1. Introduction

Atomic Energy of Canada Limited (AECL) is a crown corporation established in 1952 to develop peaceful applications of nuclear energy. It employs more than 4,000 people who are dedicated to delivering a full scope of leading edge nuclear technology and services to nuclear utilities worldwide, including:

- engineering, project management and construction of CANada Deuterium Uranium (CANDU) nuclear power plants
- research and development (R&D), reactor development and design
- reactor services and technical support to operating reactors
- fuel and fuel cycles, waste management and decommissioning

The Enhanced CANDU 6 (EC6) reactor offers a combination of proven and state-of-the-art technology. Building on the highly successful CANDU 6 reactor AECL’s continued commitment to research and product development, and an ongoing program to incorporate proven modern technology has further evolved the CANDU 6 design.

The 10 CANDU 6 reactors, operating in five countries around the world, are yielding excellent capacity factors. One more CANDU 6 reactor is under construction in Romania. The fleet average lifetime capacity factor of the operating CANDU 6’s to the end of 2005 was 87.4%. The most recent six CANDU 6 reactors entering service had a fleet average lifetime capacity factor of 90.3%. Three of the Wolsong units in Korea were in the top 10 reactors in the world over the last decade. This performance has been achieved while maintaining an excellent safety record. The CANDU 6 design includes passive heat sinks through the moderator and shield tank inventory, which remove heat and limit core damage progression.

The EC6 has set new objectives to further improve the CANDU 6 by raising its power output, simplifying operations and maintenance thereby reducing operator’s workload, deal with obsolescence issues and streamline the design. The target operating life for the EC6 will be up to 60 years, which will be achieved with replacement of certain critical equipment around mid life. A two-unit EC6 station offers significant cost advantages, flexibility in operation and ability to be connected to any grid size. With a projected capacity factor of 90% and AECL’s demonstrated ability to maximize localization and commitment to transfer technology, the EC6 is indeed well suited to meet the energy needs of the 21st century.

This paper describes the key technical features of the Enhanced CANDU 6 design that provide the benefits listed above.

2. Improved Plant Power Output

AECL’s latest CANDU 6 plants built at Qinshan site in China deliver a gross output of 720MWe per unit and the Wolsong 2/3/4 plants in Korea deliver up to 735 MWe. Advancements done by AECL since to further improve the plant output up to 750 MWe gross include:

- installation of an Ultrasonic Flow meter (UFM) - to improve the accuracy of feedwater flow measurement
- improvements to the Moisture Separator Reheater (MSR)
- reduction of steam losses across the CSDV’s and ASDV’s
- optimization of the BOP thermal cycle
Reduction of the station house loads, will be achieved by the utilization of more efficient equipment such as improved feed water heaters, more efficient pump motors, lowered pressure drop across various equipment, more efficient station transformers, and optimization of station lighting etc.

![Graph showing lifetime capacity factor % for various plants](attachment:Figure_1.png)

**Figure 1: CANDU 6 Lifetime Performance (to December 2005)**

AECL continues to develop other features to further improve the station’s power output while maintaining the proven characteristics of the CANDU 6 design, which over time have proven to be extremely reliable with an excellent performance record dating back to the early 1980’s.

### 3. 60 Year Plant Life

The EC6 design offers a target life of up to 60 years with one mid-life refurbishment of certain critical equipment, such as the fuel channels and feeders. This objective will be achieved by elongating the fuel channel bearings, thickening the pressure tube slightly, increasing the feeder wall thickness, using improved equipment and materials, better plant chemistry, and more active monitoring of critical plant parameters. All life-limiting factors have been evaluated and addressed supported by extensive R/D. By essentially doubling the useful life of the reactor, the plant owners are assured of a long-term supply of their electricity needs and improved return for their investment in the asset.

### 4. Simple Plant Operability and Maintainability

AECL has an active feedback monitoring system process that continually captures feedback from operating plants and incorporates this experience in the design of CANDU reactors. Based on this feedback, AECL is modifying a number of systems to simplify maintenance and reduce operator workload. As an example, the cooling water systems design has been improved to have dual trains that enable interconnections of these trains during maintenance or plant upset conditions. Automated safety system testing will be incorporated that not only reduces the testing workload but will also eliminate human errors that can cause inadvertent reactor trips.

In addition, AECL has developed a number of health monitors that will be incorporated in new plants or added as retrofits to existing plants.

### 5. Reduced Project Schedule

The EC6 overall project schedule is aimed at 57 months from first concrete to in-service, with a second unit to follow 6 to 9 months later. These targets will be achieved by the use of additional modularization, open
top construction using a Very-Heavy-Lift (VHL) crane, pre-ordering of some long delivery items, and standardizing various pieces of equipment such as valves, tanks, piping etc.

6. Robust Plant Security

The EC6 offers improvements to the plant’s security by including protection against aircraft strikes and external events. The containment civil structure will be thickened and more reinforcing steel added to meet this requirement. Further hardening of the safety systems and improving the spatial separation of essential safety systems is now built into the design. Group 2 safety systems, which offer a redundant path to shutdown the plant safety, will be rearranged to be protected from the impact of an aircraft strike. Depending on the location of the plant, the EC6 can also be designed to meet tornado protection. AECL implements ALARA principles in all of its safety design work.

7. Optimized Plant Maintenance Outages

As part of improving the capacity factors of the EC6, AECL undertook a detailed assessment of the requirements for maintenance outages. Periodic short duration outages once every two year will be a key target of the EC6 reactor. This objective will be achieved by automating a number of tasks such as testing of shutdown systems. Majority of these activities can be undertaken with the reactor at power. In addition, extensive use of Reliability Centered Maintenance (RCM) techniques will be employed in lieu of the equipment maintenance schedules specified by the equipment suppliers (after expiration of the warranty period). An array of health monitoring equipment will be installed to foretell impending equipment problems, which can be acted upon and avoid these from becoming more serious issues that could result in forced shutdowns.

8. Modern Computers and Control Systems

The EC6 has a number of features that modernize the plant, address equipment obsolescence, and a new control system. These features simplify plant displays, reduce the amount of wiring runs and save considerable construction effort and costs. The obsolete Digital Control Computers (DCC’s) will be replaced with more modern and state-of-the-art Distributed Control System (DCS) which will control and monitor various systems such as reactor operation, power generation equipment, fuel handling and auxiliary systems. The DCS supports both, group and device control, thus reducing the need for individual group controllers. In addition, a Plant Display System (PDS) is included that manages operator interactions with the DCS. The DCS/PDS also will include the functionality required to manage plant annunciation and support on-line procedures. The EC6 plant will incorporate the above features in a modern Advanced Control Room. Safety system operation is retained as a hardwired function. Computerized testing and displays have been added to ease the operator’s workload.

9. Improved Severe Accident Response

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

AECL has been enhancing the performance for CANDU 6 reactors under postulated severe accident conditions that go considerably 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 postulated severe accidents. In addition, the moderator is surrounded by a shield tank, which can also absorb decay heat should moderator cooling also fail. These features assure that the CANDU fuel does not melt
even if both, normal and emergency cooling systems become unavailable. The EC6 will further build on these inherent passive safety features to improve the dousing tank to supply cooling water by gravity to various systems in case of a severe accident. Severe core damage accidents would progress very slowly giving ample time for accident management and implementing necessary counter measures.

10. Flexible Fuel Cycle Options

The natural uranium fuel cycle offers simplicity of fuel design, ease of fabrication, and ready availability of natural uranium. These strategic features help to localize the technology. However, for those clients who desire to take advantage of alternative fuel cycles, the EC6 offers a number of options:

- The easiest first step in CANDU fuel-cycle evolution will be the use of slightly enriched uranium (SEU), including recovered uranium from reprocessed Light Water Reactor (LWR) spent fuel. Relatively low enrichment (up to 1.2%) will result in a two- to three-fold reduction in the quantity of spent fuel per unit energy production, reductions in fuel-cycle costs, and greater flexibility in plant operations.
- A high burnup CANDU MOX fuel design could utilize plutonium from conventional reprocessing or more advanced reprocessing options (such as co-processing).
- DUPIC (Direct Use of Spent PWR Fuel In CANDU) represents a recycle option that has a higher degree of proliferation resistance than does conventional reprocessing, since it uses only dry processes for converting spent PWR fuel into CANDU fuel, without separating the plutonium.
- Long-term energy security can be assured either through the thorium cycle or through a CANDU / FBR (Fast Breeder Reactor) system, in which the FBR would be operated as a “fuel factory,” providing the fissile material to power a number of lower-cost, high-efficiency CANDU reactors.

The 43-element CANFLEX (CANDU FLEXible) fuel bundle developed by AECL would be the optimal fuel carrier. When operated at current bundle powers, peak linear element ratings are reduced by 15-20%. Depending on burnup and fuel temperatures the fission-gas release within the fuel element will be reduced. Critical heat flux and critical channel power will be also increased, due to optimized heat removal characteristics of the bundle, which can be used to increase margins in operating reactors.

11. Improved Fire Protection System

The EC6 will be further improved as described below:

- To meet new codes and standards the EC6 will have upgraded firewalls and penetrations compared to previous designs. A new solid-state multiplex system will be used in place of the hard-wired system. Individually addressable detectors will also be used as required.
- AECL will perform a fire hazard assessment (FHA) to address potential fires and consequences in all areas of the plant, to demonstrate that safe shutdown can be achieved and maintained following all postulated fires.
- Based on FHA assessments, the EC6 design has been modified to include new approaches such as:
  - Installing clear aisle space to access cable rooms
  - Providing wider separation between stacks of cable trays
  - Locating cable trays away from potential small fire sources
  - Installing fire stops on long vertical runs of cables
  - Providing wider separation between fire retardant cables/ components for the shutdown systems
12. **Advanced MACSTOR Design for Dry Spent Fuel Storage**

AECL’s spent fuel dry storage technology evolved from the concrete canister system, which was successfully deployed at the Wolsong 1 and Point Lepreau CANDU 6 plants. The capacity of this generation of concrete canisters is 540 bundles (~10 MgU). This was followed by the development and successful use of the MACSTOR-200 modules to store spent fuel at the Gentilly 2 and Cernavoda stations.

To minimize space requirements and lower capital costs the MACSTOR design was optimized to address larger fuel throughputs. An Advanced MACSTOR design has been jointly developed with Korea Hydro and Nuclear Power (KHNP). The selected configuration is a 4-row MACSTOR module with a capacity of 24,000 bundles stored in 400 baskets, each holding 60 spent fuel bundles. The module is termed MACSTOR/KN-400 and is expected to offer a repetitive storage density increase by a factor of approximately 3, compared to concrete canisters. This module requires about 30% less space and is 10% lower in cost compared to two MACSTOR-200 modules.

13. **Enhanced Heavy Water Management Systems**

The EC6 will utilize AECL’s Combined Electrolysis and Catalytic Exchange (CECE) D$_2$O upgrader technology that has several advantages over the distillation process (DW) used by the currently operating plants. The CECE equipment is much smaller with lower capital costs, and the amount of steam, cooling water and chilled water required are also much smaller. CECE upgraders have much lower emissions of D$_2$O and tritium and lead to lower C14 from the off-gas system. This process offers several benefits including:

- A simpler, smaller layout which is more efficiently erected, resulting in a maximum of 34 months start-up after Contract Effective Date (CED), compared with 48 months start-up after CED for the DW plant
- The CECE design has approximately 40% higher tritium hold-up and a lower D$_2$O liquid hold-up of about 16%.
- The projected CECE tritium emissions are 500 times lower than DW emissions
- CECE technology can also be used for detritiation (removal of tritium) of heavy water.