ACR-1000: TECHNICAL FEATURES AND DEVELOPMENT STATUS

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1. Introduction

Atomic Energy of Canada Limited (AECL) has adapted the successful features of CANDU®* reactors to establish the Generation III+ Advanced CANDU Reactor™ (ACR™) technology [1], [2],[3]. The ACR-1000™ nuclear power plant applies this to an evolutionary product, starting with the strong base of CANDU reactor technology, coupled with thoroughly demonstrated innovative features to enhance economics, safety, operability and maintainability. This evolutionary strategy ensures that AECL’s innovations are based on current experience, and keeps development programs focused on one reactor technology. This focus reduces risks, development costs, and product development cycle times. It also assures utilities that CANDU technology will not become obsolete or unsupported, and will continue to be relevant and add value now and for the foreseeable future.

The ACR-1000 uses well-established, fundamental, CANDU design elements: core design with horizontal pressure tubes; simple efficient fuel bundle design; on-power refuelling and a separate low-pressure, low-temperature heavy-water moderator providing an inherent emergency heat sink. It includes adaptations for a light-water cooled, slightly-enriched uranium reactor, including more compact core configuration and higher steam pressure for greater thermodynamic efficiency.

The ACR-1000 benefits from AECL’s continuous-improvement approach to design, which has enabled the traditional CANDU 6 product to compile an exceptional track record of both on-time, on budget product delivery, and also reliable, high capacity-factor operation. ACR-1000 development is built around a comprehensive basic engineering program. This links the design with licensing, and with the development and demonstration of innovative features. The program emphasizes the development of the ACR-1000 from the viewpoint of the customer—the power plant operator.

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2. ACR-1000 Program and Strategy

AECL’s ACR development program initially concentrated on developing the enabling technologies supporting applications to reactor design, and on the parallel development of the ACR-700 (750 MWe output class) and ACR-1000 (1200 MWe class) conceptual designs. In order to take advantage of the modular nature of CANDU fuel channel design, and to exploit economics of scale, the program has over the past year completed the ACR-1000 product definition and has now moved on to detailed ACR-1000 design through the comprehensive Basic Engineering Program. The ACR-1000 product is well established, based on the thorough development and proof-testing of generic ACR technology:

- Key Product objectives, requirements and features defined and confirmed,
- Licensing basis established, and pre-licensing review under way with Canadian regulator
- Plant-wide Technical Description complete

Based on this design specification and safety support assessment, the ACR-1000 is ready to be considered in plant siting and environmental assessment reviews. Over the next two years, the Basic Engineering Plan will deliver the detailed ACR-1000 design ready for pre-project mobilization and will complete the safety submissions required for pre-licensing design review (under Canadian licensing practice, formal nuclear plant licensing only takes place for a specific plant project at a defined site).

The CANDU development path, leading to the ACR-1000 and beyond, is based on steady, manageable steps in design, supported by parallel expansion of the technology base. It is important to note the key role of the pressure tube concept in the development path. Pressure tubes have now accumulated well over 150,000 tube-years of in-service operation, more experience than any other major core component in any other reactor. Operating experience, materials advances, in-service performance monitoring, and replacements for pressure tubes have shown they possess key features for both performance and safety:

- Inherently modular in design, manufacturing and installation.
- Proven inspectable and replaceable for life extension.
- Benign safety characteristics, even for unlikely failure modes.
- Core subdivision so that large-scale core melt is impossible.
- Built-in passive cooling path to the moderator, for shutdown heat removal.
- Optimisation of the fuel cycle for waste minimization and flexibility.
- On-power refuelling for increased capacity factor, reactivity management and fuel cycle flexibility.

Free of vessel size and material constraints, allowing mass manufacturing to strict quality assurance standards, and coupled with an efficient moderator, the pressure tube allows the fuel channel reactor design the flexibility of differing reactor powers by simple design adaptation to different numbers of the fuel channel module included in the core. Coupled with the flexibility
of on-power fuelling, it also enables features such as using natural and low enriched uranium, and mixed U-Pu fuels as well as sustainable thorium cycles.

Prior to the current thorough pre-licensing review by the Canadian Nuclear Safety Commission (CNSC), generic ACR technology has been examined by the CNSC for the past three years. A full pre-licensing status of the ACR-1000 is given elsewhere in this conference [4].

To complete the ACR-1000 development requires completion of testing of ACR innovations, a major engineering program, and successful pre-licensing in Canada. The ACR program plan includes all these elements, centred on an ACR-1000 project plan to develop and deliver the first ACR-1000 to commercial operation.

3. **ACR-1000 Product Description**

The standard ACR-1000 design is a 1200 MWe class nuclear power plant, which has evolved from AECL’s existing successful product lines. The ACR-1000 applies the advanced CANDU technology developed in the ACR program. All innovative features of the ACR-1000 will be fully tested and proven before the first project. The design also makes extensive use of successful features of existing CANDU technology. By doing this, the ACR-1000 can be developed and applied in initial projects with a high degree of confidence. The ACR-1000 has the following major features:

- Twin-unit configuration with common control room building (can be delivered in single unit configuration)
- Compact, horizontal pressure tube core design following traditional CANDU overall configuration
- Enhanced inherent and passive safety with Moderator and Shield Tank heat sinks supplied by passive water makeup from Reserve Water Tank.
- Core consists of low-pressure, low-temperature calandria tank containing heavy-water moderator, within which fuel channels are located, each containing 12 standard-length, enriched, ACR fuel bundles. Coolant is light water.
- Fuel channel consists of a Zirconium alloy pressure tube, surrounded by a Zircaloy calandria tube, and attached to coolant system feeder piping by individual end fittings.
- Core refueling is carried out via two computer-controlled fuelling machines, on-line
- Reactivity control and shutdown mechanisms are located in the low-pressure calandria tank with no possibility of accidental high-pressure ejection.
- Four-quadrant layout with four-way redundancy of safety support systems,
- Indirect thermal cycle (similar to PWR reactors), with the reactor coolant system transferring the heat from nuclear fission, through vertical shell-and-tube steam generators, to a conventional secondary turbine cycle.
- Customer-driven improved features for operability and ease of maintenance.

While retaining proven CANDU features, innovations in the ACR-1000 design include:

- Use of light-water coolant in the CANDU coolant system, in conjunction with the continuing use of heavy water moderator in the calandria
- Design of a more compact core configuration to enable optimized reactor physics characteristics
- Use of low enriched fuel with higher burnup than the Natural Uranium (NU) fuel used in traditional CANDU reactors.
- Increased coolant system and turbine pressure to increase the overall thermal efficiency of the power plant.

The plant layout is designed to achieve the shortest practical construction schedule. This is achieved by simplifying the design, minimizing and localizing interfaces, parallel fabrication of module assemblies and civil construction, reducing construction congestion, improving access, providing flexible equipment installation sequences, and reducing material handling requirements.

Security and physical protection have also been taken into consideration in the development of the plant layout. Physical protection is provided through ample separation. The reactor building consists of a steel-lined, prestressed concrete containment structure and a reinforced concrete internal structure supported on a reinforced concrete base slab. The containment structure provides an environmental boundary, biological shielding, and a pressure boundary in the event of an accident. The building layout is arranged to provide separation by distance, elevation or barrier for safety related structures, systems and components. These features reduce the likelihood of common mode failure of safety systems due to malevolent acts such as an aircraft crash.

The ACR-1000 reactor core has the following characteristics:
- Compact size combined with on-power refuelling.
- Reduced heavy water requirements due to compact core size (lattice pitch of 240 mm versus 286 mm in current CANDU units) and the use of light water as the coolant.
- Moderate negative coolant-void reactivity.
- Simplified reactor control through negative feedback in reactor power.

The ACR-1000 reactor operates at a high radial power form factor and a relatively flat axial power shape. The ACR-1000 form factor of 0.94 compares favourably with the CANDU 6 form factor of 0.84. The flat axial power shape gives higher critical channel power than that for the centre-peaked power shape in a natural uranium-fuelled CANDU core, while enabling lower peak fuel ratings. Because of the unique light water/heavy water core configuration, the heavy water reflector plays a strong role in core characteristics. As a result, the high form factor is achieved along with increased core stability.
5. Safety by Design

A full description of ACR-1000 safety features is given elsewhere in the conference [5]. The ACR-1000 design takes advantage of inherent and engineered safety characteristics.

The core has a negative power reactivity coefficient, which provides inherent protection against transients with inadvertent increase of reactor power. Additionally, two diverse and fully capable, fast-acting, independent shutdown systems are provided. Each system can shut down the reactor for the entire spectrum of design basis and anticipated events. Also, the separate control system shuts down the reactor for Anticipated Operational Occurrences.

Further safety in-depth is derived from the inherent design features of the channel core. The moderator heavy water surrounding the fuel channels water in the calandria is itself an additional, diverse active/passive heat sink. The calandria is filled with heavy water to a level well above the top of the calandria shell. This heavy water acts as both a moderator and reflector for the reactor, as well as an assured heat removal option. The moderator system is a low-pressure and low-temperature system that is fully independent of the heat transport system. Moderator heat exchangers remove the heat generated in the moderator during reactor operation and shutdown. Passive make up to the moderator is provided, and long term cooling assured by a Reserve Water Tank.

Core retention within the vessel includes both retention within fuel channels, and retention within the calandria vessel. The moderator heavy water in the ACR-1000 calandria vessel, as in any other CANDU-type reactor, provides ample heat removal capacity in severe accidents. The ACR-1000 calandria vessel design permits for passive rejection of decay heat from the moderator to the shield water. Also, the calandria vessel will be designed for debris retention. Core damage termination is achieved by flooding of the core components with water and keeping them flooded thereafter. Successful termination can be achieved in the fuel channels, calandria vessel or calandria vault by water supply by the Long Term Cooling pumps and by gravity feed from the Reserve Water System.

The ACR-1000 containment is required to withstand external events such as earthquakes, tornados, floods and aircraft crashes. Containment integrity maintenance is achieved through control of containment pressure, flammable gas control, and control/prevention of the core-concrete interaction. The containment system includes the steel-lined, prestressed concrete reactor building containment structure, access airlocks, building air coolers for pressure reduction, and a containment isolation system, consisting of valves in certain process lines and ventilation ducts that penetrate the containment structure.

6. Ease of Operation and Maintenance

The design basis lifetime capacity factor for ACR-1000 is 90% over the operating life of 60 years. The year-to-year design capacity factor is 93%. Customer feedback has resulted in many detailed operational and maintenance improvements being incorporated into the design to meet the performance targets. Additionally, use of CANDU operating experience facilitated by the
information network provided by the CANDU Owners Group (COG) will further improve the performance of the plant.

On-power maintenance and testing are optimized, reducing the frequency of outages to once every three years, with planned maintenance outages not exceeding 25 days. The forced outage rate will be less than seven days/year through design optimization, and through the use of System-Based Maintenance strategy. The plant layout is optimized to facilitate online maintenance and inspection, to provide access for equipment exchange, and to provide effective common services for the two-unit plant design resulting in reduced maintenance costs. For Plant Life Management purposes, there is provision of space and services to support a rapid, mid-life full-scale fuel channel and steam generators replacement program. Maintenance activities are enhanced to maximize component life and minimize component replacement time, thereby minimizing radiation exposure, replacement costs, and the number of operating and maintenance personnel required.

Application of existing CANDU computer control knowledge and experience, enhanced by state-of-the-art information system technology, has produced advanced plant control and monitoring systems that enable the plant to operate at higher capacity factors with a reduced operations staff. SMART CANDU™ modules provide on-line health monitoring and diagnostics for plant chemistry, predict future performance of components, determine maintenance requirements and optimal operating conditions and ensure optimal margins and maximum power output.

Enhanced radiological protection further reduces worker exposure and occupational dose such that the dose to an individual member of the station staff is expected to be less than 100 mSv over a five-year period with a maximum of 50 mSv in any single year.

7. Program Timetable

Currently the main focus of the ACR-1000 program is completion of design ready for project mobilization, and completion of pre-licensing in Canada. This provides both “country of origin” review, to enable the ACR-1000 to be evaluated internationally, and also ensures readiness for new nuclear construction in Canada.

Recently, the Ontario (Canada) government has announced that it will maintain the current portion of nuclear energy in its long-term electricity supply mix plan for the province. To follow this up, the Government has directed Ontario Power Generation (OPG) to proceed with an Environmental Assessment for nuclear new build at one of its existing sites.

The ACR-1000 program is planned to enable this advanced design to be ready for application in the Ontario market, with the first ACR-1000 in-service in 2016. Interest in new build in Canada is also increasing in other provinces, so that an ACR program of build projects can be envisaged, providing a platform for projects overseas.

8. Stepping into The Future

ACR-1000 advancements lead to the significant reduction in capital cost compared to present-day nuclear plants. But the development potential of the pressure tube concept does not stop there, as we examine the developments needed for even larger market penetration worldwide in the time frame 2025 or later.
In the medium term, the flexibility of the fuel channel concept means that ACR plants can be readily adapted to use advanced fuel options, including Pu and Thorium fuel cycles.

In the longer term, advanced reactor concepts naturally evolving from the ACR, have been identified. The pressure tube concept allows for great flexibility in the design of a Generation IV Supercritical Water Reactor (SCWR), as the density, power and flux profiles can be optimized. Further reductions of capital cost are also feasible. Moreover, having existing SCWR turbines means that no turbine development is needed, which further facilitates cost reduction. Safety is also enhanced in the SCWR concept, as the thermal energy per unit volume of is reduced, and containment can be optimized for reduced thermal loading.

8. References


