Enhanced CANDU 6 (EC6): A Proven Mid-Sized Reactor with Fuel Cycle Capability

Jerry Hopwood, Michael Soulard and Ian J. Hastings
Atomic Energy of Canada limited, Mississauga, Ontario L5K 1B2, Canada

Abstract

Atomic Energy of Canada (AECL) is finalizing development of the Enhanced CANDU 6®* (EC6®*), which incorporates the CANDU 6's well-proven features, and adds enhancements that make the reactor even more safe and easier to operate. The EC6 is the only mid-sized reactor (700 MWe class) with a proven pedigree that meets modern reactor expectations and regulatory standards. It is sized for smaller grids and also has outstanding fuel-cycle capability. Changes are incremental and consistent with the CANDU 6 project approach. The EC6 utilizes modern computers and a distributed control system housed in an advanced control room which, along with automated testing and on-line diagnostics, make the plant easier and safer to operate, with minimal operator intervention. Containment and seismic capability are upgraded to meet modern standards. The first deployment of the EC6 is anticipated in Canada; international markets are also being pursued. AECL is performing a comprehensive review of the EC6 design in the wake of the Fukushima accident, will review lessons learned, and incorporate any necessary improvements into new build design.

1. Introduction

The Enhanced CANDU 6 (EC6) [1] is a 700 MWe-class, heavy water moderated, pressure tube reactor, designed to meet modern regulatory requirements and provide safe, reliable, nuclear power. In the EC6, the CANDU 6 design continues its product evolution since the initial construction of the plants at Point Lepreau, Gentilly-2 and Embalse; safety and operational improvements have been incorporated in subsequent projects at Wolsong and Cernavoda, then further enhancements at Qinshan. The EC6 reactor builds on this success of the CANDU 6 fleet by using the project, operational, and feedback experience to upgrade the design and incorporate improvements to meet modern safety standards. Well-proven CANDU reactor strengths, retained in the EC6, include:

- Neutron economy
- Modular, horizontal fuel channel core
- Separate low-temperature and -pressure moderator
- Reactor vault filled with light water surrounding core

- On-power refuelling
- Two independent passive, safety shutdown systems

Further advantages accruing to the EC6 are proveness, track record (low project risk), unique size and operating performance. The EC6 satisfies modern safety and plant criteria, typically characterized as Generation III.

Also, the EC6 can use a variety of nuclear fuels in addition to the standard natural uranium. High neutron economy, on-power refueling, a simple fuel bundle, and the fundamental CANDU®* fuel channel design provide the EC6 with flexibility in accommodating a range of advanced fuels and fuel cycles [2].

2. EC6 Design Features

2.1 Reduced Project Schedule

AECL and its partners have already demonstrated on-time, on-budget project performance with the CANDU 6. The EC6 first-concrete-to-in-service project schedule is targeted for 57 months, with a second unit to follow six months later. These targets will be achieved by the use of additional modularization, open-top construction using a Very-Heavy-Lift crane as demonstrated at Qinshan Phase III, pre-ordering of long lead-time items, and standardization of equipment such as valves, tanks and piping.

2.2 Extended Plant Life

The EC6 target design life is 60 years, with replacement of critical equipment, such as fuel channels, around mid-life. All life-limiting factors have been evaluated and addressed, supported by extensive R&D. The objective is achieved by elongating the fuel channel bearings, thickening the pressure tube, increasing the feeder wall thickness, using improved equipment and materials, better plant chemistry, and more active monitoring of critical plant parameters. Doubling the useful life of the reactor assures the plant owners of a long-term supply of electricity, with an improved return on investment.

2.3 Simplified Operability and Maintainability

AECL utilizes feedback monitoring, receiving input from operating plants (OPEX) and incorporating it into the design of CANDU reactors. Based on this feedback, AECL is modifying systems to simplify maintenance and reduce operator workload. For example, the cooling water system design has been improved to have dual trains that enable interconnections of these trains during maintenance or plant upset conditions. Also, automated safety system testing will be incorporated. This will not only reduce the testing workload but will also eliminate human errors that can cause inadvertent reactor trips. In addition, AECL has developed plant health monitors that will be incorporated, or added as retrofits to existing plants.

2.4 Modern Computers and Control Systems

The EC6 has enhancements that modernize the plant and address equipment obsolescence. These features simplify plant displays, reduce the amount of wiring runs and save construction effort and costs. The Digital Control Computers will be replaced with a modern, state-of-the-art Distributed Control System (DCS), designed to control and monitor systems such as reactor operation, power-generation equipment, fuel-handling and auxiliary systems. The DCS supports both group and device control, reducing the need for individual group controllers.

In addition, a Plant Display System (PDS) to manage operator interactions with the DCS will be included. The DCS/PDS also will include the functionality required to manage plant annunciation and support on-line procedures. The EC6 incorporates the above features in a modern Advanced Control Room. Safety system operation is retained as a hardwired function. Computerized testing and displays have also been added to ease the operator's workload.

2.5 Optimized Plant Outages

To improve the EC6 capacity factor, AECL performed a detailed assessment of the requirements for planned maintenance outages. Periodic short-duration maintenance outages of 30 days once every 36 months are planned. The increased interval will be achieved by automating tasks such as shutdown systems testing. Most of these tasks can be undertaken with the reactor at power. Additionally, Reliability Centered Maintenance techniques are used extensively, and plant health-monitoring equipment predicts impending equipment problems, which can be acted upon immediately, avoiding forced shutdowns.

2.6 Containment Design

The EC6 features a reactor building with a 1.8m thick wall/dome, with a steel liner, in line with current industry practice. This provides protection against aircraft strikes (malevolent acts) and other external events. Further hardening of the safety systems and improvements to the spatial separation of essential safety systems are being built into the design. Group 2 safety systems, which offer a redundant path to shut the plant down safely. Depending on the location of the plant, the EC6 can also be designed to meet tornado protection.

2.7 Seismic Response

Also in line with modern industry practice, and a Gen III/III+ expectation, the EC6 is designed for seismic 0.3g peak ground acceleration, with a 10^{-4} frequency of occurrence. This is achieved via a thicker base slab and rock anchors. Other systems are also strengthened: calandria support, thicker pressure tube/calandria tube, stronger spacer and positioning assembly, hardened fuelling machine and upgraded piping material.

2.8 Severe Accident Response

To further improve EC6 plant safety, the design incorporates features to mitigate core degradation and contain the consequences of severe accidents. Such features include provisions for additional heat sinks as well as a cooling system to manage the containment temperature and pressure. The number of penetrations is reduced and the steel-lined containment structure strengthened to meet a higher design pressure. All radionuclide releases following any severe accident will be confined within containment.

AECL has already been enhancing the performance for CANDU 6 reactors under postulated severe accident conditions that go beyond the normal design basis for nuclear power plants. The heavy water moderator surrounding the fuel channels in the calandria vessel effectively mitigates the consequences of such postulated severe accidents. In addition, the moderator is surrounded by a shield tank, which also absorbs decay heat should moderator cooling fail. These features ensure fuel cooling even if both normal and emergency cooling systems are unavailable.

The EC6 will further build on these inherent passive safety features by improving the reserve water tank to supply cooling water by gravity to key systems in case of a severe accident. Also, there is the addition of a low-flow containment spray, and passive autocatalytic combiners. Postulated severe core damage accidents progress slowly, giving ample time for accident management and implementation of counter measures.

AECL is performing a comprehensive review of the EC6 design in the wake of the Fukushima accident. Post-Fukushima, the Canadian Nuclear Safety Commission made a presentation [3] to the Convention on Nuclear Safety on Canada’s response, including re-affirming the CANDU two-group philosophy against common mode failure, and the presence of numerous, diverse heat sinks to manage severe accident conditions. Also noted was that AECL would review lessons learned, and incorporate any necessary improvements into new build design.

3. Fuel Cycle Options

AECL has had a continuous fuel cycle program and vision [4, 5] for more than 40 years, including: reactor physics and core design, fuel design and fabrication, irradiation and demonstration, reprocessing and separation, cycle optimization and commercial deployment options. The advanced CANFLEX™ fuel bundle [6, 7] has been developed as the optimal fuel-cycle carrier. AECL anticipates that the first step in the evolution of CANDU fuel cycles will be the introduction of Recovered Uranium (RU), and its variants, derived from conventional reprocessing.

3.1 Recovered Uranium

Recovered Uranium (~0.9% enriched) from reprocessed LWR fuel can be used in CANDU without re-enrichment—offering access to a potentially economical supply of LEU fuel at the optimal enrichment level [8]. The enrichment level is dictated primarily by the limit placed on fuel discharge burnup. Benefits of RU include potentially low fuel costs, because, until recently, RU has been considered a waste product and a further reduction in spent fuel volumes.

A low-risk CANDU RU variant that is being currently demonstrated envisages a combination of RU and Depleted Uranium (DU), both waste streams, giving an NU equivalent (NUE). With favourable RU and DU prices, this is the most economic option, requiring no changes in the reactor or licensing and utilizing 100% waste products from other reactors. With equivalency of the RU/DU mixture to NU established, impact on the reactor core will not be different from that in current CANDUs. This fuel cycle—providing the ability to burn two former waste products (RU and DU)—differentiates CANDU plants from all other reactor options. CANDU plants offer the simplest and most cost-effective way of burning these products.

An NUE demonstration irradiation [9] is currently underway in the Qinshan Unit 1 CANDU reactor in China. Of 24 test bundles, four have already been removed; initial examination has revealed no unexpected behaviour. The next stage in this process is a full-core NUE transition.

3.2 Thorium Cycles

Thorium is a key element in AECL's fuel cycle vision for CANDU and represents a low-uranium-consumption fuel cycle option [10, 11]. Thorium capability is attractive to countries with thorium reserves but no uranium—addressing the need for energy self-reliance.

In a short-term strategy**,** the low-risk approach to initiating the thorium fuel cycle in a CANDU reactor is by adding the fissile component as LEU in separate elements in a mixed LEU/Th fuel bundle, using an existing fuel design. The enrichment of the LEU elements can be varied to give the desired burnup, which can be gradually increased with experience. The *in-situ* fissioning of the U-233 produced through neutron capture in Th-232, also builds up a strategic resource of ^{233}U.

However, the major benefit is achieved via closed thorium fuel cycles. In the medium term, the plutonium from reprocessed LWR fuel can be used as the fissile component in a homogeneous Pu/Th CANDU fuel bundle. A full core of Pu/Th fuel could further increase the energy derived from utilizing thorium, require no new natural uranium, and produce additional U-233 in the used fuel for future recovery and recycling. In the longer term, a self-sufficient thorium fuel cycle would be the most economically attractive, breeding enough ^{233}U that—through its recycle—could keep the fuel cycle running indefinitely, without the need for an additional, external supply of fissile material. In the future, a CANDU-FBR synergism could allow a few expensive FBRs to supply the fissile requirements of less-expensive, high-conversion-ratio CANDU reactors, operating on the thorium cycle.

Currently, AECL is exploring the feasibility of a multi-bundle thorium demonstration irradiation [9], employing the low-risk option described above. The next logical step would be a full-core demonstration. At the same time, AECL is initiating the conceptual design of a purpose-designed thorium-capable CANDU reactor, based on the C6/EC6 platform.

4. Other Fuel Cycles

AECL is continuing to develop other fuel options—including MOX and actinide waste. CANDU's ability to use low-fissile fuels also makes possible a unique synergism with light water reactors (LWRs). Recently, there has been considerable attention paid to CANDU as a "burner" of the transuranic (TRU) actinide waste that comes from reprocessing used LWR fuel [12-14]. Many TRU actinides are long-lived (e.g., Am, Cm, Np) and produce decay heat long after being discharged from the reactor. This decay heat provides waste management challenges, including the management of extended heat loading of storage/disposal facilities. CANDU's neutron economy results in a high TRU destruction rate, and on-power fuelling permits the optimum location and residence time of actinide targets.

5. Summary

Capitalizing on the proven features of CANDU technology, AECL has designed the EC6 to achieve high safety and performance standards consistent with customer expectations. Changes have been made to meet current licensing requirements. The resultant EC6 reactor product provides a low-risk evolution of the Qinshan CANDU 6s, while providing safety, maintainability and operability enhancements. We have presented the basic EC6 design enhancements; AECL works with its customers to assess their individual design requirements.

AECL is performing a comprehensive review of the EC6 design in the wake of the Fukushima accident, will review lessons learned, and incorporate any necessary improvements into new build design.

In fuel-cycle development, AECL anticipates Recovered Uranium and Thorium will be first new fuels used in CANDU, thus introducing low-uranium consumption cycles. AECL is also developing other fuel options—with a focus on destroying actinide waste. The CANFLEX fuel bundle is the optimal carrier, tailored for individual fuels.

6. References

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