18th International Conference on Structural Mechanics in Reactor Technology (SMiRT 18)
Beijing, China, August 7-12, 2005
SMiRT18-S02-4

ADVANCED CANDU REACTOR, EVOLUTION AND INNOVATION

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Advanced CANDU Reactor, ACR-700, ACR-1000, CANDU Pressurized Tube Reactor, Calandria, Fuel channels, On-Power refuelling, Heavy Water Moderator, slightly enriched uranium, Hydrogen production, Oil sands

ABSTRACT

Atomic Energy of Canada Limited (AECL) has developed the ACR™ (Advanced CANDU(1) Reactor™) to meet today's market challenges. It is a light water tube type pressurized water reactor and is the latest evolution of CANDU technology. The design was launched to be cost-competitive with other generating sources, while building on the unique safety and operational advantages of the CANDU design.

The ACR is an evolutionary design that retains the proven CANDU features delivered at Qinshan Phase III, while incorporating a set of innovative features and proven state-of-the-art technologies that have emerged from AECL's ongoing Research, Development and Demonstration programs. This approach ensures that key design parameters are well supported by existing reactor experience and R&D. The result is a design that delivers a new threshold in safety, performance and economics while retaining ample design margin.

AECL has developed the enabling technologies and components for the ACR design, and has applied them to two plant sizes, ACR-700 and ACR-1000.

The ACR integrates hallmark characteristics of traditional CANDU plants (e.g. horizontal pressure tubes, on power fuelling, automated reactor control systems, and dual independent shutdown systems), new innovations (e.g. state-of-the-art control room, extensive use of modular construction techniques, smaller reactor core, enriched uranium fuel), and certain PWR features (e.g. light water coolant, negative void reactivity). The ACR is designed for a high capacity factor and low operation and maintenance costs. It fully exploits the construction techniques that contributed to the impressive schedule accomplishments at Qinshan Phase III and therefore features a very short construction schedule, 40 months construction schedule (First Concrete to Fuel Loading) for the first unit with improvements to 36 months for later units. The ACR is a true Gen-III plus product with a broad application. It has been proven to be an ideal burner for MOX and Thorium fuel and is the promising backbone technology for a large-scale sustainable development of nuclear power in the world. It has also been assessed for application in hydrogen production and in the development of Canadian oil-sands resources

This paper presents an overview of the Advanced CANDU®* Reactor concept, summarizes the advanced technologies used to achieve construction and operational improvements, and other key features introduced to enhance its competitiveness

1. INTRODUCTION

Recent changes in the energy supply marketplace, in particular price volatility and supply uncertainties for hydrocarbon based energy, and the aftermath of the Kyoto agreement have led to greatly increased recognition of the value of the existing fleet of operating nuclear power plants (NPP's). The proven reliable low-cost electricity supply from mature operating NPP's are leading for example, to a strong trend to implement Plant Life Extension Projects for operating plants and to build new plants in the USA, Canada and elsewhere in the world.

The newly emerging electricity and energy marketplace presents new challenges for the construction of new NPP's:
- Plant financing depends increasingly on private equity, where high rates of return are expected.
- Greater volatility of the market drives shorter payback times.
- Project sponsors expect strong and well-supported licensing cases, high reliability and top capacity-factors.
- Rapid construction and generally shorter project durations, to reduce financial risk.
- Competitive cost of power generation.
- Increased safety.
- Operational advantages.

2. TRADITIONAL CANDU FEATURES

CANDU uses natural uranium as fuel and heavy water as moderator. In the traditional CANDU configuration, the fuel coolant and the moderator are separate. Natural uranium contains 0.7% fissile U-235, a trace of U-234, and the remainder is U-238. Since fission cross sections are highest at low neutron energies, it is necessary to slow the neutrons down to very low energies, below about 0.6 eV. This is called "moderation" and is characterized by neutron collisions with materials such as water (H2O), heavy water (D2O), and graphite, which have relatively high cross sections for scattering and relatively low cross sections for neutron absorption. In a traditional CANDU, heavy water increases the efficiency of the core since it moderates the neutrons while absorbing relatively few of them. For other reactor designs, where light water is used as a moderator, the fuel is enriched to 3 to 5% to overcome the higher neutron absorption.

The CANDU reactor has a modular core, made up of fuel channels. Each fuel channel contains 12 or 13 small fuel bundles, each of which is 50 cm long and 10 cm in diameter, and weighs about 24 kg. The fuel bundles consist of a number of small ~1.2 cm diameter tubes, called fuel elements, filled with UO2 pellets. A bundle containing natural uranium with 0.7% fissile U-235 remains in the core for 12 to 18 months, and generates about 1 million kWh of electricity. This is sufficient energy to provide a typical family with electricity for about 100 years.

The fuel channels are aligned horizontally in a large vessel, called the calandria. The calandria vessel is filled with heavy water to slow down (moderate) the energetic neutrons produced in the fission process, as discussed above. Each fuel channel consists of two concentric tubes. The inner pressure tube contains the fuel and the high temperature, high pressure cooling water (about 310°C and 10 MPa). The outer calandria tube isolates the low pressure and temperature moderator from the high temperature pressure tube, and is insulated from the pressure tube by a small annulus filled with carbon dioxide. The power output from the reactor can be increased or decreased by changing the number of fuel channels in the core.

The entire core structure fits into a large steel-lined vault filled with light water, which acts as a radiation shield. The presence of this shield and other aspects of the design mean that many maintenance activities can be performed without shutting the reactor down. The combination of the calandria and the shield tank is called the reactor

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assembly. The reactor assembly is connected to the heat transport system and steam generators via feeder tubes and headers, as shown in Figure 2. A thick-walled pre-stressed concrete containment building surrounds the reactor assembly and other major equipment such as the steam generators, to protect the reactor against external events and to contain any radioactivity in the unlikely event that the normal and safety systems fail.

A second important characteristic of the CANDU core is on-power fuelling. To achieve this, fuelling machines attach to each end of a fuel channel while the reactor is still operating. New fuel bundles are pushed into one end of the fuel channel and the used fuel bundles are collected at the other end. LWR's are typically shut down approximately every 18 months to refuel the core. CANDU reactors only need to be shut down for scheduled maintenance.

The CANDU core has a number of passive safety features. For example, the moderator is a passive heat sink for the core if normal and emergency cooling are both unavailable. The shield vault surrounding the core holds even more water than the moderator and will contain the core material if the moderator is also impaired. These, and other, passive safety systems are discussed in a later section.

It is the combination of efficient moderation using heavy water, modular fuel channel configuration, on-power fuelling, simple fuel bundle design, and passive heat sinks that are the defining features of any CANDU reactor.
Globally, there are more than 100 reactor years of experience in the operation of CANDU 6 units alone. The performance of these units, shown in Table 1, has been consistently good and the average capacity factor for all units over their lifetime is 86%.

CANDU 6 reactors at Wolsong occupy three of the top six world lifetime performers [3]

3. ECONOMICAL CONSIDERATIONS TODAY

In today's economy, the traditionally high initial capital cost of nuclear power must be reduced to maintain nuclear generation competitive with other sources of electricity, particularly natural gas (ignoring for the time being the undesirable greenhouse effects produced by the latter). If the initial capital cost of nuclear plants could be reduced, then even comparing it with relatively modest natural gas price increases, nuclear power would be the least expensive option for large-scale energy production.

Utilities could take a very long-term approach to stable energy production and could also access capital at rates that made large investments viable. With these premises, the ACR-CANDU® reactor would have to result in a cost reduction of 30-40%.

4. EVOLUTION AND INNOVATION

AECL has consistently adopted the evolutionary approach to the development of nuclear power plant designs. Central to this strategy is the discipline of basing next generation technology on the current technology.
Innovations are never radical but rather based on current experience and research-supported advances. Development programs are focused on one reactor concept, reducing risks, development costs, and product development cycle times.

The CANDU system is ideally suited to an evolutionary development strategy. The modular fuel channel reactor concept can be modified progressively, through a series of incremental changes, to improve economics, safety margins and performance. This approach builds confidence in CANDU development and assures our customers that the product will never become unsupported.

AECL has evolved the Advanced CANDU Reactor (ACR) design from its highly successful CANDU-6 design. Since the early 1990's, six new CANDU 6 plants were delivered on or ahead of schedule and on budget. This record is a remarkable achievement for large construction projects. It demonstrates the maturity of the CANDU technology.

The CANDU reactor design is extremely flexible and with much space to improve, since the core had been originally designed to optimize the performance of natural uranium fuel and to achieve high neutron economy. Since there is a smaller fraction of fissile material in natural uranium, a somewhat larger reactor core was needed. However, by switching to slightly enriched fuel, ACR can provide the same energy output from a much smaller and hence economical core.

The ACR design was retrofitted with all the continuing CANDU research-based innovations and improvements driven by operating feedback and by state-of-the-art advances supported by enabling technology, with strongly rooted scientific data and testing. For this reason, the ACR concept will likely remain competitive for a number of years and lead to the next phase of CANDU development, the Supercritical Water Reactor (SCWR).

5. EVOLUTION OF THE ACR DESIGN

In order to meet today's economic drivers, the following economical enhancements were adopted as high-level performance objectives of a new advanced CANDU design:

- Capital cost reduced by 40% for the n^{th} advanced reactor units.
- Construction and project schedule reduced by two years for the n^{th} units.
- Safety margins enhanced or maintained;
- Maintainability and operability of the plant enhanced to support even lower lifetime costs.

In order to achieve these objectives and in keeping with the evolutionary development principle, every improvement had to be an extrapolation from the currently established CANDU design. In addition, only improvements that had firm technical foundations were adopted, based on several years of R&D activity to secure the underlying knowledge. Finally, only changes that could be demonstrated in the R&D programs within a five-year period were accepted.

The following enabling technologies made available in steps through R&D over the years that witnessed the deployment and operation of current generation II reactors were used:

- Slightly enriched uranium fuel to achieve increased burn-up due to increased fissile content of the fuel.
- Light water replacing heavy water as the reactor coolant, which allows a core size reduction.
- More compact core design with reduced lattice pitch, reduced heavy water inventory reduced excess reactivity and a flat core neutron flux.
- Increased safety margins via an optimized power profile and negative void reactivity.
- Higher operating pressures and temperatures of the coolant and steam supply resulting in improved thermal cycle efficiency.
- Reduced emissions.
- Improved performance and more precise maintenance planning through an advanced operational and maintenance information systems.
- Improved project engineering, manufacturing and construction technologies.

Given these guiding principles and objectives, the major issues involved for the engineering of the advanced CANDU reactor became the optimization of the reactor physics, fuel and fuel channel design, reactor control, heat-mass transfer efficiency, and materials performance.

6. IMPROVED DESIGN MARGINS

The starting point for the optimization process was the fuel design, which was the central enabling technology for the ACR. The evolution of CANDU fuel has led to increasing the surface area of the fuel, which allows more efficient heat transfer to the coolant. More effective heat transfer allows the fuel to achieve higher burnups (the total amount of energy extracted from the fuel) and to better accommodate other types of fuel, such as slightly enriched uranium.

A key decision for the ACR was to switch from natural uranium fuel to enriched uranium fuel. With enriched fuel, the CANFLEX fuel bundle could achieve much higher burnups than current fuel, which reduces the amount of wastes. For example, with the enrichments used in ACR, the burnup can be increased almost by a factor of 3 compared to natural uranium fuel, with the same reduction in the volume of spent fuel. In addition, the significantly improved critical heat flux margins and lower element power ratings enabled an increase to the fuel channel output, without degrading operating margins and the core radial power distribution could be improved. In current CANDU designs, the outermost channels produce less than 60% of the power produced by the inner channels due to the radial neutron flux distribution, which falls off in the outer regions of the core, notwithstanding a layer of D_2O reflector surrounding the core.

The smaller core size for the ACR with enriched fuel results in more uniform fluxes due to the increased importance of moderation in the D2O reflector. The more uniform radial flux distribution across the fuel channels results in a much flatter radial power distribution.

A higher degree of passive safety can be achieved if the void coefficient is slightly negative – (where the void coefficient is a measure of the change in power if a reactor core were to lose coolant). If the void coefficient is positive, the change in power is also positive in other words with voiding in the channel due to an upset condition, the reactor power would increase, but if the void coefficient is negative then core voiding would result in a power decrease.

The lattice spacing of the core's fuel channels is the key parameter that determines the coolant void reactivity in CANDU reactors. For the ACR, the coolant void reactivity was reduced by decreasing the lattice pitch (from 28.5 cm to 22 cm), resulting in an under-moderated lattice condition.

7. INCREASED THERMAL PERFORMANCE

The thermal efficiency of the reactor was also increased by increasing the temperature and pressure of the coolant and steam supply systems. The peak reactor outlet temperature is 324ºC, an increase from the CANDU 6, but still below the highest temperatures used in PWRs. The higher coolant temperature produces a steam supply pressure of 6.5 MPa, which is 2 MPa higher than the CANDU 6. These increases improve the thermal efficiency of the ACR steam cycle, which in turn, improved the turbine cycle efficiency, providing the plant with greater electrical output. The increase in thermal efficiency has resulted in a much smaller heat transport system, about half the size of the CANDU 6. Due to the fewer channels and the reduced fuel channel pitch, the diameter of the ACR core is also reduced. The smaller heat transport system and smaller core minimize the use of expensive assets such as heavy water and core materials. For example, the volume of heavy water used in the ACR-700 has been reduced to about 130 tonnes from 450 tonnes for the CANDU 6. Since heavy water costs about $300/kg, the savings just for the heavy water are substantial.

8. SAFETY IMPROVEMENTS

The ACR and other CANDU reactors are the only commercial reactors to incorporate two fast-acting, diverse and separate shutdown systems, that do not require access or entry into the high pressure primary circuit, and are physically and functionally independent of each other and from the reactor power regulating system. One system consists of mechanical shutoff rods, which drop by gravity into the core when needed. The second system injects a concentrated solution of gadolinium nitrate into the low-pressure moderator to absorb neutrons and drive the core to a sub-critical state. Either system can shut the reactor down within about two seconds.

If an accident occurs where the heat transport system coolant has been lost, then the Emergency Core Cooling system (ECC) provides cooling water. If the ECC also fails, then heat is transferred passively from the fuel into the moderator system. If the moderator system were to fail as well, then the third level of cooling is the shield water tank containing about 700 cubic meters of light water that prevents escape of core material out of the calandria vessel.

A 2500 cubic meter Reserve Water Tank (RWT) at the top of the reactor provides an additional passive safety source of water that is fed by gravity to various heat sinks in the reactor, including makeup water for the moderator, shield tank, steam generators, and ECC systems.

The containment system is the next barrier to the potential release of radioactivity to the environment. The containment system includes a steel-lined, pre-stressed concrete reactor building, access airlocks, building air coolers for pressure reduction, and containment isolation for process lines and ventilation ducts that penetrate the building. Heat removal is provided by local air coolers distributed in various compartments inside the reactor building.

If hydrogen could be produced and released to containment, hydrogen concentration control is provided by AECL's passive catalytic recombiners (PARS). These limit hydrogen content to below the deflagration limit within any enclosed compartment of the containment system. The PARS use natural circulation flow to remove the hydrogen.

There are several other safety enhancements for the ACR, including:

- Use of small, negative void reactivity coefficient;
- A more negative power coefficient over the operating range;
- Larger thermal margins due to the configuration of the ACR fuel bundle;
- Ability to contain a pressure-tube failure within the calandria tube;
- Interconnections of water and electrical systems between units of a twin-unit plant, enhancing reliability of the safety support systems;
- Inherent shutdown on single-channel failure;
- Extended seismic qualification;
- Severe accident prevention and mitigation features; and
- Design enhancements from CANDU Probabilistic Safety Assessments

9. THE BALANCE OF PLANT DESIGN

The balance of plant (BOP) consists of the turbine building, steam turbine, generator and condenser, the feedwater heating system with associated auxiliary, and electrical equipment. The BOP also includes the water treatment facilities, auxiliary steam facilities, pumphouses, main switchyard, and associated equipment to provide all conventional services to the ACR two-unit plant.

Two steam generators per loop are provided in the heat transport system. They discharge steam into a common header located in the turbine building that supplies the required steam to the turbine generator and the auxiliary steam systems. The power generating equipment consists of the following:

- A turbine generator set based on a tandem compound, reheat condensing type steam-driven single shaft turbine. The thermal cycle includes a two-stage moisture separator/reheater vessels located between the HP turbine exhaust and the LP turbine inlets. The generator is cooled with water and hydrogen and is provided with a static excitation system.
- A condenser with tubes at right angles to the turbine axis.
- A regenerative feedwater heating system with low-pressure stages, deaerating feedwater heater and high-pressure stages.
- Other auxiliaries associated with the turbine generator set.

Heat-balance calculations were performed for the ACR using HP turbine exhaust pressures ranging from 0.9 MPa to 1.4 MPa. From the calculation, the optimum value for HP turbine exhaust pressure was found to be approximately 1.1 MPa.

Heat-balance calculations for the condenser pressure (LP turbine exhaust pressure) were performed for pressures ranging from 4 kPa to 7 kPa, and included consideration of LP turbine-exhaust loss.

Increasing the condenser pressure increases the saturation temperature in the condenser, thereby increasing the mean temperature difference between the steam from the LP turbine exhaust and the CCW, permitting a reduction in the required heat-transfer area in the condenser. On the other hand, a higher condenser pressure reduces the output.

A LP turbine exhaust pressure of 4.9 kPa (a) was chosen as the reference for the ACR design, however this may vary depending on site-specific cooling-water conditions.

There is maximum thermal cycle efficiency at a particular final feedwater temperature, which can be considered the "optimum" final feedwater temperature for the given set of conditions. Final feedwater temperature also depends on the extraction steam condition and the turbine design.

The turbine-generator system, as well as the condensate and feedwater heating plant, are based on conventional designs. These include, for example, materials requirements (i.e., titanium condenser tubes, absence of copper alloys in the feed train), chemistry control requirements, feed train reliability requirements, feedwater inventory requirements and turbine bypass capability.

In order to achieve enhanced performance, higher TG steam operating temperature and pressure has been used compared to earlier CANDU 6 designs, resulting in higher thermal efficiency.

10. MODULARIZATION, AND CONSTRUCTION TECHNIQUES

The ACR design includes features and layouts to facilitate fast and efficient construction. New construction techniques and plans have been incorporated based on experience with these techniques at Qinshan in China. A four-part construction strategy has been adopted.

Paralleling activities: Running major construction activities in parallel rather than in series leads to a change in sequencing (logic) of activities, while many durations remain the same as traditional methods.

Modularization: Module fabrication goes on in parallel with construction, removing critical-path dependencies that exist with traditional construction methods. Modularization also reduces costs, reduces on-site manpower, reduces on-site congestion and results in improved labour productivity and safety, as well as in a higher product quality.

Open top (vertical) construction: By placing modules and major equipment directly into position inside the civil structures (and in particular the reactor building), temporary construction openings are eliminated and critical-path dependencies optimised. The required Very Heavy Lift (VHL) crane is utilized in all areas of the site.

Advanced construction technologies: Up-to-date construction technologies significantly shorten the construction schedule. These include the use of climbing formwork, prefabricated rebar, large volume concrete pours, use of bridging systems and prefabricated permanent formwork, use of pipe bending and automatic welding. A 3D CADDS model is used for the design, construction visualization and planning, and it is part of the overall integrated project control system.

By integrating advanced design features with advanced delivery technology from the start of design, the ACR achieves greater improvements than would be possible otherwise. The number of large modules used in the ACR reactor building alone has increased significantly relative to what was achieved on a CANDU 6 project due to the up-front emphasis on constructability. As a result, the n^{th}-of-a-kind ACR can be built in 36 months with a 48-month project duration.[1]

11. CAPACITY FACTOR AND OPERATION AND MAINTENANCE

[1] 36 months from first concrete to fuel load; 48 months from the contract-effective date to the in-service date.

The CANDU design has excellent reactor control characteristics that allow for efficient, reliable operation. Another important advantage stems from CANDU's use of on-power refuelling. This means that planned plant outages, e.g., for routine maintenance, can be timed at the plant operator or grid operator choice, unlike the case for other reactor designs, where outages for refuelling must occur at imposed intervals

12. HYDROGEN PRODUCTION AND DEVELOPMENT OF CANADIAN OIL SANDS RESOURCES

AECL has conducted extensive studies on sustainable and economic hydrogen cogeneration using nuclear energy.

The current technology of choice for hydrogen production is generally a Steam-Methane Reforming (SMR) process that requires a substantial amount of natural gas. Recent uncertainties in the availability and the price of natural gas have identified water electrolysis as a competing and promising alternative technology (DC electricity required). Electrolysis also has an added benefit of zero NOx, SOx and greenhouse emissions, a benefit that is expected to have a greater importance in the coming decade.

While electrolysis, generally can be more costly than SMR on a large scale, with current natural gas prices, there is data suggesting electrolysis will be a less costly approach for a small-scale production. This is because electrolysis is modular in nature, versus SMR where capital equipment requirements remain relatively fixed. In addition, further increases in natural gas prices can make electrolysis derived hydrogen competitive even at large scale manufacturing.

Large-scale water electrolysis can be integrated with the electrical grid to provide load balancing capability. The surplus power or off-peak power can be utilized to produce electrolytic hydrogen.

Another initiative being explored by AECL is the potential for ACR applications to Oil Sands in Alberta.

The need for clean, sustainable energy supply to enable the large-scale exploitation of Alberta's oil sands reserves has been discussed on many occasions over the years.

The Alberta oil sands bitumen deposits represent one of the largest sources of hydrocarbons in the world. Production of crude oil for bitumen has emerged as the fastest growing source of crude oil in Canada and it will soon be its largest.

The basic product of a CANDU reactor is pressurized hot water, which is used to produce steam. The steam can be used to generate electricity or used directly for any process needs, such as the Steam Assisted Gravity Drainage (SAGD) process. SAGD is an enhanced oil recovery process applicable to recovery of crude bitumen from deep oil sands deposits.

The steam pressure desired at the starting point for delivery to the SAGD well-head can range between 5 and 6.3 MPa at the ACR plant gate. In addition to steam supply, SAGD production facilities are significant consumers of electricity. The rapidly increasing level of industrial activity associated with the oil sands industry is also increasing the overall regional electricity demand.

In practice, each large oil sands project will have its own unique characteristics in terms of: steam supply quantity and quality; desired steam pressure; geographic location; electricity demand; etc. As a result, for each project, an ACR configuration would be defined and adapted to meet individual project needs with minimum changes to the standard design. AECL has defined and studied a range of configurations to take advantage of ACR characteristics and to meet various oil field conditions likely to be experienced in diverse SAGD projects.

The ACR presents an economically attractive option that can be adapted to wide variations in configuration to meet individual oil sands project specifications. Recent studies have established that ACR offers a cost advantage over the current energy source, natural gas.

Table 1. CANDU 6 Plants Operating or Under Construction

CANDU 6 Station	Location	In-service Date	Lifetime Capacity Factor
Point Lepreau	Canada	1983 February 1	83%
Wolsong Unit 1	Republic of Korea	1983 April 22	86%
Gentilly 2	Canada	1983 October 1	80%
Embalse	Argentina	1984 January 20	85%
Cernavoda Unit 1	Romania	1996 December 2	86%
Wolsong Unit 2	Republic of Korea	1997 July 1	92%
Wolsong Unit 3	Republic of Korea	1998 July 1	93%
Wolsong Unit 4	Republic of Korea	1999 September	96%
Qinshan Unit 1	China	2002 December	95%
Qinshan Unit 2	China	2003 July	-
Cernavoda Unit 2	Romania	2007 September(a)	-

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