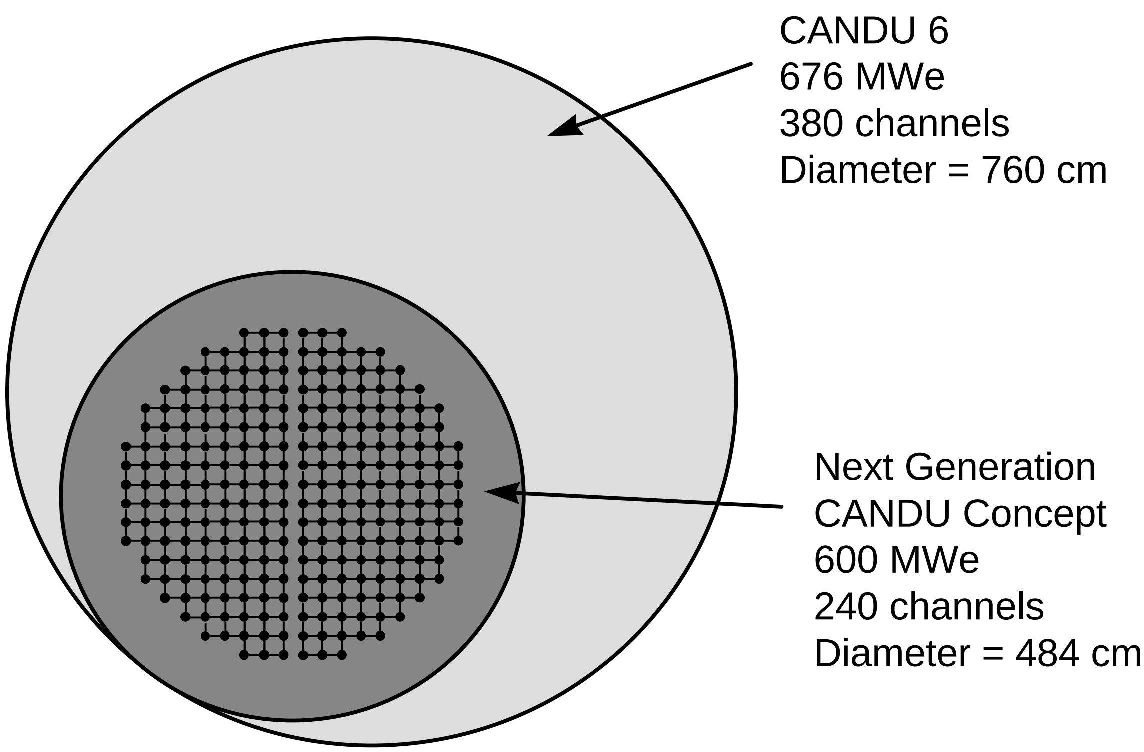

Figure 3. Calandria Reduction by Core Optimization

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. 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.

Thermodynamic Efficiency

The outlet temperature and pressure for the CANDU 6 are 310^0C and 10 MPa, respectively. The secondary steam temperature for these conditions is 260^0C and the resulting thermal efficiency is 32.2%. By increasing the outlet temperature to 330^0C, for example, the secondary steam temperature could be increased to 290^0C. This would result in a thermal efficiency of almost 35%. Further increases to supercritical conditions would result in thermal efficiencies that could exceed 40%.

An increase in the outlet temperature would require careful consideration of materials properties and behaviour to ensure that the "hot" components would perform well over the life of the plant. One approach is to design the "hot" components so that they can be quickly and easily replaced as required. For example, a thicker fuel channel that is easily replaced would appear to be an effective means to ensure that operating margins and capability factors would be maintained over the life of the plant. An alternative is a high-temperature fuel channel design where the pressure tube is thermally insulated from the hot coolant, and is in direct contact with the cooler moderator. There are many advantages to operating the fuel channels at lower temperatures; for example, corrosion rates and ingress of hydrogen into the pressure tube would be substantially reduced.

Safety Enhancements

As mentioned above, one of the constraints we have established for the next generation CANDU is that safety margins must be maintained. In addition, AECL is developing a number of passive systems that take advantage of the large heat sinks that already exist in CANDU reactors – such as the moderator, the shield tank, and the reserve water system in the CANDU 9.

CANDU reactors are unique in that a loss of coolant and loss of emergency coolant does not lead automatically to severe fuel damage. The reason for this 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 thermal siphoning 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. For example, the CANDU 9 uses an emergency core cooling (ECC) design based on passive burst discs that rupture when the pressure in the HTS drops below a prescribed level. The design increases the reliability of the ECC, while reducing the number of valves. A reduction in the number of valves reduces the capital cost and the requirements for testing and maintenance.

Plant Operability and Capacity Factor

AECL is carrying out a comprehensive assessment of the critical components, structures, and systems in CANDU reactors to identify the key plant life management factors. As a result of this assessment, we have given priority to developing advanced diagnostic tools for monitoring the health of the most important plant systems. The "Smart CANDU" concept is a technology that not only monitors the critical systems, but also recommends actions that can be taken to ameliorate any conditions that could lead to incapability in the future.

An example of this development is ChemAND, a technology that monitors plant data and uses state-of-the-art codes to predict adverse chemistry conditions, fouling, and other phenomena that would impact on plant operations. For the next generation CANDU, such technology would be used by AECL experts to monitor and assess the plant to ensure that all the critical components and systems were operating within tolerances. The monitoring systems would also be used, wherever possible, to automate plant chemistry conditions, such as the heat transport system pH.

Automating the plant chemistry systems and continual monitoring of plant conditions by experts would have an appreciable effect on performance over the life of the plant. It would allow the plant owner to focus on generating power and would ensure that plant systems are receiving constant attention from experts, thus freeing the operator from the need to maintain expertise in every area. This technology would enable a new business model where both the vendor and operator work together to ensure the "certainty" of performance over the life of the plant. Such an approach would allow countries or jurisdictions with limited technical support to introduce nuclear power technology with the confidence that the technical support required for effective plant performance would be in place.

Conclusions

The CANDU reactor design has continued to progress over the years by evolutionary improvement to components and systems. This approach has led to an extensive knowledge base that forms the starting point for the next generation CANDU reactor. We believe that by expanding the knowledge base aggressively over the next 5 years, we can optimize the performance of the various systems and components, while retaining the essential features of the CANDU reactor. The enabling technologies arising from this work will result in next generation CANDU designs that will achieve significant cost and operability improvements.